Journal of Marine Science and Application
https://doi.org/10.1007/s11804-018-0053-1

RESEARCH ARTICLE

Study on Operation of Arctic Offshore Complex by Means of Multicomponent Process-Based Simulation

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Received: 22 September 2017 / Accepted: 8 May 2018

Abstract
We developed a detailed simulation model of the Arctic marine transport system (MTS) for oil platform Prirazlomnaya. The model has a multidisciplinary nature and involves: sub-models of various transport and technological processes; stochastic weather generator to obtain time series of 15 environmental parameters; and contextual planning algorithm to build voyage plan considering several types of ships and cargoes. We used a significant amount of real operational data to identify model parameters and to prove its statistical reliability. Our main scientific task is to investigate the interaction of various processes of a different nature, while the practical aim is to find a set of measures to increase the efficiency of MTS. The results of the study reveal many examples of the mutual interaction of various processes that need to be considered at the design stage to avoid technical mistakes. The study formed a basis for making managerial decisions at the top level of Gazprom Neft Shelf Company.

Keywords Marine transport system · Discrete event simulation · Offshore oil platform · Stochastic weather generator · Vessel voyage planning · Supply vessels operation · Arctic tankers

1 Introduction

Modern technical systems have a variety of subsystems and involve various elements and interconnections. Each element may have its original behavior pattern, while the interaction of elements is nonlinear and difficult to predict. Therefore, the design and analysis of large technical systems are connected with the complexity of various types. Several specialized theoretical characteristics are introduced in the literature to resolve the complexity.

Redundancy represents the ability of complex system to cope with an unpredictable deterioration of operation conditions in a passive way. Flexibility (adaptability) reflects the ability of the system to adapt actively to unexpected future events of a different nature. Beesemyer et al. (2011) noticed the importance of providing a sufficient level of redundancy in the complex system; the significance of considering the flexibility was described by Neufville and Scholtes (2011) and Weijnen et al. (2007). The infrastructure capacity management (Weijnen et al. 2007) is a useful technology to maintain the flexibility that helps to use the available capacity better (or to avoid unprofitable overcapacity) by means of planning. Risk-based design of marine systems (Breinholt et al. 2012) allows measuring the risk and helps to find an appropriate solution using probabilistic simulation. Risk evaluation is closely connected with such terms as survivability and environmental safety. Survivability of the system is the ability to remain functional and to continue the designated mission during the whole operational period. Beesemyer et al. (2011) called this parameter one of the primary criteria to differentiate between design alternatives. Another aspect of the system design process is the preferences of stakeholders that are to be taken into account (Agis et al. 2016). Complex mutual interaction of system elements could be described by the emergence that represents the nontrivial interaction between different parts, which results in another domain of complexity (Weijnen et al. 2007). Disregard for this aspect may lead to the fact that system will represent a patchwork of local solutions that decrease its efficiency and can lead to significant financial losses. The effective tool to model systems with complex behavior of many elements is the agent-based simulation (Weijnen et al. 2007). It allows estimating the system performance as a result of mutual interaction of the elements.

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Published online: 10 October 2018

In this study, we applied a multidisciplinary approach (Tarovik et al. 2017) to the problem of analysis of a real Arctic marine transportation system (MTS) for oil export and delivery of supply cargoes to/from the offshore ice-resistant oil-producing platform (OIFP) Prirazlomnaya. During the study, we tried to take into account such important characteristics of the system as emergence, redundancy, flexibility, and survivability. We also paid additional attention to introduce the elements of risk analysis and capacity management in different parts of the simulation model. The results of the study are obtained in close cooperation with the stakeholders from Gazprom Neft Shelf Company.

According to the system-based approach, each Arctic offshore project could be studied as a complex highly specialized system that involves transport, technological, natural and organizational processes. Typical elements of such a system are the ice-going cargo and supply vessels, icebreakers, ice-resistant offshore units (platforms, rigs, floating units, etc.), shore operational control office, and other objects. The primary processes in such a system are the following:

- Sea transportation of mineral resources (downstream logistics)
- Delivery of supply cargoes and taking out of backward cargoes (upstream logistics)
- Operation of offshore unit: technological processes and the influence of natural conditions

In most practical cases, these processes could be investigated separately. For example, cargo transportation process is usually analyzed independently from the supply process and in disregard for the operation of offshore units. At the same time, in some particular cases a mutual interaction of various processes can significantly impact the system performance. Many examples could be given here even for the case of operation of offshore systems in open-water conditions, but the interaction phenomenon becomes the most relevant in case of Arctic offshore systems. It follows from their complexity and severe non-stationary ice environments. OIFP Prirazlomnaya is one of the quite complicated examples of such Arctic system because it involves all the mentioned processes. The platform operation started in 2014. Since that, a considerable experience in the area of OIFP and fleet operation has been accumulated.

Our main scientific task was to investigate the interaction of various processes of a different nature in this system considering the gained operational experience and a number of described system's theoretical characteristics. Our practical task was to find a set of measures to increase the efficiency of MTS and reduce the level of uncertainty based on the conducted study of process interaction. From the practical point of view, MTS performance should ensure the planned growth in the rate of oil production from 2.1 million tons in 2016 up to 5 million tons by 2023. The full horizon of the study is the period from 2017 to 2038.

Therefore, the case study of Prirazlomnaya made it possible to analyze the interaction of complex and nonlinear processes in the Arctic offshore system based on the real operational data.

To make the article statements clear, we put the case study description before the section with an analysis of state of the art. Section 1 describes the features of the investigated transport system, as well as considered factors and assumptions made; here, we also describe the approach to build the simulation model considering the main details of Prirazlomnaya platform. Section 2 describes state of the art in the field of transport systems research using simulation and other related fields. The most massive Section 3 contains the description of the simulation model and its elements. Data on verification of the model is given in Section 4. The results are discussed in Section 5.

2 Statement of the Studied Case

2.1 Description of the Complex Offshore System

Linear transport system OIFP—Murmansk includes two principal directions of cargo flow: upstream delivery of supply cargoes to the platform and downstream export of oil and technological wastes. MTS includes the platform itself, two shuttle tankers, and a number of offshore supply vessels (OSV). Despite the apparent simplicity, the transport system is quite specific due to four important features.

Firstly, the variability of meteorological and ice conditions significantly influences the performance of MTS and the platform. This demands the detailed description of environmental conditions both at the area of platform location and on vessel routes. In addition, we need to create the corresponding calculation algorithms, which describe the influence of weather on operational performance of vessels and the platform.

Secondly, the oil offloading system at OIFP is not typical; oil is loaded to shuttle tankers directly from the platform together with processing of supply cargoes. At the same time, simultaneous cargo operations of tanker and PSV near the platform are restricted. This fact forces vessels of different types to compete for weather windows of terminals. However, unlike platforms located on the shelf of the Norwegian and Northern seas, Prirazlomnaya is available for cargo operations within 24 h per day. The platform has alternative cargo terminals for crude oil and supply cargoes, and each terminal has its limitations due to natural conditions. Eastern and western cargo cranes are intended to handle supply vessels, while north-western and south-eastern direct oil offloading systems

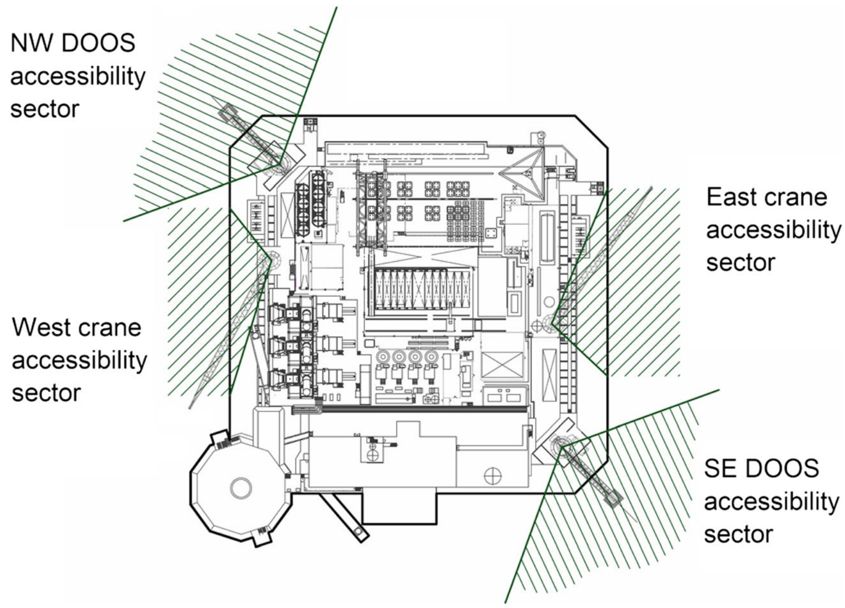


Fig. 1 Sectors of accessibility of OIFP cargo terminals in the direction of the integral impact of winds, waves, currents, and ice drift

(DOOS) are designed for tankers. Figure 1 shows a schematic layout of accessibility sectors of cargo terminals in the direction of integral force from wind, waves, currents, and ice drift. The helicopter deck is also treated as a separate passenger terminal having its own weather limitations.

Restrictions related to the weather and to the variability of natural conditions lead to the fact that cargo-handling process of tankers and supply vessels is noncontinuous. Several berthings of the ship to the platform are needed to reach the full load. Each berthing includes a variety of technological and organizational suboperations (mooring, hose connection, document processing, etc.). Various types of random distributions describe their duration.

The third principal feature of the investigated system is the complexity of cargo flows of crude oil and supplies. During the considered period of platform operation, cargo flows vary significantly both in their quantity and in structure. The multiple types of supply cargoes, as well as the usage of a single type of container for different types of supplies need to be taken into account. Also, the relationships between the volumes of supplies and the amount of the exported backward cargoes need to be considered.

And the last, fourth, main feature is the limited capacity of oil tanks, deck areas, and supply storages on the platform (for example, oil tanks volume is approx. 101 000 m^3). This makes it impossible to create dead stocks of cargoes, whereas just-in-time organization of supply and oil export processes is essential. Both a high-filling level of oil storage and depletion of supply storages are strongly undesirable events. Special measures need to be done in advance to avoid them. For example, if there is a risk of full filling of oil storage, a local decrease of oil production rate should be done.

2.2 Main Assumptions of the Model

We made a number of assumptions to make the model simpler, without depriving it of practical usefulness:

1) There are no delays of tankers and PSVs in the port of Murmansk due to any organizational and technical reasons. We assume that oil export from Murmansk by open-water tankers does not obstruct the operation of ice-class shuttle tankers; the dynamics of oil storage filling in Murmansk do not influence the duration of ship operations. We also assume that there are no delays of supply cargoes that are to be delivered to the OIFP, and storage of these cargoes in Murmansk does not have any operational limits.
2) Only normal operation of the fleet and platform is considered, emergency scenarios are not analyzed.
3) Bunkering of ships is not modeled, since it is assumed to be done during cargo operations in Murmansk without increasing the duration of the latter ones.
4) Docking of ships is also not modeled, because it is to be done during the annual scheduled off-stream period of OIFP without affecting MTS performance.

2.3 The General Plan of the Research

We found out that it is possible to study the described offshore system with an acceptable level of accuracy only within the integrated dynamic simulation model. This model should consider the following aspects:

- Operation of tankers and supply vessels in stochastic ice- and wind-wave conditions

- Dynamics of natural conditions in the area of OIFP location
- Accessibility of OIFP cargo terminals due to natural conditions
- Dynamics of oil production at the OIFP, as well as consumption of supplies and production of backward cargoes
- Various types of supply cargoes and their transportation in the corresponding cargo spaces of supply vessels
- Limited storage capacities of OIFP for different types of cargo
- Logistical voyage planning of transportation
- The complicated logic of ship cargo operations at OIFP including the possibility of several berthings and unscheduled interruption of operations due to weather conditions

We detached three main research tasks that need to be solved to realize the model with abovementioned capabilities:

1) Development of the comprehensive simulation model able to integrate the processes of transportation, platform operation, and dynamics of natural conditions.
2) Creation of the stochastic generator of natural conditions at the area of OIFP location. This generator will allow modeling of the accessibility of cargo terminals in time.
3) Development of the voyage planning algorithm that takes into account the multiple types of cargoes and technological processes on the platform.

State of the art section is divided into three parts according to the enumerated tasks.

3 State of the Art

3.1 Simulation of Offshore Systems

Despite the fact that simulation is a widespread technology and a useful approach to investigate complex technical systems, its application in the field of Arctic fleet operation is quite limited. We found out that first published studies on analysis of Arctic MTSs by means of modern discrete-event simulation (DES) are dated to the beginning of the 2010s.

In most of the studies, the stochastic simulation serves as a calculating instrument to address various scientific and applied tasks related to MTS operation. The most frequent one is the estimation of fleet size and optimization of main particulars of ships. For example, Kosmin and Tarovik (2013) used a DES-model to optimize the number and capacity of LNG carriers considering a requirement of regular ship arrivals to destination ports under non-stationary voyage times. Bergström et al. (2014) built the simulation model to determine the required number of Arctic LNG carriers, their propulsion power, design speeds, and ice class taking into account various stochastic factors. The other fields of application of simulation technology are the cost estimations, risk-based design, etc. For instance, Schartmüller et al. (2015) applied a DES-model to assess the cost of TEU transit along the Northern Sea Route (NSR). Bergström et al. (2015) described a DES-model to solve the tasks of the risk-based design of Arctic ships.

Regarding the technique of simulation we could note that cargo volumes are usually modeled as entities (in terms of DES), while ships are the resources that transport these entities along the flowchart diagram. Ship operation is represented as a sequence of time delays; also, a number of relatively simple sub-models are introduced to represent some special cases of system behavior, such as port operations and other. The following simplifying assumptions are frequently made. Shore storage filling is not considered; cargo flow is constant during the period of modeling; the influence of weather windows in ports is supposed to be negligible; icebreaker operation is modeled in a simplified manner. Most of the studies do not consider logistic aspects. As a rule, a quite simple model of ship movement is applied (level ice and open-water performance), while the main efforts are made to determine ice conditions and to deal with uncertainties in their prediction. Stochastic distributions of various parameters are often defined by an expert-based approach based on the very small amount of real operational data.

So, we could conclude that most of the published simulation models of fleet operation in the Arctic have a quite low level of detail. No attention is usually given to various non-transport processes that may influence MTS significantly. Such subject fields as logistical planning, vessel routing, and speed selection are out of consideration as a rule. The latter issues are studied in detail in the logistic field, which now is somewhat separate from the ship design field. Logistic models for ship scheduling are usually deterministic, while simulation model is used as an instrument to test the robustness of previously created logistic plan considering various stochastic factors. The description of corresponding simulation models is given in Section 2.3. Those simulation models also could be classified as simplified ones, because the level of detail is not high and various non-transport processes are not taken into account as usual.

However, if we expand the horizons and go beyond the Arctic topic, we could see that there are quite a few applications of simulation to different tasks related to the fleet operation. Several papers are devoted to the application of DES models to the tasks of ship operation in ports and on container terminals. There are also some studies, where simulation models of fleet operation are integrated with the planning tools and models of various sub-processes. We will consider two of them.

Richetta and Larson (1997) applied a high-detailed DES-model to solve the operational problems of marine transportation of wastes in the city of New York. The model considers the multiple types of cargoes, barges, tugs, and trucks. The following sub-models are introduced to describe the logic of a real system: waste transfer (transshipment) stations, landfill, waste incinerator, digging operation, and the model of tide dynamics. Logistic scheme of the system is complicated by various types of transport and by the presence of transfer stations. Simulation model incorporates preprocessed planning tools that are based on dynamic programming heuristics. The model allowed obtaining operational parameters of nine alternative configurations of MTS based on "what if" principle.

Vanek et al. (2013) developed a detailed agent-based simulation model of vessel transit through piracy-affected waters. It incorporates the behavior models of merchant vessels, patrol ships, and pirate vessels. They are realized on the finite state machines technology representing the principal mental states of the vessel agent (move, attack, hijacked, patrol, etc.). Interaction of patrol, attack, and transit ships is described as a game of individual agents in geo-information space. Simulation model contains specific sub-models, such as: ship routing in piracy-affected waters by the risk-distance objective function using A* algorithm; optimization of navy ships allocation; selection of target area for pirate attack; and optimization of vessel group transit by the criterion of minimal time losses. At the same time, the behavior of cargo vessels is not governed by any higher ranking planning algorithm, i.e., vessels move towards some random ports of a given region according to the overall origin-destination matrix.

So, the last two examples represent a successful integration of simulation model with the different subject-oriented models and planning tools. Following this principle, in this study we applied a multidisciplinary approach for Arctic MTS design, simulation, and analysis (Tarovik et al. 2017). The main idea of the approach is to synthesize geographic information system (GIS), shipbuilding disciplines, fleet planning instruments, and agent-based simulation models in an integrated software framework on the basis of object-oriented programming. This allows creating a detailed model of the transport system according to the problem statement in Section 1.

3.2 Modeling of Natural Conditions in Simulation Experiments

There are several basic approaches to model natural conditions of a region or some particular point in simulation experiments.

According to the first one, the dynamics of natural conditions is modeled based on the time series of actual observations. For example, this approach was used in Maisiuk and Gribkovskaia (2014) and Shyshou et al. (2010), where the time series of long-term (54 years) observations over the wind and wave characteristics were divided into the blocks corresponding to one calendar month. Weather conditions for the next model year are generated using a combination of twelve monthly blocks selected from a set-available field realizations. In this way, it is possible to obtain an almost unlimited number (54^{12}) of virtual annual weather scenarios. As an argument in favor of this approach, the authors note that the dynamics of modeled conditions within a month will exactly correspond to the real one. At the same time, there remains a question about the accuracy of artificial stitching of the months from different years. The other question is related to the level of statistical variability of weather parameters and to the representativeness of obtained model results. Furthermore, the absence of the necessary measurements is a significant restriction on the use of field data. The latter is also relevant in our case.

The second approach is the use of artificial (synthetic) weather data produced by numerical algorithms instead of the field data. This enables to obtain more representative model results and to make statistically sound conclusions. There are two ways to simulate weather conditions within this approach: process-based models and stochastic generators.

The process-based approach uses the physically grounded models of global circulation that describe mass and energy transfers in some region. Ratios of mass and energy balances, laws of mechanics and thermodynamics, and ideal gas equations are used to describe the principal relations between pressure/density and temperature (Michalakes et al. 2000). The obtained system of nonlinear equations of mathematical physics could be solved by the numerical methods on a frequent spatial grid. The algorithmic and computational complexity of even the simplest physics-based model significantly exceeds the complexity of applied transport models, where the weather model needs to be included as one of many other blocks. Therefore, the only reasonable way to integrate global circulation models to the transport simulation models is to use the pre-calculated weather scenarios (Intergovernmental Panel on Climate Change 2005). These scenarios could be fed into the simulation model as an input signal (Edmunds et al. 2014).

Stochastic weather models are not based on the real physics, but consider the dynamics of meteorological characteristics as a random process that needs to be reproduced. Actual observations serve as a base to identify quantitative parameters and qualitative patterns of weather behavior at a given point. A large number of stochastic weather generators of different levels of complexity have been implemented using this principle. For example, a classical method of statistical modeling of independent random variables that obey a given distribution type was used by Milaković et al. (2015). Both continuous—(wave height and wind speed) and discrete parameters (visibility levels and presence of a polar low) are modeled. However, the use of independent random variables is the simplest way of weather modeling. This approach does not consider the statistical interdependence of various parameters (so called cross-correlation, e.g., the relationship between wave height and wind speed), and temporal correlation of the values of each parameter (auto-correlation).

The correlation aspects play an essential role when weather affects not vessel movement, but the accessibility of port infrastructure for operations. This is because cross- and auto-correlation directly determine the weather windows of the particular terminal, i.e., the frequency and duration of the open and closed periods. Therefore, in many cases of port simulation the description of external conditions is reduced to explicit stochastic simulation of weather windows (Mastryukov 2013). The accessibility of a port is described using two alternative states: good weather (operations are permitted) or bad weather. Duration of each state is modeled by the probabilistic distribution that is obtained from time series of field observations and a set of constraints on wave height, wind speed, visibility, and other parameters. However, in our study this approach is not applicable, since Prirazlomnaya has several cargo terminals and each terminal has its own limitations. In this case, the weather windows concept fails to consider the interdependence of accessibility of various terminals in the same or neighboring time.

To construct a consistent simulation algorithm, we need to model all the environmental parameters explicitly and calculate the accessibility of various terminals of the studied platform on the fly during the running of the model. For this purpose, we created a stochastic weather generator that describes the weather as a multidimensional random process. We take into account all the environmental factors that affect cargo operations.

3.3 Routing and Scheduling in Offshore Applications

Currently, there are a variety of studies devoted to the problem of vessel routing and scheduling. The detailed description of methods to solve these problems for cargo ships is given in Christiansen et al. (2007) and Pantuso et al. (2013). Unlike planning of cargo ships, the task of the planning of platform supply vessels (PSV) operation involves several specific features, such as time constraints on deliveries, the need for servicing several rigs, the multiple cargo types, etc. Therefore, specialized methods are created to solve such problems.

Fagerholt and Lindstad (2000) firstly defined the problem of PSVs planning as an integer-programming problem on the example of servicing a set of offshore installations (customers) in the Norwegian Sea. Planning algorithm allows determining the optimal fleet, routing policy, and corresponding regular weekly schedule. It answers the question of which vessel, when, and in what sequence will visit each of the offshore installations. The planning horizon is set to 1 week, and it is supposed that supply fleet operates on one regular weekly schedule throughout the year. The number of port calls per week models supply requirements for each customer. Fleet is assumed to be homogeneous. Only deck cargoes are taken into account, while bulk cargoes supposed to have an insignificant effect on system performance. The algorithm also considers such an important feature of offshore operations on the Norwegian shelf as banning of cargo operations at night. The model is completely deterministic and does not take into account the probabilistic nature of weather conditions. Therefore, the authors noted that generated plan should be adjusted to account for the weather. The main difficulty of the approach is a high-resource consumption of computational process. Therefore, a number of considered customers and vessels are quite limited, as well as the planning horizon. Most of the subsequent studies are based on the described concept, supplementing and improving it.

Aas et al. (2007) and Gribkovskaia et al. (2007) considered the task of finding the optimal sequence of visiting several customers by one PSV. Attention is given to the problem of backward cargoes removal. Aas et al. (2007) made this task extended with capacity restrictions at customers, while they noted a difficulty to solve the large dimension problems. Gribkovskaia et al. (2008) presented an attempt to increase the computational performance using a tabu search heuristic algorithm. Halvorsen-Weare et al. (2012) additionally took into account a restricted amount of cargo at supply depot by limiting the number of vessel loadings per day at various installations, but the backward cargoes remained outside consideration. Shyshou et al. (2012) used the instants from the latter study to demonstrate an increased speed of mixed integer linear programming problem solution when using the Large Neighborhood Search algorithm. Maisiuk and Gribkovskaia (2014) were one of the first who applied a DES model to carry out a robustness test of previously created weekly schedule taking into account the probabilistic weather conditions and their change throughout the year.

Eskandari and Mahmoodi (2016) presented an idea of going beyond the concept of regular weekly scheduling. They focused on the comparison of two alternative approaches to solve planning problem: a regular weekly scheduling and non-regular demand-based voyage planning. The latter considers the actual demand of offshore installations in cargoes and nonhomogeneous supply fleet. The authors concluded that the efficiency of fleet operation upon irregular schedule is 5% higher in comparison with the alternative weekly oriented plan. Despite that, the used irregular scheduling algorithm is schematic, the obtained results form a basis for further study of non-regular planning.

So, most of the reviewed planning methods are aimed at obtaining an optimal weekly schedule for servicing a large number of platforms. The use of formal mathematical optimization algorithms makes it possible to find a strictly optimal solution. However, due to the high-computational complexity, the level of detail in the description of the transport system and cargo flows remains relatively low. The following assumptions are usually applied:

- Only deck cargoes are taken into account in cargo flows and ship load; limitation on vessel payload is ignored.
- Due to the absence of bulk and liquid cargoes, the corresponding ship cargo spaces are not taken into account when generating a voyage plan.
- The fleet is usually considered as homogeneous that does not correspond to the real practice.
- Distribution of cargo flows in time within the planning horizon is uniform, while the actual distribution may have significant dynamics for various types of supply cargoes.

These assumptions prove to be inapplicable in the current study (see the statement of the studied problem in Section 1. At the same time, in our case, supply fleet feed only one platform that operates 24 h per day. It reduces a computational complexity significantly. For this reason, we have developed a special contextual planning algorithm for tactical planning of PSV operation.

4 Integrated Simulation Model

4.1 General Description of the Model

In accordance with the principles of the multidisciplinary approach to MTS analysis (Tarovik et al. 2017), in this study all vessels are represented as separate dynamic objects (agents) that move and interact in geo-information environment (GIS). Natural conditions (winds, waves, and ice) in the region of ships operation are modeled as stochastic processes; navigation restrictions are also taken into account (see Fig. 2).

At each step of simulation experiment (one model hour), the model calculates vessel speed and fuel consumption in ice or open water. Vessels routes in ice-covered waters are calculated using previously developed technology of ice routing (Tarovik et al. 2017). It makes it possible to simulate the actual practice of vessels navigation in the Arctic along ice leads and the areas of the weak ice. However, these aspects of the simulation model are beyond the scope of this article. Here, we pay the main attention to the details of modeling OIFP Prirazlomnaya operation and to the related aspects.

In this study, we integrate various sub-models and add-ons (see Fig. 3) into the general simulation model. The basic logic of the resulted model consists of several interacting computational processes, each of which could be treated as a separate simulation algorithm:

a) Cargo transportation, i.e., vessel operation according to the voyage plan
b) Generation of weather conditions in the area of platform location (Section 4.2), and determination of the accessibility of cargo terminals (Section 4.3)
c) Dynamics of filling/discharging of platform storages in accordance with specified cargo flows (Section 4.4)
d) Ship operations near the platform (see Section 4.5)
e) Auxiliary stochastic processes and events, such as addition/removal of vessels from operation, the arrival of a helicopter, etc.

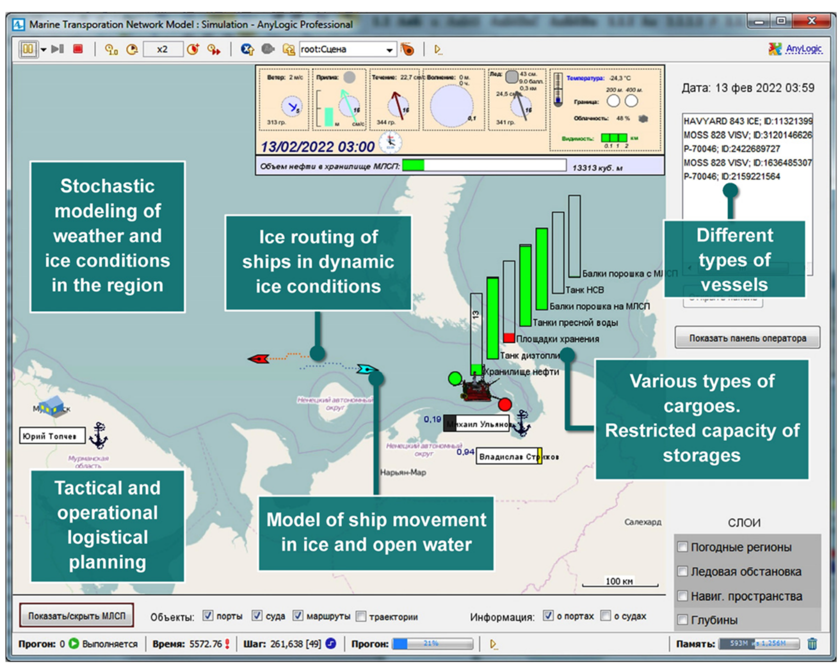
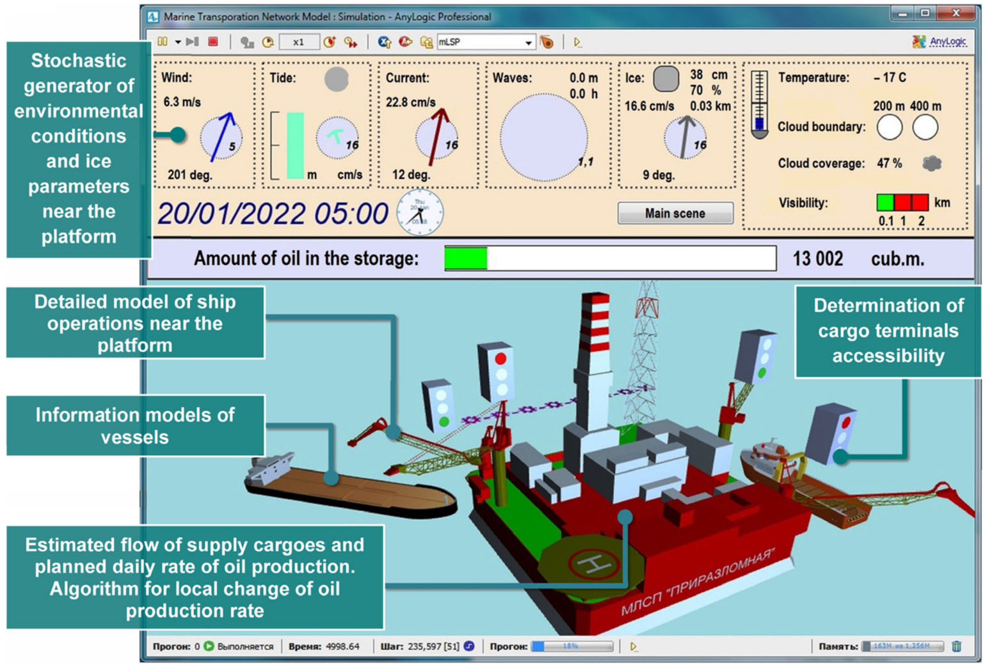


Fig. 2 The general scene of the simulation model

Fig. 3 The platform sub-model



Execution of the vessel voyage plan is the central process of simulation. Voyage plan contains the information on cargo loading of all vessels in each voyage, and satisfies two limitations:

- Ensuring the integral shipment volumes according to the preset cargo flows
- Delivering the cargo by certain dates

The fact that voyage plan is to be created before running the simulation model is somewhat of principal importance. The procedure of voyage plan generation is described in Section 4.6. Basic principles of voyage plan execution are schematically shown in Fig. 4. Main types of agents involved in this process are vessel—the executor of transportation tasks; operator—a special object that is responsible for managing transport process and coordinating the actions of individual agents; scene—an aggregator object of the entire model. At the start of the model, operator searches through all available transport resources and tries to give the task to each vessel according to the voyage plan. Ship operations in the plan can be of two types: port call or movement. In the first case, a new entity is created and passes through the flow diagram operation in port (see Section 4.5); in the latter case, the vessel-agent conducts a global movement operation to the destination port.

Movement operation is carried out during the simulation in two stages: planning and action. At the first stage, the model calculates an optimal route for the vessel of a given type from the point of departure to the destination point with a specified date of voyage start. To do it, we used an ice-routing algorithm. It takes into account the main parameters of natural conditions by their mean values and considers the dynamics of their change during the time period of vessel movement. The second stage consists of a vessel passing along this route in model time mode. In this case, we stochastically model ice and weather conditions using Monte Carlo method as random values with a given distribution law. As a result, the travel time along the route in each voyage is different. It makes it possible to carry out the computational experiments with replications to obtain statistics of targeted operational parameters.

When the vessel reaches the last point of the route or completes the port operation, the special program messages are given: vessel arrived and vessel departured, respectively. When the operator receives these messages, it releases the vessel from its current task. After that, the simulation algorithm searches for the uncompleted tasks in the voyage plan. Depending on the result of this check, the process either goes on, or simulation model stops.

4.2 The Stochastic Generator of Natural Conditions at the Area of OIFP Location

4.2.1 Principles of Approach to Create the Weather Generator

There are two principal approaches to generate the autocorrelated sequences of random variables in the theory of stochastic modeling: autoregressive algorithms and serial algorithms.

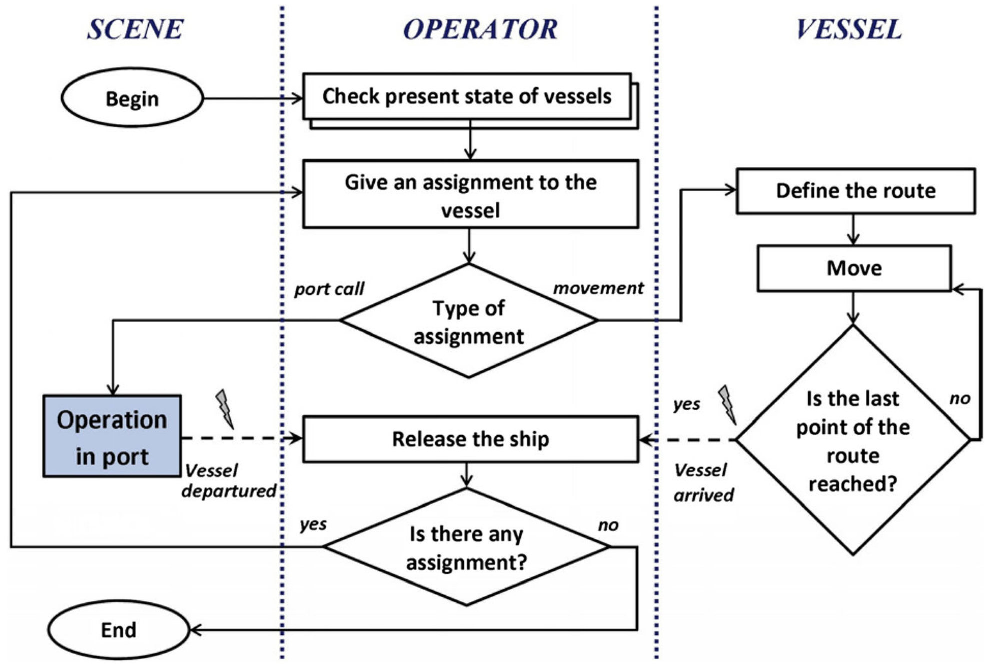


Fig. 4 Schematic diagram of the execution of voyage plan

In the first case, generated values are modeled sequentially, i.e. the values at the previous steps are used to obtain the value at the current step. There are two areas in this field: discrete Markov chains and theory of stochastic shaping filters. The first one is intended to simulate a discrete random variable when a number of subintervals could present the entire interval of variable change. The transition matrix determines the probability of falling into subinterval i under the condition of being in subinterval j at the previous step. The simplest example of using this algorithm is a modeling of the sequence of dry and wet days in Richardson and Wright (1984) and Topaj (1992). Shaping filters are used to model continuous physical quantities based on a recurrent algorithm, according to which a certain value x at some model time k can be written as follows:

$$x_k = f(x_{k-1}, x_{k-2}, \ldots x_{k-n}, \varepsilon_{k+1}) \quad (1)$$

The next value x_{k+1} is calculated in (1) from the x values at n previous steps (such filter is called as the n-th order filter) and with the use of a random correction ε (usually, ε has a normal distribution). If the function f is a linear combination of its arguments, the corresponding shaping filter is linear. The extension of Formula (1) to the multidimensional case (i.e., the replacement of scalar variables by vectors) makes it possible to use the mechanism of shaping filters for the simultaneous generation of several linked interdependent meteorological parameters. Not only the auto-correlation but also the cross-correlation of the multidimensional random process will be considered in this case.

Under a serial approach, the value of time interval when the modeled parameter remains constant or quasi-constant is generated directly (Golubyatnikov 2004), instead of modeling its change at each relatively small time step. The serial technique allows modeling arbitrary distributions of weather windows duration (Semenov et al. 1998), while in case of using the autoregressive algorithms these distributions are obtained automatically and had a specific type (for example, geometric distribution results from a discrete first order Markov chain). Therefore, the serial approach is to be used when the distribution of duration of the corresponding weather windows is under investigation.

In this study, we need to model the weather parameters explicitly. Therefore, we applied an autoregressive approach to develop an original stochastic generator of sea weather at a specific geographical point. The principal features of the algorithm that make it different from other ones are the following:

- Simultaneous modeling of a broad set of natural parameters
- The use of shaping filters to generate not only interconnected scalar variables, but also the physical vectors
- The use of a hybrid modeling method, according to which the generator contains both the elements of formal statistical modeling, and the physics-based approaches

The latter feature should be explained. We applied statistical modeling to describe weather realizations as a multidimensional discrete random process with set auto- and cross-correlation properties using the methods of shaping filters and Markov chains. The physics-based elements are used to model the tidal and wind components of surface currents, and to determine the wind wave characteristics, as well as the ice floe drift velocity and direction.

4.2.2 Calculation Relations

The generator enables to obtain time series of 15 simulated parameters: air temperature; wind speed and direction; cloudiness and cloud height; visibility; height and direction of wind waves; speed and direction of current; high/low water periods; speed and direction of ice drift; and ice concentration and thickness. The time resolution of the generator (i.e., the frequency of weather conditions updating) is adjusted in the interval of 1–24 h.

Wind speed and direction at the current simulation step are determined using a two-stage algorithm. The first stage is the calculation of the reduced (centered and normalized) wind vector using a first-order linear-shaping filter:

$$\boldsymbol{w}_{k+1} = \alpha_W \cdot \boldsymbol{w}_k + \sqrt{1-{\alpha_W}^2} \cdot \boldsymbol{\varepsilon}_k \tag{2}$$

where $\boldsymbol{w}_{k+1}$ and $\boldsymbol{w}_k$ are the reduced direction vectors of the wind force at two successive steps, and $\boldsymbol{\varepsilon}_k$ is a random vector obeying the two-dimensional normal distribution type with zero mean and single-unit variance. The shaping filter parameter α_W is selected in such a way as to provide the desired correlation of the wind speed vectors at adjacent time steps. To do this, it must be exactly equal to the empirical correlation coefficient, defined as:

$$\alpha_W = \rho = \frac{M\left(\left(\hat{W}_{k+1} - M\left(\hat{W}\right)\right) \times \left(\hat{W}_k - M\left(\hat{W}\right)\right)\right)}{M\left(\left(\hat{W}_k - \mathrm{M}\left(\hat{W}\right)\right)^2\right)} \tag{3}$$

where $\hat{W}$ is the dimensional vector of the wind, M is the operator of taking a mean of the distribution, and the asterisk corresponds to the scalar product of the vectors. Based on the results of processing data from four sources, it was found that in the region of the OIFP location, the value of α_W varies in the range of 0.85–0.96 for the hourly time step, and is practically unaffected by seasonality. Therefore, $\alpha_W = 0.9$ was taken for the entire calendar year at a 1-h generator step (in case of selecting a time resolution, for example, of 2 h, $\alpha_W = 0.9^2$ should be taken). Formulas (2) and (3) represent a modification of the standard algorithm for modeling a one-dimensional auto-correlation random process (Richardson and Wright 1984) for a vector variable.

The second stage is the recalculation of the reduced normalized values into dimensional characteristics. Polar coordinates are typically used to describe wind speed and direction, but this is very inconvenient for the use in auto-regressive algorithms due to the difficulty in transition through 360°. Therefore, we represent both the empirical distributions of wind parameters and the generated model distributions in Cartesian coordinates *X*-*Y*. We used a standard transformation algorithm (Golubyatnikov 2004) to obtain dimensional parameters of wind speed. The algorithm is based on the equalization of the theoretical probabilities P_X and P_Y (4) (they correspond to the generated values of reduced projected velocity w_X and w_Y) with the similar probabilities computed by the inverse transformation from the empirical distribution function of the dimensional velocity.

$$\begin{cases} P_X = 0.5 \cdot \left(\mathrm{erf}\left(w_X/\sqrt{2}\right) + 1\right) \\ P_Y = 0.5 \cdot \left(\mathrm{erf}\left(w_Y/\sqrt{2}\right) + 1\right) \end{cases} \tag{4}$$

The latter, in turn, is set by a two-dimensional empirical distribution histogram, which within the framework of this study was determined for each calendar month on the basis of the reference book (RMRS 2003). The obtained values of wind speed dimensional projections are then merely recalculated into absolute velocity and direction.

The surface current vector $\boldsymbol{V}_{\mathrm{flow}}$ (5) is calculated as a superposition of the tidal $\boldsymbol{V}_{\mathrm{tide}}$ and wind $\boldsymbol{W}$ components at the same time step, while the stochastic component, reflecting the influence of unknown unaccounted factors, is neglected as insignificant.

$$\boldsymbol{V}_{\mathrm{flow}} = \boldsymbol{V}_{\mathrm{tide}} + \alpha_{\mathrm{flow}} \cdot \boldsymbol{A}_{45} \cdot \boldsymbol{W} \tag{5}$$

where $\boldsymbol{A}_{45}$ is the matrix that allows considering the effect of Ekman spiral (the influence of Coriolis force) by means of rotating the wind vector $\boldsymbol{W}$ to the right by 45 degrees; α_{flow} is the constant weight coefficient that was assumed to be 0.03, according to the actual measurements at OIFP and some estimations from the literature (Botuk 1949).

The absolute value of the velocity of the tidal component $\boldsymbol{V}_{\mathrm{tide}}$ is determined by the basic formula of the tide prediction. The pre-computation is carried out according to the harmonic constants of the 8 main tidal waves M_2, S_2, N_2, K_2, K_1, O_1, P_1, and Q_1, taken from the tidal model of the Arctic Ocean Tidal Inverse Model (Padman and Erofeeva 2004).

Ice conditions near the platform are described by a set of three parameters: ice concentration, ice thickness, and horizontal size of the ice floes. Many aspects of the ice modeling algorithm, which we presented below, are of an approximate and simplified nature. It is caused by the lack of field data that prohibits us to identify a more detailed model. The presence of ice at the OIFP is modeled as the simplest discrete Markov chain with two states: ice period (state 1) and ice-free period (state 0). The probabilities of transition to the ice (P_{01}) and ice-free (P_{10}) states are determined separately for each calendar month, and depend on the severity of ice conditions (light, moderate, and severe). This approach allows us to implicitly describe the probability distribution of the start- and end-dates of ice period. If the fact of ice presence was obtained at the current simulation step, the vector of actual ice parameters is generated in standard stochastic modeling algorithm. Its first step is the calculation of the centered normalized values of the ice indicators using independent linear filters:

$$x^i{}_{k+1} = \alpha_i \cdot x^i{}_k + \sqrt{1-\alpha_i{}^2} \cdot \varepsilon^i{}_k, i = 1...3 \tag{6}$$

where $i = 1$ corresponds to ice concentration, $i = 2$—to ice thickness, $i = 3$—to floe size, $\varepsilon^i{}_k$ is the standard normal random variable, and $x^i{}_{k+1}$, $x^i{}_k$ are the indicator values at the actual and previous simulation steps.

The value of the shaping filter coefficient α_i for all ice indicators was taken as 0.9 (for 1-hour time step) that corresponds to the field data from OIFP. Thus, all parameters of the ice state are modeled as independent auto-correlated random variables.

We recalculate the values (6) into dimensional ones in a different way. The simplest linear transformation is used for ice concentration (C), which is determined in percent:

$$C = \hat{\sigma}^1 \cdot x^1 + \hat{M}^1 \tag{7}$$

where $\hat{\sigma}^1$ and $\hat{M}^1$ are the sample variances and mathematical expectations of ice concentration estimated for each calendar month. Ice thickness (h) is assumed to have gamma distribution (under the constraint $h \geq 0$), which parameters are determined from the system of equations.

$$f(h) = h^{k-1} \cdot \frac{e^{-\frac{h}{\theta}}}{\theta^k \cdot \Gamma(k)}, \theta = \frac{(H_{3\%} - M_H)^2}{4 \cdot M_H}, k = {}^{M_H}/_{\theta} \tag{8}$$

where $H_{3\%}$ and M_H are the three-percent-assured and average ice thickness for a given calendar month respectively. Jöhnk's (1964) algorithm was used to model h based on gamma distribution. The conversion of ice floe size into the dimensional values is carried out under the assumption that empirical distribution function of this variable can be specified in the form of a distribution histogram with a number of characteristic intervals: P_{3000} is the probability of a floe with an average size of 3 km, P_{1000}—1 km, P_{300}—300 m, and P_{30}—30 m. The results of generator parameters identification on the basis of a number of sources for the average severity of ice conditions are given in Table 1.

Ice drift velocity vector $\boldsymbol{V}_{\text{ice}}$ is calculated almost in the same way as the total flow vector (5). It is determined through the addition of a wind turn component to the surface current vector:

$$\boldsymbol{V}_{\text{ice}} = \alpha^V_{\text{ice}} \cdot V_{\text{flow}} + \alpha^W_{\text{ice}} \cdot \boldsymbol{A}_{28} \cdot \boldsymbol{W} \tag{9}$$

where $\boldsymbol{A}_{28}$ is the matrix that rotates the wind vector $\boldsymbol{W}$ to the right by 28 degrees. The parameters α^V_{ice} and α^W_{ice} were assumed to be 0.9 and 0.02 respectively. This corresponds to the expert estimations and indirect data form the literature (Leppäranta 2011). In addition, an empirical limitation is applied: if the wind speed is more than 20 knots, the ice drift is directed by wind and the first component in (9) is assumed to be zero.

Sea disturbance is modeled only as wind waves, since this type of disturbance is predominant in the considered region. It is assumed that waves are always directed the same as wind. Wave height is estimated using the simplified technique (Coastal Engineering Manual 2002), according to which significant height H_{sig} is defined as:

$$H_{\text{sig}} = \min\{h_{\max}, h_{\text{dist}}, h_{\text{time}}\} \tag{10}$$

where h_{dist} is the wave height limited by the acceleration distance L; h_{time} is the wave height limited by the acceleration time T_R; and $h_{\max} = 21.15 \cdot u_f^2$ is the maximum possible height of a fully formed wave. In the presence of ice, $H_{\text{sig}} = 0$ is assumed.

The other components of (10) are defined as:

$$h_{\text{dist}} = \frac{0.0413 \cdot u_f{}^2}{g} \cdot \left(\frac{L \cdot g}{u_f{}^2}\right)^{0.5}$$

where L is the characteristic distance (estimated approximately based on wind direction, the geographical position of the point of interest, and the contour of the coastline); u_f^2 is the conditional wind speed at the surface, which is connected to the previously calculated reference wind speed by the relation $u_f^2 = C_D \cdot W^2$; and C_D is the water surface coefficient of aerodynamic resistance calculated by an empirical formula $C_D = (1.1 + 0.035 \cdot W) \cdot 10^{-3}$.

$$h_{\text{time}} = \frac{0.00299 \cdot u_f{}^2}{g} \cdot \left(\frac{T_R \cdot g}{u_f}\right)^{0.75}$$

$$T_R = \Delta t \cdot \left(1 + \sum_{i=1}^{N_M} \frac{\boldsymbol{W}_k{}^* \boldsymbol{W}_{k-i}}{\boldsymbol{W}_k{}^2}\right)$$

where Δt is the weather generator step, N_M is the number of previous generator steps, during which the difference between previous and actual wind directions did not exceed 45 degrees. It is assumed that the contribution of the duration of each previous step to the total wave acceleration time is determined by the relative projection of the corresponding velocity vector $\boldsymbol{W}_{k-i}$ onto the actual direction.

Air temperature and cloudiness are the statistically interrelated random variables. We model them according to the standard procedure (Richardson and Wright 1984). Firstly, we carry out a recursive recalculation of the vector of reduced values of modeled indicators using a two-dimensional linear-shaping filter.

$$x_{k+1} = \boldsymbol{A} \cdot x_k + \boldsymbol{B} \cdot \varepsilon_k \tag{11}$$

where $\boldsymbol{\varepsilon}_k$ is the two-dimensional discrete white noise, each component of which is a normally distributed random variable

Table 1 Parameters of the weather generator for the average ice conditions

Month	P_{01}	P_{10}	$\hat{\sigma}^1$ /%	$\hat{M}^1$ /%	M_H/ m	$H_{3\%}$/ m	P_{3000}	P_{1000}	P_{300}	P_{30}
January	1	0	5	95	0.51	0.79	0.30	0.40	0.24	0.06
February	1	0	10	95	0.64	0.94	0.32	0.34	0.32	0.02
March	1	0	15	95	0.72	1.02	0.30	0.40	0.25	0.05
April	1	0	20	95	0.80	1.10	0.34	0.37	0.24	0.05
May	1	0	20	83	0.70	1.03	0.25	0.30	0.33	0.12
June	0	0.26	20	68	0.57	0.92	0.14	0.18	0.50	0.18
July	0	0.74	20	12	0.10	0.30	0.09	0.09	0.61	0.21
August	0	1	0	0	0.05	0.15	0	0	0	0
September	0	1	0	0	0	0	0	0	0	0
October	0.06	0	20	30	0.12	0.20	0	0	1	0
November	0.81	0	32	73	0.23	0.41	0.11	0.19	0.51	0.19
December	0.99	0	24	95	0.30	0.59	0.11	0.19	0.52	0.18

with zero mean and single variance. To reflect the correlation properties of generated random process adequately, the filter coefficient matrices (**A** and **B**) must be calculated by the following formulas:

$$\begin{aligned} \boldsymbol{A} &= \boldsymbol{M}_1 \cdot \boldsymbol{M}_0^{-1} \\ \boldsymbol{B} \cdot \boldsymbol{B}^{\mathrm{T}} &= \boldsymbol{M}_0 - \boldsymbol{M}_1 \cdot \boldsymbol{M}_0^{-1} \cdot \boldsymbol{M}_1^{\mathrm{T}} \end{aligned} \tag{12}$$

where $\mathbf{M}_0$, $\mathbf{M}_1$ are the cross-correlation and auto-correlation matrices respectively. These matrices were identified on the basis of the field measurements of the Fedorov meteorological station (RP5.ru Reliable Prognosis 2008) for each month of the year. For example, for February and June:

$$\boldsymbol{M}_0(\mathrm{Feb}) = \begin{bmatrix} 1.000 & 0.595 \\ 0.595 & 1.000 \end{bmatrix}$$

$$\boldsymbol{M}_0(\mathrm{Jun}) = \begin{bmatrix} 1.000 & -0.266 \\ -0.266 & 1.000 \end{bmatrix}$$

$$\boldsymbol{M}_1(\mathrm{Feb}) = \begin{bmatrix} 0.992 & 0.563 \\ 0.596 & 0.764 \end{bmatrix}$$

$$\boldsymbol{M}_1(\mathrm{Jun}) = \begin{bmatrix} 0,928 & -0.248 \\ -0.260 & 0.760 \end{bmatrix}$$

We used the Jama v.1.0.3 open library and the built-in solver that uses a Cholesky algorithm to decompose the symmetric positive-definite matrix (12). The further recalculation of the conditional indicators to dimensional temperature values (in degrees Celsius) and cloudiness (in points) was carried out by the simplest linear transformation similar to (7). We identified the corresponding mean monthly values and standard deviations of temperature and cloudiness based on an open data archive (RP5.ru Reliable Prognosis 2008). The linear interpolation was used to obtain the modeled indicators on a specific day. To model the change of the air temperature during the day, we identified special additive corrections. We also modeled the height of the lower cloud boundary as an additional indicator that determines the possibility of helicopter operations. It is done based on the obtained total cloudiness using conditional probability formulas. We described the lower cloud boundary in the model as a discrete random variable with a range of values (above 400 m, 200–400 m, and less than 200 m); the probability of each of the state depends on the current total cloudiness. To identify the parameters of these algorithms we used the field data from Varandey and Cape Bolvansky meteorological stations (RP5.ru Reliable Prognosis 2008).

Horizontal visibility range is calculated as an independent indicator of the meteorological state. We described this parameter as a random variable with four states (under 100 m, from 100 m up to 1 km, 1–2 km, and over 2 km), which are taken from the loading/unloading and operational constraints of OIFP. Statistical analysis of the field data from Varandey and Fedorov stations (RP5.ru Reliable Prognosis 2008) did not reveal the significant correlations of the horizontal visibility range with other meteorological parameters. Also, despite certain priori assumptions, the dynamics of this variable did not show any significant trends in the annual or daily cycle. Therefore, only the auto-correlation properties of visibility change were taken into account in the model using the simplest Markov chain with the constant transition probabilities (see Table 2). The predominance of the diagonal values in Table 2 allows us to conclude about the serial nature of the distribution of successive realizations of visibility.

So, the internal logic of the weather generator is a synthesis of formal statistical models and physics-based approaches to describe the natural processes. Running the weather generator in the future mode allowed us to emulate the presence of hypothetical short-term (4–7 h duration) weather forecasts characterized by 100% justification. Such a forecast enables

Table 2 The matrix of the transition probabilities of Markov chain to model the horizontal visibility

To state–from state	Over 2 km	2 km–1 km	1 km–100 m	Under 100 m
Over 2 km	0.9450	0.0329	0.0214	0.0007
2 km–1 km	0.3551	0.5365	0.1040	0.0044
1 km–100 m	0.2428	0.0844	0.6554	0.0174
Under 100 m	0.1228	0.0539	0.3427	0.4806

planning cargo operations. Figure 3 shows the appearance of weather generator panel in the simulation model.

4.3 Determination of the Accessibility of Cargo Terminals in Different Natural Conditions

Not one natural parameter, but the joint values of several indicators play a fundamental role when determining the accessibility of OIFP cargo terminals for vessel operation in given natural conditions. At the same time, the number of possible combinations of 15 simulated natural parameters is almost unlimited that excludes the use of exhaustive search methods to describe the accessibility. Instead, we used a special heuristic algorithm that focused on the key indicators and their joint threshold values. To create an algorithm for accessibility estimation, we have taken into account the following data: regulations for cargo operations on the OIFP; statistical data on real cargo operations; results of modeling the vessels operation near OIFP at the KSRC navigation simulator (Kazantsev et al. 2017); and assessments of the skippers that carry out cargo operations near OIFP. The accessibility of all OIFP cargo terminals is modeled on the traffic light principle:

- Green—approaching, mooring, and cargo operations are allowed
- Yellow—only cargo operations are permitted (approach is prohibited)
- Red—approaching, mooring, and cargo operations are prohibited

Figure 5 shows the basic logic diagram of the algorithm for determining the accessibility of DOOS, where the resulting indicators of the traffic lights are highlighted with color.

At first, the algorithm checks the basic conditions: visibility range not less than 300 m, air temperature not less than −40 °C, and ice compressions should be absent. If the basic conditions are met, the further check is carried out for the cases of ice presence and the absence of ice. In both cases, this check begins with the main regulatory conditions. If there is no ice, the main regulatory conditions examine whether the directions of wind, waves, and currents correspond to the DOOS availability sector (see Fig. 1); the absolute values should not exceed: wind—20 m/s, and three percent-assured wave height—3.5 m. In case of ice presence, these requirements are supplemented by the requirements on ice thickness and drift direction. If the main regulatory conditions are not fulfilled, this does not mean that cargo operations are impossible; therefore, the algorithm makes the further specific checks.

If ice is absent, we successively examine the following cases: the case of strong wind (10–20 m/s) of favorable direction, with weak current (under 0.2 m/s) of arbitrary direction, and favorable wave under 3.5 m in height; the case of an arbitrary weak wind (less than 7 m/s) with strong favorable current (over 0.2 m/s) and wave height of less than 0.5 m; the case of almost calm sea (wind—under 3 m/s, wave—no more than 0.3 m) with a weak favorable current.

If ice is present, we consider: the case of thick-concentrated ice with favorable drift direction (separate checks if the ice management is present or absent); the case of thick- and low-concentrated ice with a favorable drift direction.

We developed the similar in principle algorithms to describe the accessibility of supply cargo terminals, as well as the hypothetical external full-rotating ice-resistant oil terminal. The latter was analyzed as one of the ways to increase MTS efficiency. Not the joint values of natural parameters, but the rates of change of direction of external impacts were taken into account in case of the full-rotating terminal. We adopted an angle of 90° as the permissible angle of change in the direction of the wind, wave, current, and ice drift within 1 hour.

4.4 Cargo Flow Model

4.4.1 Planned Cargo Flows of Crude Oil and Supplies

We calculated the parameters of cargo flows of supplies and commercial crude oil for the period up to the year 2038, when the simulation ends. Despite the high level of the uncertainty of cargo flows, we model them in a deterministic way. This is because the main practical task of this study is to compare the degree of influence of various measures on MTS performance. Therefore, if cargo flows are probabilistic, this will not affect the relative efficiency of MTS variants under equivalent conditions, but will only increase the number of calculations.

To determine the flow of supply cargoes we used an operational data on turnover of containers in 2015–2016 years and the planned values of generalized (i.e., not tied to containers)

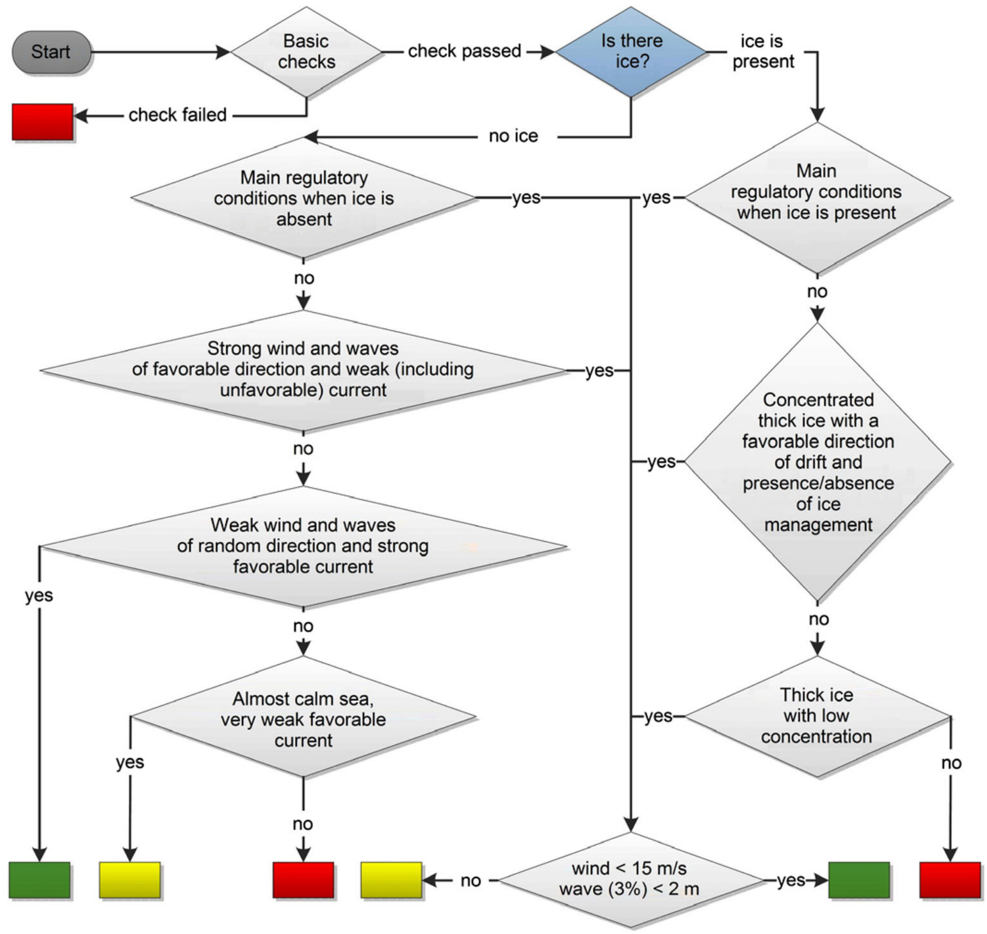


Fig. 5 Schematic block diagram of the algorithm for determining the accessibility of DOOS

upstream cargo flows till the year 2038. Generalized upstream cargo flows contain bulk materials, diesel fuel, fresh water, oily water, chemical reagents, equipment, food, domestic solid waste, industrial waste, pipe products, and sludge. We needed to determine the annual upstream cargo flows as a number of transported packaging units and amounts of bulk cargoes in the direction "to OIFP" (direct cargo flow) and "from OIFP" (back flow). To address this task, we used the following algorithm.

At first, based on the statistical data we determined the types of the most frequently used packaging units (containers and transport baskets). We left only ten types of packaging units for further modeling out of 25 actually used; these units account for 95% of upstream cargo flow. Next, we determined the mass of each packaging unit with various types of cargoes (see Fig. 6) and estimated the statistical share of each packaging unit in the upstream cargo flow for each type of cargo. For example, 8%–12% of the volume of chemicals is delivered in 6-ft containers, 68%–74%—in 10-ft containers, and 14%–25%—in 20-ft containers.

After that, we packed the generalized cargo flows into the selected packaging units taking into account that the cargoes "from OIFP" are transported using the same packaging as the cargoes "to OIFP." We used a mathematical programming search algorithm to balance the number of all types of packaging units imported and exported during each model year. As a constraint of optimization task, we used a specially created matrix that determines the correspondence of types of cargoes in imported and exported units.

Further analysis had shown that the obtained data on upstream cargo flows is inconvenient in practical use due to a large number of unit types. Therefore, we simplified the description of cargo flows according to the approach given in Gribkovskaia et al. (2007). We represented all packaged cargoes (except the mud skip containers and pipe bundles, which are directly connected with the intensity of drilling and well repair) as some conditional containers having different properties at "to OIFP" and "from OIFP" directions. A number of conditional containers is assumed to be equal to the number of real cargo units, but their area, mass, and volume are the average values that indirectly reflect the ratio of used types of packaging units and the actual structure of cargo flows. The use of the conditional containers instead of ten packaging units allowed us to model the loading conditions of PSVs and the duration of cargo handling operations correctly, while the computational complexity of the model was

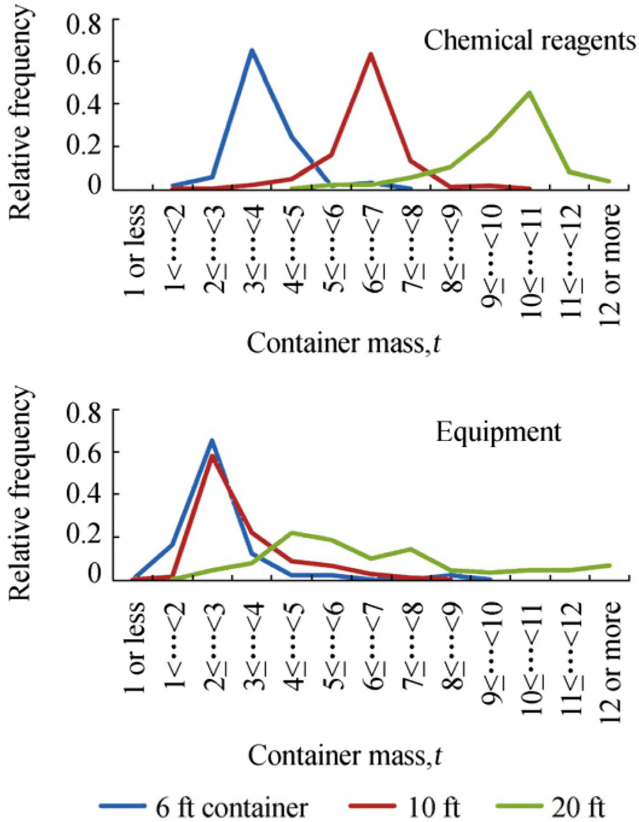


Fig. 6 Distribution of masses of 6, 10, and 2-ft containers loaded by the equipment or chemicals

significantly reduced. Therefore, the final description of cargo flows included the following cargoes in both directions: conditional containers, bundles of pipes, bulk cargoes, mud skip containers, diesel fuel, and fresh water.

To assess the intensity of oil production at OIFP in the period till 2038 we used an actual drilling schedule and the values of planned annual production of oil, liquid, and gas at each well. As a result, we obtained deterministic daily oil production rates (see Fig. 7) taking into account the individual well repairs (during which well production stops), and OIFP maintenance (when oil production stops completely). The obtained data on cargo flows along with the current configuration of MTS fleet are the main initial data for further planning of transportation.

4.4.2 The Algorithm to Control the Intensity of Oil Production

The equipment of OIFP allows making a local situational decrease in the intensity of oil production in comparison with the planned rates. This significantly increases the flexibility of the entire system, allowing compensating for long-term adverse weather events and various deviations from the logistic plan. To model this technological feature, we created a production management sub-model that schematically describes real technological processes of OIFP.

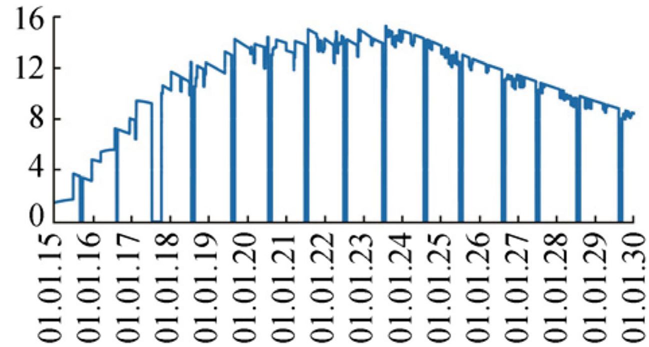


Fig. 7 Calculated intensity of oil production at the OIFP, thousand tons/day

To realize the sub-model, we used a simple finite state machine with five possible states: planned production, reduction, reduced production, shutdown, and recovery of production. We introduced the time period until the full storage filling as an indication value; this value is assumed to be 3 days according to the time of normal shutdown of oil-production pumps. If the remained free storage volume is less than the volume required for 3 days of planned production, then the production gradually decreases at a rate of 0.55% per hour until it reaches the bottom limit (63% of the planned intensity). If the storage is completely filled even with the reduced production intensity, a shutdown occurs. After the storage is free, volume becomes sufficient to provide at least 3 days of production at a planned rate (as a result of oil offloading to tankers); a gradual increase in pump output is made at a rate of 0.28% of the planned intensity per hour. Figure 8 shows an example of production dynamics and storage filling for the case of the constant planned intensity of 12 000 m^3/day, where the storage level corresponding to 3-days complete filling period is marked as filling threshold.

4.5 Discrete-Event Model of Ship Operations near OIFP

We developed the sub-model of vessel operation at OIFP that permits to model the following operations of tankers and PSVs: consecutive operations with cargoes of various types; timely termination of cargo operations when the weather window of the terminal is expected to come to an end; vessel stay near OIFP waiting for the accessibility of the terminals; vessel transshipment to an alternative terminal, or departure beyond the OIFP 3-mile zone. Figure 9 shows the complete view of the corresponding discrete-event flow diagram in AnyLogic® notation.

When the vessel approaches the boundary of OIFP 3-mile zone, a new entity is generated in the element ①. This entity is uniquely related to the instance of the vessel. If the vessel is ahead of schedule, a delay ② is triggered. The check ③ allows determining whether there is at least one operation with

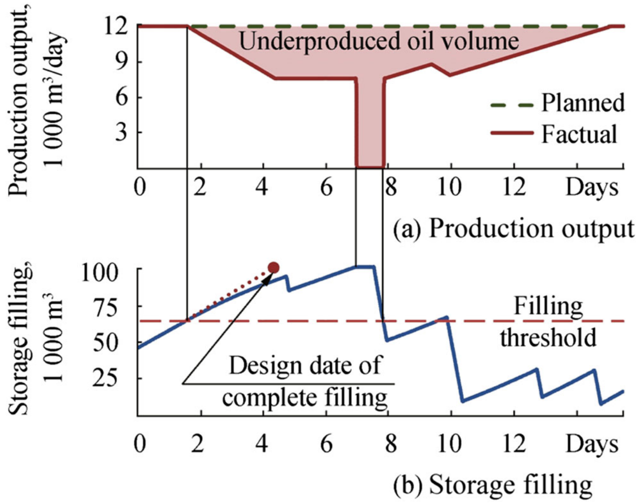


Fig. 8 The situational decrease in oil production rate

OIFP among the scheduled operations of the vessel (this is a check for mistakes in the schedule). Short-term planning of the sequence of cargo operations for the entity is carried out in the element ④ by ranking the priority of all cargoes based on the actual filling level of OIFP storages. The element ④ has a formal character for tankers that have only one cargo, but PSVs may unload/load their cargoes in a different sequence. A check for the presence of a minimum cargo amount to start cargo operations is done at the barrier ⑤. The minimum cargo amount is 17% of the planned shipment for supply cargoes and 13 000 m^3 for oil. No delay occurs in the barrier ⑤, if the current operation is of an auxiliary type, e.g., stand-by operation or icebreaking assistance. The latter ones are simulated by the delay ㉕ with certain duration. Operation type is checked in element ⑥.

Cargo operations of a vessel start with the assignment of a specific terminal of OIFP in the element ⑦. This element has zero base duration, but with its help, a queue of entities waiting for terminal release is formed. Entity cannot leave the delay ⑦ until opening the barrier ⑧, which represents a check of the terminal availability. This check involves an operational planning algorithm that analyzes all terminals of OIFP for their compliance with both the current state of the entity and the general picture of all executed entities at the given moment. Criteria for assigning the terminal to the entity are the following: suitability of the terminal for the dimensions of vessel and for the handled cargoes; absence of other vessels at the considered terminal or at the adjoining terminal, where simultaneous operation is prohibited; presence of a weather window for the terminal with an appropriate duration; and absence of the higher priority entities claiming this or adjoining terminal (e.g., tankers have priority over PSVs when a level of storage filling is high).

In case of a positive result in ⑧, the entity is attached to a suitable terminal. After that, the vessel approaches the terminal (time delay ⑨) and gets moored ⑩. If there is currently a weather window ⑪, then a hose connection ⑫ is done, and cargo operation begins. Element ⑬ is a time delay that corresponds to the process of cargo operations with all types of cargoes. Simulation step in cargo operations modeling is 1 h. Loading rate is a random variable that obeys a given stochastic distribution for a particular combination of the type of cargo, the type of vessel, and the terminal. Cargo operations stop when any of the following events occur: end of the loading/unloading of the planned volumes; runout of the current cargo or lack of free space in the storage; end of weather window of the terminal; and arrival of a helicopter. When one

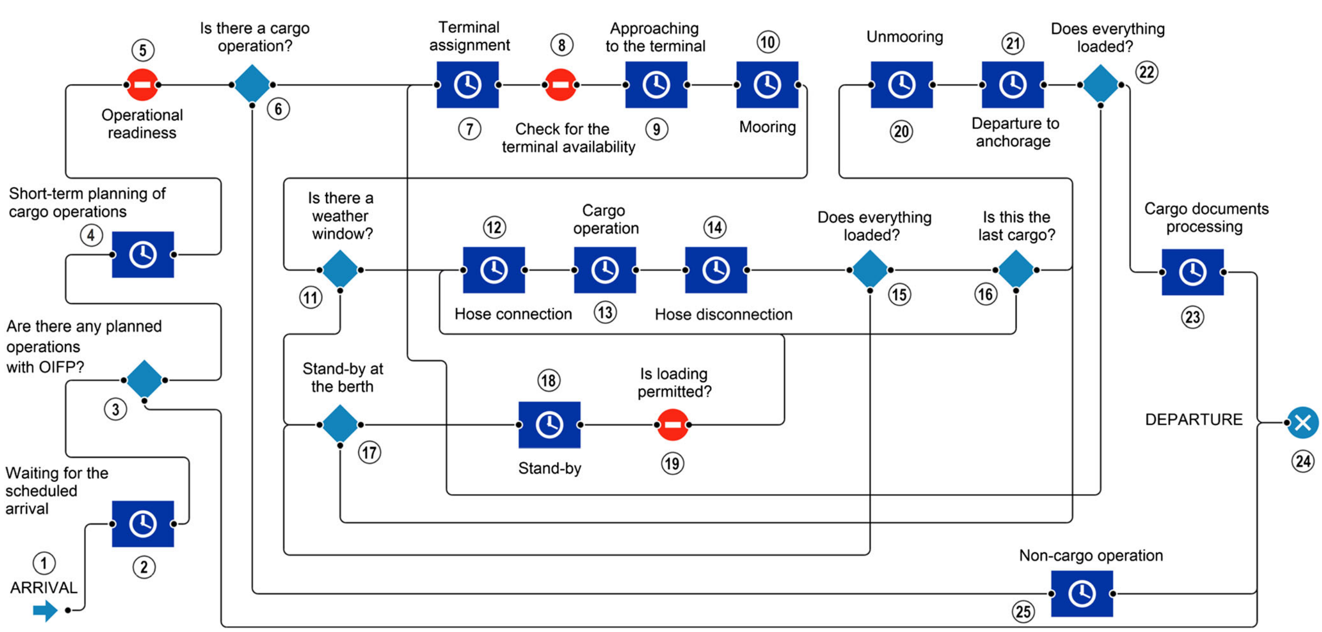


Fig. 9 Flow chart of the passage of queries for loading/unloading a vessel at the OIFP

of these events occurs, the vessel disconnects hose ⑭ and then the element ⑮ determines whether the cargo operation with the current cargo has been completed. If it has not yet been completed, then the entity goes to the element ⑰ that checks the possibility of a vessel waiting out a bad weather without unmooring and departing from the terminal. If the last condition is not met or if check ⑯ has determined that the vessel has fully completed its cargo operations with all cargoes, the vessel departs from the terminal beyond the boundaries of the 3-mile zone of OIFP. The entity passes to the element ⑱ in case if waiting at the terminal is allowed; it stays in ⑱ until opening the barrier ⑲. This barrier checks the availability of a dedicated terminal by the same criteria as the barrier ⑧, but with additional consideration of the presence of a minimum cargo amount.

Ship departure beyond the 3-mile zone is modeled by the delays for unmooring ㉑ and the departure itself ㉒. Element ㉓ checks whether the cargo handling plan for all cargoes has been completed. In case of a positive result, delay ㉔ models the execution of final organizational formalities related to document handling. The life cycle of the entity ends in the element ㉑, where the information about all operations is recorded.

We obtained the parameters of probabilistic distributions for the duration of operations ⑨, ⑩, ⑫, ⑬, ⑭, ⑳, ㉓, and ㉓ by means of statistical processing the records of ship operational logs for the full period of Prirazlomnaya operation. We analyzed the statistics for 11 000 operations of tankers (Kirill Lavrov, and Mikhail Ulyanov), supply vessels (Vladislav Strizhov, Yuri Topchev, Aleut, Kigoriak, Wengeri, Murman, Dina Star, Bourbon Rainbow, Fivel, Bourbon Viking, Havila Crusader, and Sayan Princess), and other vessels that were involved in operations for short periods (Khatanga, Varzuga, Neptune, and Poseidon), as well as helicopters. This data was also useful as initial information for analyzing the logic of vessels and helicopters operation during the development of the model.

4.6 Contextual Planning Algorithm to Generate Voyage Plan of Supply Vessels

Planning of PSVs operation is a more general task from the methodological point of view than planning of tankers. Therefore, we further describe the developed planning algorithm through the example of PSVs, but it can also be applied for tankers.

The main idea of the algorithm is to meet the critical supply needs on “from beginning to end” principle and to choose the best vessel executor, taking into account the restrictions on volumes of platform storages and vessel capacities and duration of voyages and cargo operations. Planning module is organized in a way to maximize the time to overflow/deplete (depending on the direction of cargo flow) storages on a platform. Algorithm reproduces the dynamics of cargo spaces filling, however, unlike the simulation model, there are no stochastic factors. The voyage plan is generated to be optimistic, i.e., enabling to reveal all the capabilities of transport system during its execution. The following data serve as input parameters to build the voyage plan:

- Complete parametric description of the objects within MTS, including the number and type of ships, description of cargo spaces of each ship, and the platform
- Locations of the platform, port for oil shipment, and supply base
- Parameters of transported bulk cargoes and packaging units (volume, mass, density, and area), as well as the matrix that determines a possibility of simultaneous transportation of various cargoes in the same cargo space of the vessel
- Planned cargo flows for all types of cargoes
- Natural conditions on vessel routes to determine the voyage time for any day of the year
- Average statistical durations of cargo operations at the platform and supply base for each type of vessel by months of the year

Fig. 10 shows the object model of the planning module in UML notation (Fowler 2003).

The technical classes (their objects exist only at the time of the module operation) are highlighted in green, while the classes that directly form the plan are highlighted in blue.

The voyage plan is the collection of the objects of cargo operation and movement classes that extend the abstract class operation. Each operation has a start and end date fields, as well as the field with reference to the vessel executor. Movement operation contains the data on departure and destination ports of the route. Cargo operation class includes the location of the operation, as well as cargo batch structure describing a list of cargoes of a certain type (cargo type) that are characterized by the quantity parameter. The request class contains information on an individual need of the port in the quantity of cargo and the date to deliver it. We describe a platform using port class. The other elements of the object model are described below.

Figure 11 shows the sequence of calculation operations in the planning module, where the elements that are executed only during PSV planning are highlighted with color.

At first, the algorithm forms a planning task on the basis of initial data on cargo flows. The schedule of needs class describes a planning task for each type of cargo and contains the daily plan (a set of request type objects for the day period), and monthly plan (the same for a month). The daily plan expresses the actual daily needs of the platform, while the monthly one serves to control the progress of planning. The direct and backward cargo flows have separate plans.

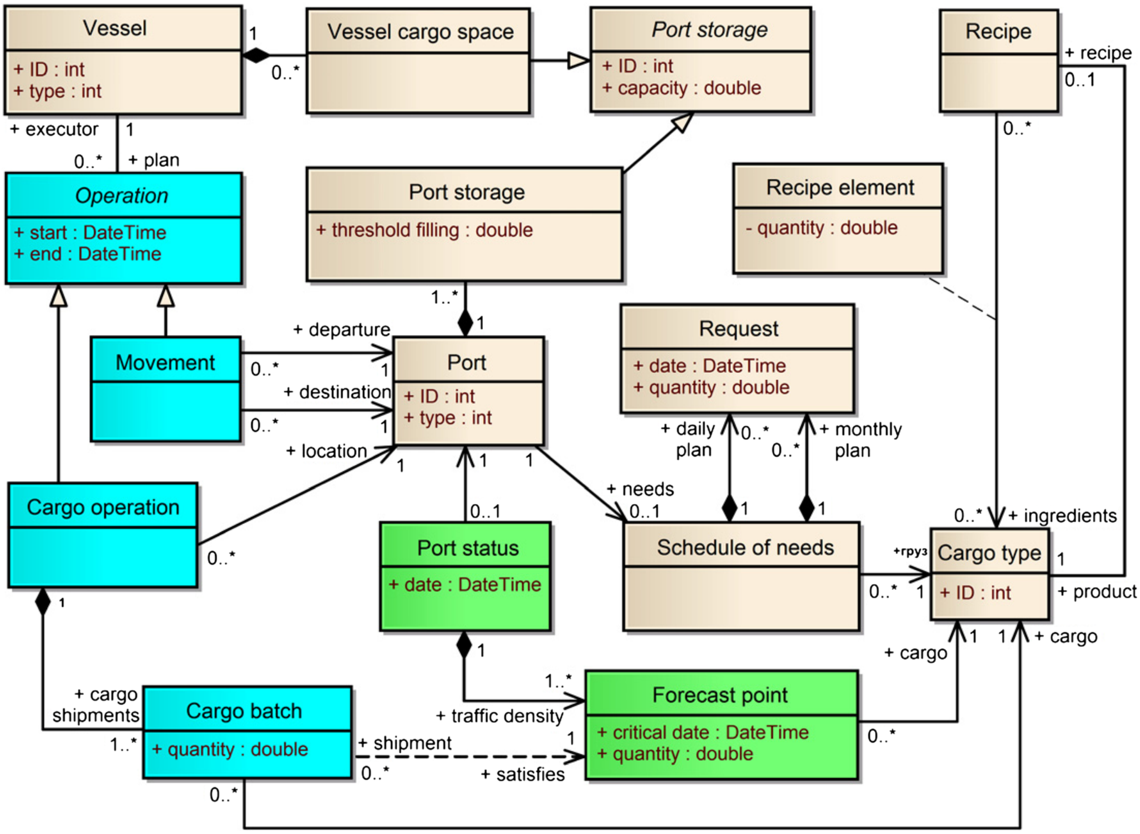


Fig. 10 Class diagram of objects involved in tactical planning module

In the next step, the algorithm defines the initial state of all system elements and starts the planning cycle. This cycle simulates the dynamics of the transport system in a simplified manner allowing obtaining forecasted values of system

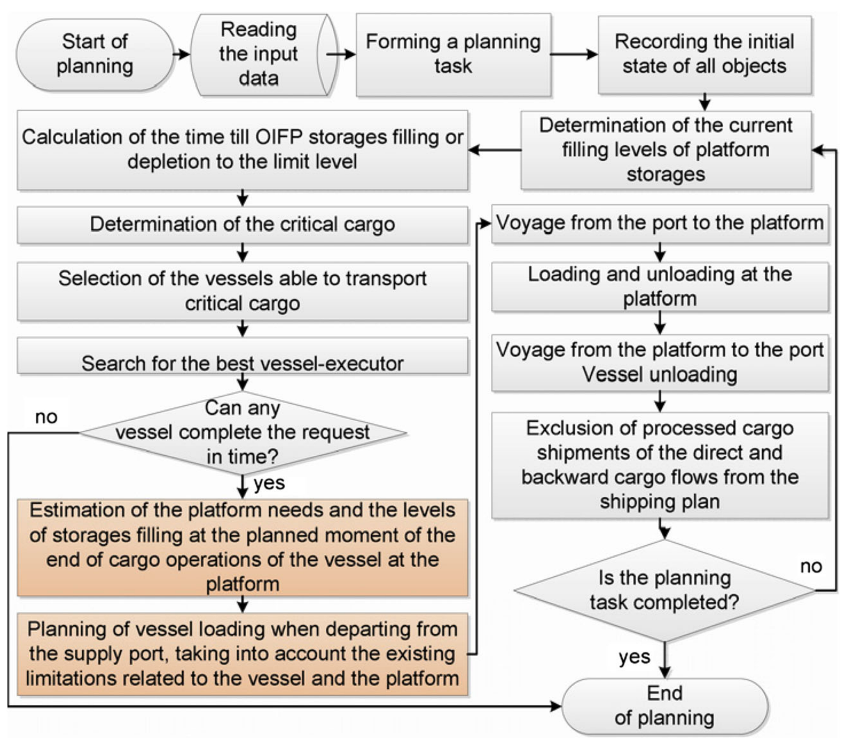


Fig. 11 An enlarged block diagram of the tactical voyage planning algorithm

indicators at each step. Each loop of the cycle describes a round voyage of one vessel and consists of several steps.

The first one is the calculation of the time till OIFP storages filling or depletion to the limit level. To do it, the algorithm uses the data on the last cargo operation at the platform, as well as the information from port status service structure, which stores the actual quantity of each type of cargo in the port. The date field defines the point in time for which the stored data is relevant. The traffic density attribute is a set of objects of the forecast point class that contains the information on the required cargo quantity of each type and the critical time of its deficit.

Next, the algorithm calculates the dates to reach the critical (maximal or minimal) level of storage filling for each type of cargo using the daily plan structure. These dates are saved in the objects of forecast point class (critical date field). Thus, the algorithm forms an array of *forecast points* for all types of cargoes and sorts them by dates. The earliest of the dates is a critical date T_{crit} and the corresponding cargo is considered as critical.

After this, the algorithm selects the vessels that can transport the critical cargo and choses the best one using the efficiency criterion K.

$$K = Q/t \qquad (13)$$

where Q is the volume or area on the vessel to transport the critical cargo, t is the characteristic time.

There are several strategies to calculate the characteristic time t: either the prolongation of the period till the overflow/depletion of critical cargo storage or the use of a minimum number of vessels.

In the first case, the time t is defined for each vessel as the following:

$$t = t_{min} - t_0 \qquad (14)$$

where t_0 is the date of the end of the last operation of any vessel with the platform (it is taken from the existing records of the voyage plan); t_{min} is the calculated date of the fastest delivery of critical cargo.

$$t_{min} = t_{release} + t_{load} + t_{voyage} + t_{platform}$$

where $t_{release}$ is the date of vessel release from its last operation (it is taken from the end date field of *operation* class); t_{load} is the duration of port loading operations with the critical cargo and the other cargoes; t_{voyage} is the duration of the voyage; $t_{platform}$ is the duration of loading and unloading operations at the platform.

When the task is to use the minimum number of vessels, the time t is defined as the time to deliver the critical cargo (and other cargoes also) from the supply base to the platform:

$$t = t_{load} + t_{voyage} + t_{platform} \qquad (15)$$

When the existing fleet configuration is studied, it is preferable to calculate parameter t using (14), because it is aimed at the full use of available resources. Formula (15) allows planning operation of the system using only the most efficient vessels and taking additional ones into operation in critical cases only. However, the use of (15) can lead to a premature appearing of a critical event in case of high-load operation of the transport system. Under both strategies, selection of the best vessel executor is done by maximizing the value (13) while satisfying the restriction $t_{min} \le T_{crit}$. If this condition is broken for the entire list of ships, the planning algorithm ends.

The next step after the selection of the vessel executor is the estimation of platform needs and the levels of its storages filling for the moment of the planned end of cargo operations of the vessel. Such foresight is essential to determine the number of cargoes that can be placed on the platform (i.e., free volumes of storages), as well as the cargoes for the return voyage. We used a simplified deterministic model of technological processes on the platform to do it. The description of this model operation is given below on the example of containers with supplies, while the same logic is applied for bulk cargoes. So, the platform consumes the supply cargoes from the delivered containers; after that the container becomes empty and occupies some area on OIFP. Cargo flows of the MTS determine the time of consuming of the delivered supplies on the platform, as well as the amount of produced backward cargoes that are to be exported. After that, the empty container is loaded with backward cargoes and exported from the platform. We realized this logic using specially introduced recipe class. It contains the information on the quantity of by-products that are formed when each of the units of direct cargo flow is consumed on the platform (the quantity field of the recipe element association class). Also, the recipe class contains the ingredients for the backward cargoes, i.e., a list of required cargo types (empty containers and components) for the production of each unit of a backward cargo flow.

After the described model predicts the state of OIFP storages, the planning algorithm determines the load of vessel-executor when departing from the supply port (Murmansk). It defines the number of objects of cargo batch type and the quantity of cargo in each batch. To do it, we used an iterative procedure aimed at maximum delaying the date of storage overflow/depleting for all types of cargoes. The principle of this algorithm is that current critical cargo is loaded until another cargo becomes critical. We considered a set of constraints in this procedure:

- Priority of cargoes according to the needs of the platform, i.e., ranked array of forecast points
- The capacity of vessel storages for each type of cargo. If vessel cargo space for critical cargo is entirely filled, then corresponding forecast point is deleted

- Vessel payload. Loading of the vessel in Murmansk is carried out until its payload is depleted
- Available free spaces in platform storages. These volumes cannot be exceeded when planning the loading of the vessel
- The influence of the exported backward deck cargoes on the free area on a platform

After the algorithm completes the planning of vessel load, it saves the parameters of the object of cargo operation class in the voyage plan.

The next planning step is adjusting of the date of ship departure from Murmansk and generation of the appropriate movement operation. This adjustment aims to ensure that fully loaded vessel reaches OIFP at a time when there is a significant filling level in the storage of critical cargo. This level is determined by the filling threshold parameter of the port storage class. We used a module of ice routing to determine the duration of the voyage for each vessel and each date of voyage start. To estimate the duration of cargo operations at OIFP we used a statistical data. During the planning of voyages from the platform to the port, we assume that supply vessels load all backward cargoes available on the date of departure, while the tankers leave the platform only at full load. The algorithm includes the return voyage in the plan and planning cycle continues until the end of the planning task. Figure 12 shows a fragment of the final voyage plan.

4.7 Vessel Information Models

We describe the vessel in the context of MTS using the following characteristics (Tarovik et al. 2017): main design parameters; cargo spaces; cargo-handling equipment; loading conditions; resistance and propulsion parameters; and groups of propellers. This data is essential for voyage planning and simulation of ship operation. We created the information models of the following projects of ships:

- Arctic shuttle tanker P-70046 (Mikhail Ulyanov);
- icebreaking supply vessel Moss 828 MISV (Vladislav Strizhov);
- icebreaking AHTS Havyard 843 Ice (Aleut).

Cargo spaces are the tanks, bulks, and cargo decks, where liquid, powdered, and general cargoes can be transported. Each cargo space is defined by the area or volume and cargo compatibility options. Vessel cargo-handling equipment is described by its capacity.

We defined two loading conditions for tankers (loaded and ballasted) and only one for supply vessels because of their similar draft in all operational loading cases. The following parameters describe the loading condition: operational data (displacement, icebreaking capability, economical speed, cargo load); main dimensions at the waterline; hull shape parameters; and propulsion characteristics (resistance in calm water, thrust-deduction coefficient curve, etc.). Data on propulsors includes main characteristics (diameter, shaft power, and rpm limit); thrust and torque factors; and coefficients of hull-propeller interaction. Figure 13 shows an example of the interface to describe a vessel.

We reconstructed the hull shapes of given ships (see Fig. 14) to determine their hull shape parameters and to calculate both resistance in open water and the interaction coefficients. We carried out verification of obtained propulsion parameters on the basis of the protocols of full-scale commissioning tests. This allowed confirming a high degree of accuracy of the model parameters and the used calculation methods. In particular, deviations of calculated achievable vessel speeds from full-scale data in equivalent wind-wave conditions were within a ± 0.2 knot interval.

Vessel	ID	Name	Type	Start Date	Duration	Context
Kirill Lavrov	34324456465	Ship entry: The port of Murmansk	Ship entry	16.06: 2020 5:47	00.22:14	The port of Murmansk
Kirill Lavrov	34324456465		Moving	17.06: 2020 3:52	02.05:47	MTS
Kirill Lavrov	34324456465	Ship entry: The "Prirazlomnaya"	Ship entry	19.06: 2020 9:39	04.14:20	The "Prirazlomnaya"
Aleut	23867563677	Ship entry: The port of Murmansk	Ship entry	20.06: 2020 15:14	03.01:46	The port of Murmansk
Juriy Topchev	56345646477		Moving	21.06.2020 4:10	02.17:51	MTS
Vladislav Strizhov	76230764861	Ship entry: The "Prirazlomnaya"	Ship entry	21.06.2020 4:10	05.00:00	The "Prirazlomnaya"
Mikhail Uljanov	35289374394	Ship entry: The port of Murmansk	Ship entry	21.06.2020 5:11	00.22:14	The port of Murmansk

ID	Type	Start date	Duration	Context	Quantity
65543453267	Cargo operation	20.06.2020 15:14	03.01:15		
35435546	Loading	20.06.2020 15:14	03.01:15	Conditional container	17.00
75245365	Loading	20.06.2020 15:14	03.01:15	Empty mud skip container	28.00
45456466	Loading	20.06.2020 15:14	03.01:15	Drill pipes	24.00
34576556	Loading	20.06.2020 15:14	03.01:15	Fresh water	349.04
23467658	Loading	20.06.2020 15:14	03.01:15	Bulk cargoes	10.53
12357765	Loading	20.06.2020 15:14	03.01:15	Fuel oil	65.89

Fig. 12 Fragment of the tactical operations plan display interface

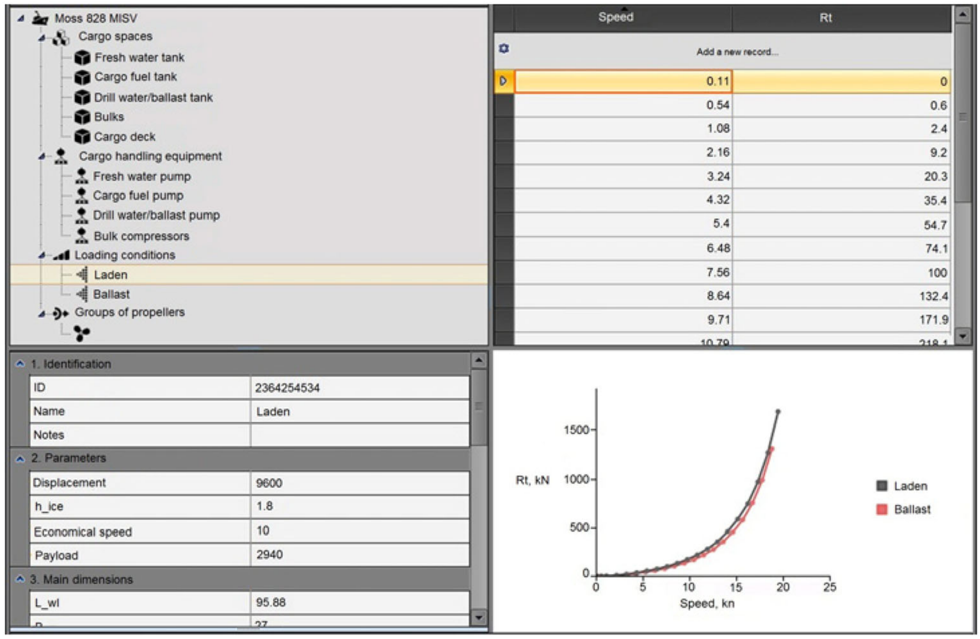


Fig. 13 The description of vessel parameters in the information model

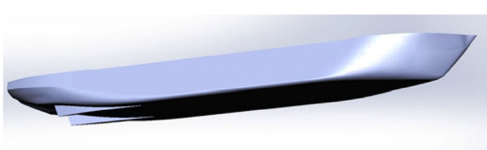
Calculations of vessel speeds and fuel consumptions at all types of operating conditions in the simulation model were made in accordance with the basic principles specified in Tarovik et al. (2017).

5 Verification of the Simulation Model

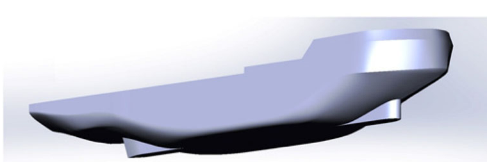
A fundamentally important step in the development of simulation model was its verification based on the field data. It should be noted that we used the field data at all stages of the model development, i.e., when identifying the parameters of all elements of the complex simulation model described in Section 4. However, we selected some integral parameters for special verification purposes. These integral parameters for the tanker fleet are the number of tanker approaches to DOOS before the full load and the duration of one continuous loading of the tanker at the DOOS. Each of these parameters is the product of a complex interaction of a number of simulated processes, such as: dynamics of natural conditions; vessel scheduling and estimation of ship load at each voyage; and interaction of tankers and PSVs during an operation near OIFP. Therefore, verification of the model based on this data allows us to judge how adequately the model describes the reality, as well as to understand how justified the made assumptions are.

Figure 15 shows the comparison of the field data and the modeled parameters of tanker performance for the existing configuration of MTS. As can be seen, there is a good agreement between modeled and full-scale data.

Also, we verified the model based on the following full-scale data: duration of vessel voyages between OIFP and Murmansk; duration of stay of tankers and supply vessels near OIFP; the number of annual voyages of supply vessels; and other parameters. During the verification, we calibrated the model parameters to achieve the best match with the field indicators. As a result, all key model and field parameters turned out to be statistically close to each other. This enabled us to prove that developed simulation model statistically adequately describes the operation of the real system.



(a) Tanker hull form

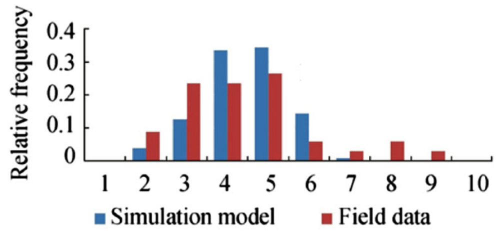


(b) Supply vessel hull form

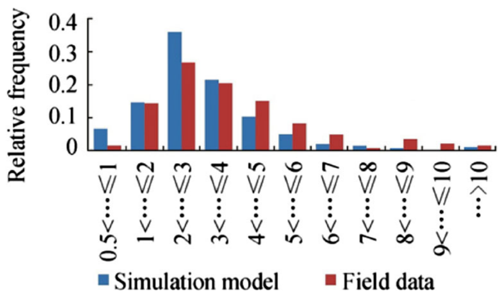
Fig. 14 Reconstruction of ship hull forms. **a** Tanker hull form **b** Supply vessel hull form

6 The Results of Simulation and Analysis of the Mutual Interaction of Various Processes

Program of the study included an analysis of 11 various organizational and technical measures (see Table 3) to increase the efficiency of MTS. Each of the measures has different



(a) Number of tanker approaches to the DOOS until the full load



(b) Duration of one uninterrupted loading of the tanker/h

Fig. 15 Comparison of field and model parameters of tanker operation. **a** Number of tanker approaches to the DOOS until the full load. **b** Duration of one uninterrupted loading of the tanker/h

complexity and cost of implementation. In total, we investigated 32 configurations of the transport system. We evaluated the degree of influence of each measure on MTS in comparison with some base variant of the system. The base variant corresponds to the existing MTS configuration with some minor improvements that planned to be implemented in 2017. To investigate the details of realization of specific organizational measures (No. 1–6 in Table 3), we used not only the field data and skippers' opinion, but also the results of modeling of vessel operations at KSRC research navigation simulator (Kazantsev et al. 2017). The latter allowed us to assess the achievable level of enhancement of various operational parameters in cases of implementation of different measures. We also carried out special design studies to evaluate the technical and economic parameters of measures No. 10–11 that imply capital construction.

As we mentioned in the introduction, the practical aim of the study was to find the best combination of improving measures based on the ratio of the cost and the achieved reduction in volumes of under-produced oil for the entire period of MTS lifecycle. Actually, detailed cost estimations are out of the scope of this paper; therefore, further we will reference the costs at a qualitative level only. We accepted the following plan of calculation experiment. At first, we investigated the isolated influence of each measure on the efficiency of MTS in ice conditions of various types. This allowed us to put various measures in order according to their influence on MTS performance. After that, we investigated the configurations with complex improvements that were agreed with the management of Gazprom Neft Shelf Company. We needed to run the simulation model for many times to obtain the statistical estimations of all necessary parameters of each MTS variant with a high level of confidence under the wide statistical variability of random events. In total, more than 12 000 runs of system operation until 2038 has been carried out during the study; this required more than 3000 h of computer time.

Table 3 shows the main practical results of the study given in the form of average percentage decrease in the volumes of under-produced oil. In the case of isolated improvements, Table 3 shows the results that correspond to each separate measure. For the case of combined improvements, the integral

Table 3 Organizational and technical measures to increase the MTS efficiency

No.	Measures that increase the efficiency of MTS	The decrease in the average volume of under-produced oil/%	
		Isolated	Combined
1	Permission for tankers and supply vessels to operate simultaneously on the opposite terminals of the platform	6	69
2	Reduction in the average duration of mooring and hose operations of tankers at OIFP from 1.5 to 1.2 h	8	
3	Permission for tankers to operate at OIFP at the time of arrival of a helicopter (arrival frequency, once per 4.5 days)	13	
4	Reduction in the average duration of document processing after loading of tankers from 10.8 to 2.0 h	25	
5	Increase in the average rate of oil offloading from OIFP by 60%	38	
6	Reduction in the minimum duration of weather windows used for cargo operations of tankers from 6 h down to 4 h	44	+16
7	Putting into operation an additional shuttle tanker of the same type	30	+ 7
8	Increase in the average voyage speed of two tankers by 1 knot	21	+ 5
9	Using an additional icebreaker for ice management near OIFP	3	+ 1
10	Construction of an external full-rotating ice-resistant oil terminal	100	–
11	Construction of an additional oil storage facility near the OIFP	100	–

effect of the main measures No. 1–5 is shown along with the additional effect that can be obtained if one of the measures No. 6–9 is applied in addition to the main improvements No. 1–5.

As one can see, the positive effects from the various measures are not additive that is a result of the complex and nonlinear interaction of multiple processes. The degree of influence of various measures in case of their combined implementation does not change significantly. The following facts prove it. The direct sum of individual effects from the measures No. 1–5 gives a 90% decrease in the volume of under-produced oil, while the real effect from their simultaneous use is 69% only. The effect of the most efficient organizational measure No. 6 decreases from 44% down to 16% in case of its implementation simultaneously with measures No. 1–5. Along with that, the order of measures No.6–9, which are listed by their effectiveness, do not change in case of their individual or combined implementation. So, despite the fact that these particular figures are valid for the studied system only, they give a good example of nonlinear interaction in the complex offshore system in general.

We found out that the construction of permanent structures, such as a terminal (measure No. 10) or additional storage (No. 11), shows an absolute effect, i.e., the absence of under-produced oil. However, the practical implementation of these measures proved to be so costly and technologically complicated that they were excluded from further consideration. The volume of the hypothetical additional gravity-type oil storage was found to be 60 000 m^3.

Despite that, the volume of under-produced oil is a good criterion to compare the alternatives in our case, we also used the other parameters to reveal the interaction of modeled processes in more detail and to compare various measures. At first, we analyzed the statistical parameters of the events of a local decrease in oil production (Fig. 16 shows an example of such event).

We disclosed that the volume of total under-produced oil is well described by a gamma distribution for all variants of MTS; Poisson's distribution could be applied for the total number of cases of production decrease; the duration of the production decrease event is a gamma distribution close in shape to the exponential one. Figure 17 shows an example of these distributions for MTS configuration with organizational improvements (No. 1–6) in light ice conditions. The average volume of under-produced oil is 150 000 tons, which is only 0.2% of the 70 000 000 tons of recoverable reserves and very close to the error of estimating the latter. An unplanned shutdown of oil production can occur only during a period of local decrease that ensures the use of standard technological procedures for its implementation. The number of unplanned shutdowns is 0.3%–1.2% of the total number of cases of decrease (smaller values correspond to the improved configurations).

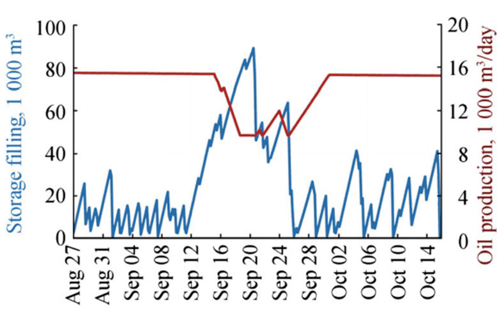


Fig. 16 Dynamics of the model intensity of oil production according to the production decrease algorithm

Distribution of under-produced oil volumes over the years 2017–2038 is proportional to the cargo flow of oil; the same is relevant for the events of a local decrease in oil production. Distribution of the latter parameters by months of the year (see Fig. 18) has the evident peaks in autumn (due to storms) and winter-spring (because of ice) periods. The ratio of these peaks depends on the severity of ice conditions: the more severe winter, the more frequent are the events of a local decrease in this period.

The expansion of accessibility of DOOS using the short weather windows (4 h or more) has the highest positive effect on system efficiency among of all other measures No. 1–9. At the same time, the difference between the total duration of 6-h and 4-h weather windows is quite small: the first ones occupy 51% of total time of year, and the second ones—60%. Nevertheless, not the total duration of weather windows is of decisive importance for the studied MTS, but the availability of tanker to approach the platform at a desired moment of time and on a regular basis.

The regularity of DOOS accessibility turned out to be much better in case of 4-h windows in comparison with the 6-h ones.

The same reasons lead to an unexpected effect when putting an additional shuttle tanker into operation has a little effect on considered MTS despite the 50% increase in carrying capacity of sea transportation line. This is because production of oil is carried out on a schedule, while storage volume is limited and offloading system has environmental restrictions. To analyze this effect we made additional investigations. Figure 19 shows the distribution of annual OIFP time budget during the period of maximum oil production for the alternative variants of MTS with two or three tankers and with different duration of weather windows. As one can see, the time required for cargo operations of tankers takes only 18% of total time of the year. The total time when at least one tanker is present near OIFP is 82% for MTS with two tankers and 100% for MTS with three ships. For the case of three tankers, OIFP is either in the state of cargo handling (18%), or waiting for a weather window when the tanker is present (40%), or accumulating an oil when there is a weather window (42%). If there are two tankers in MTS, the time of tanker absence near OIFP is divided into: time when there is no weather window

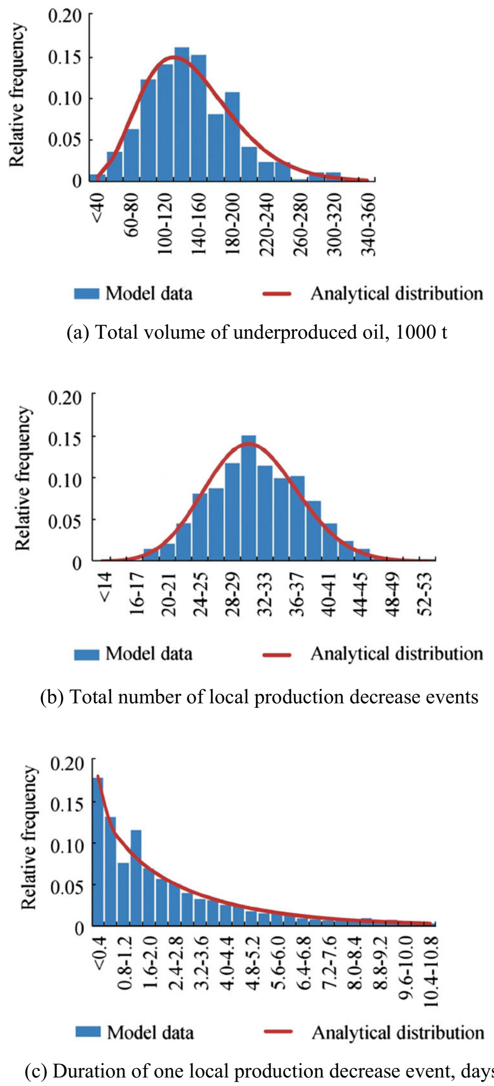


Fig. 17 Main parameters of one of the improved MTS configurations. **a** Total volume of under-produced oil, 1000 t. **b** Total number of local production decrease events. **c** Duration of one local production decrease event, days

(6%–8%); time when the weather window occurs, but not enough oil has been accumulated for its loading to tanker (8%–11%); and time when there is the required amount of oil and an appropriate weather window is present (1%–3%). The last component can be called the time of missed opportunities, which turned out to be very small. At the same time, the average time of a tanker stay near OIFP in the two-vessel system is 4.5 days (it is determined by the time of accumulation of the oil cargo batch); and in the system with three tankers it is 9.6 days (because of tankers are idle for $^1/_3$ of their operating time). These non-trivial results are formed by the complex interaction between the dynamics of oil production and the dynamics of accessibility of cargo terminals under weather change.

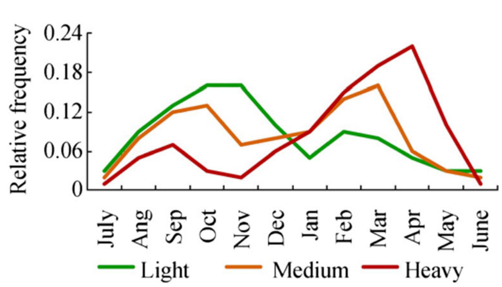


Fig. 18 Distribution of events of a local decrease in oil production by months of the year when operating in ice conditions of various types

Therefore, the main practical result of the study is that we clearly showed that the variants associated with costly capital construction could be reasonably rejected, while the combined organizational improvements with the low cost of realization were proved to be sufficient for the studied MTS.

Also, we should note three special conclusions that were obtained when considering the theoretical variants of MTS. However, these variants are of practical value and can be taken into account in the design of future Arctic offshore systems.

We studied the hypothetical system, where the supply vessels made no difficulties for cargo operation of tankers. The results had shown that this measure could significantly improve the efficiency of MTS reducing the amount of under-produced oil and the number of events of local decrease by 30%–50%. In other words, if there is a possibility to place the supply and product offloading terminals in such a way that they do not create mutual restrictions, this possibility should be used.

We also conducted many numerical studies for various configurations of MTS when disabling an algorithm to control the oil-production intensity. For each variant of such MTSs, we iteratively determined a constant intensity of oil production that minimizes the probability of a conditional overflow of oil storage. These experiments have shown that the achievable cargo flows of oil in such systems are several times lower, than in case of applying a situational decrease algorithm. The reason is that the peak values of storage filling may be 7–10 times higher than typical operational filling levels. This is because of the rare adverse combination of natural and logistical events. Therefore, to guarantee the safety of the system, it is much more reasonable to provide a possibility to reduce the production level during unfavorable periods (and to under produce small amount of oil), than to build a storage facility aimed at the maximum peak filling. This conclusion also underlines the importance of considering the technological processes and storage filling during the study of complex offshore systems. So, the interaction of technological processes on the platform with the other ones may influence the system dramatically.

The last conclusion is related to the interaction of transportation process with the dynamics of oil production under the restricted storage capacity. We investigated several MTS configurations with two and three tankers to determine the

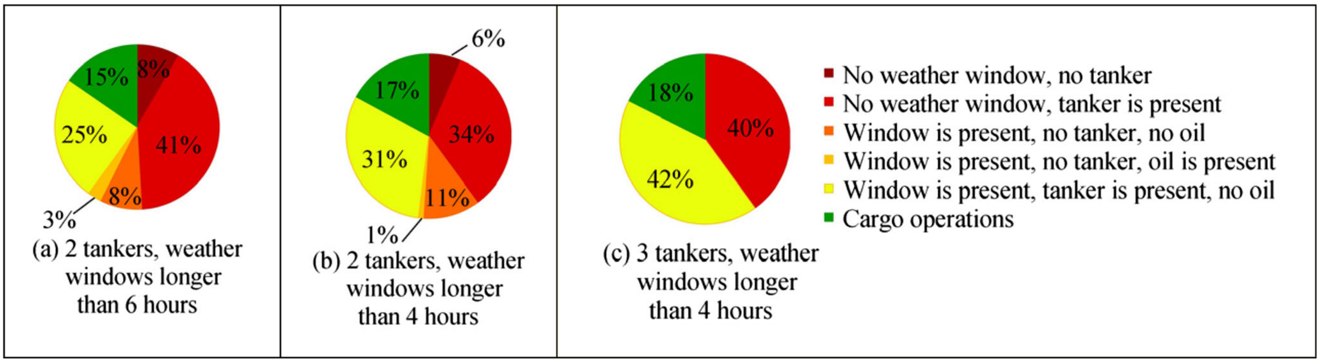


Fig. 19 Averaged data on the use of the time of year in a period of maximum oil production (data are given as a percentage of year duration)

nominal carrying capacity of the sea line, i.e., to assess the amount of oil that can be transported in case if there are no restrictions due to oil production dynamics. We assumed that there is an unrestricted amount of oil at OIFP and tankers can load as much oil as they can. It is important to note, that we took into account the natural conditions and corresponding restrictions of terminals as well as the operation of PSVs. Also, the operational speed of ships and their operational period remained the same as in previous calculations. As a result, the annual achievable cargo flow of the system with two tankers reached the value of 6.1–6.7 million tons, while the average time of tanker loading at OIFP decreased from 4.5 days down to 1.9 days. In case of three tankers, the cargo flow has risen to 8.6–8.9 million tons and average loading time decreased from 9.6 days down to 2.2 days. The obtained cargo flows are much higher than the actually studied cargo flow of 5 000 000 tons per year that the considered system provides with some amount of undelivered oil. This allows us to conclude that the dynamics of production and the restrictions associated with the storage capacity may have a significant impact on the performance of the overall system. This is because real MTS should maintain the balance between the oil production and its export. The restricted capacity of storage makes it impossible to ramp-up average production level up to the nominal carrying capacity of MTS because it will lead to a high risk of storage overflow.

7 Conclusion

In this research, we used a variety of theoretical instruments to resolve the complexity of investigated MTS. We studied the redundancy of the system using the simulation of the entire period of its operation taking into account the statistical variability of weather dynamics and non-stationary cargo flows. Targeting at the redundancy led us to the necessity to estimate the flexibility, i.e., to consider the active adaptation of MTS to the uncertain external conditions. To do that, we introduced the elements of infrastructure capacity management such as an algorithm for voyage planning and sub-model to control the oil-production intensity. To compromise the costs of various measures with the achieved reduction in the volume of underproduced oil, we applied the elements of a risk-based analysis. We also considered the survivability of the studied MTS by means of including the restrictions on terminal accessibility into the model. These restrictions are based on the safety recommendations and prevent an unsafe interaction of the platform with the ship in high-risk conditions. During the study, we held the regular meetings with shipmasters, drilling engineers, project managers, captain of OIFP, and other stakeholders from the industry. The main features of the model resulted from the joint discussions.

At the same time, in this study we developed a number of applied scientific solutions to practical tasks. We created and verified a detailed simulation model of MTS operation in the Arctic that includes several sub-models of various transport and technological processes. To model the environmental conditions, we developed stochastic weather generator that combines the elements of probabilistic modeling and physics-based approaches. We also applied a new contextual planning algorithm to generate the voyage plan taking into account multiple types of ships, various cargoes, dynamics of voyage time, change of cargo flows, and other specific elements of Arctic transportation. The combination of these solutions within the framework of a single integrated simulation model allowed us to achieve a new quality of MTS modeling. The most important advantage of the presented model is an opportunity to take into account the entire range of logistical, technological, natural, and other processes.

Using this opportunity, we revealed the mutual interaction of various processes that forms the emergence of the system and determines its efficiency. The results of the study showed that there are many examples of mutual interaction of various processes in the investigated system. Disregard for one of them may result in wrong conclusions, technical mistakes, and significant financial loses. In other words, the supply fleet itself may be sustainable, the tankers themselves may have a high-carrying capacity, and the platform itself may have the robust technological equipment, while the entire system will not operate properly. This is because Arctic system for offshore development is a complex entity with a large number of internal relations and restrictions. The balance between the level of detail in the description of simulated processes and the level of transparency (interpretability) of the model is the main challenge for the one who intends to model complex offshore systems.

The practical results of this study formed a basis for making managerial decisions at the top level of Gazprom Neft Shelf Company, while the obtained recommendations were introduced into the practice of operation of Prirazlomnaya platform and implemented in the form of guidelines.

Acknowledgements We are sincerely grateful to the management of Gazprom Neft Shelf Company for permitting us not only to publish the technical details of the current study but also to reveal its central practical results and conclusions. We believe that this open and responsible position will contribute to the development of polar science and the safe future of the Arctic.

We are also deeply grateful to Dr. Otto Sormunen and Prof. Soren Ehlers for their kind comments and recommendations on the structure of this article.

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