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Operational planning and combinatorial optimization in simulation models of marine transportation systems

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Abstract

This paper investigates the problem of using the operative planning instruments in the simulation models of Arctic transport systems. It is claimed that the presence of the operational planning algorithm significantly influences the behavior of a simulated system even at the early design stage. Neglecting the planning aspects leads to a significant underestimation of the overall efficiency of a system and possible errors in its logic. The paper describes the idea of incorporating an external optimal planning engine into the simulation model. The approach is demonstrated with two simplified examples: icebreaker fleet management on one-dimensional graph and planning of oil transshipment using floating storage facilities. The paper also contains the comparison of the proposed planning approach with the alternative simplified solutions, such as the situational algorithm for local choice of proper resource for each arrived agent. The obtained results made it possible to conclude that the incorporation of rather complex combinatorial optimization algorithms into simulation model leads not only to more adequate modelling of the system behavior, but also to a decrease in the stochastic volatility of simulation results.

Keywords: Arctic shipping, icebreaker fleet management, combinatorial optimization, simulation modeling, transshipment

1. Introduction

Computer simulation is a useful and powerful tool for analyzing both organizational and design solutions in the development of the large-scale marine transport systems. After all, the cost of building and analyzing computer simulation models is negligible compared to the cost of port or offshore infrastructure itself or the losses that follow possible design errors.

The main result of a single run of the simulation model at a given time interval is a set of specific integral characteristics of the analyzed system. It is also possible to set and solve the inverse problem, i.e. to optimize system characteristics by varying the input parameters. Typical approaches and methods for combining simulation modeling with the methods of algebraic optimization are considered in many theoretical studies, such as (Fu, 2020) and (Bachelet and Yon, 2007). The most common method is to use the optimization as an external contour over a dynamic simulation engine. It means that the optimal values can be found by successive iterations (model runs) as a part of optimization computational experiment. Typical problems in marine logistics that can be solved using such integration of mathematical modeling and algebraic optimization are the Contract analysis problem and Fleet size and mix problem (Fagerholt, 2010).

However, it is often necessary to take into account the intellectual operational aspects of the simulated transport system even at the early design stage. Indeed, the actual operation of any multifunctional facility (sea port, container terminal, oil platform, etc.) requires the local dispatching service in order to resolve incidents of a different nature and conflicting interests of entities of different levels of organization. The simplest aspect of such dispatching is the scheduling of current or predicted service requests over a short time interval. Certainly, algorithms and computerized systems of operative work or resource control belong to other management level than the pre-design analysis of the system under study. Nevertheless, neglecting these aspects in the simulation model, that is, the absence of a certain built-in dispatcher module, can lead to a significant underestimation of the integral efficiency and throughput of the system.

A simplified approach is often used in order to solve such problem. The idea is to set some strict predefined rules to arrange the service requests in the model, e.g. FIFO (first in, first out). However, the experience in model development and analysis shows that any such simplifications turn out to be internally contradictory in most cases. They allow neither obtaining adequate numerical efficiency estimates for a particular system configuration, nor even making reasonable conclusion about the best variant among several compared ones. The only solution that guarantees obtaining adequate results is the implementation of some parts of a smart operational control directly inside the logic of the simulation model. As a rule, the algorithms and methods of combinatorial optimization and mathematical programming are the mathematical core of such internal optimization. Thus, the interaction between simulation and optimization procedures in pre-design analysis of transport systems can be described as three-level scheme: Algebraic parameter optimization → Simulation model → Combinatorial operational planning.

In this paper, we illustrate the peculiarities of integration of the involvement of combinatorial optimization methods in a simulation model of Arctic transport system using two examples. The first one is the icebreaker fleet management on one-dimensional graph and another one is the planning of oil transshipment using floating storage facilities.

The rest of this paper is structured as following. Materials and Methods section contains a short description of the studied example problems (icebreaker fleet management and offshore transshipment planning). We also describe there the external combinatorial optimization engine OptaPlanner and provide the object models that represent studied tasks in terms and concepts of this solver. Results and Discussion section contains the comparison of the used approach with alternative solutions on several test cases. In Conclusions section, an analysis of the results obtained is made. It also contains the considerations about the problems and prospects for implementing the proposed approach, as well as the experience of its application in simulation.

2. Materials and Methods

We use the AnyLogic framework (www.anylogic.com) as the main tool to build the simulation model, and the external library OptaPlanner (www.optaplanner.org) as a built-in optimization engine. OptaPlanner is a free distributed Java class library that allows solving a wide range of combinatorial optimization problems. Its core contains a large set of applied algorithms to form the correct initial approximation (such as the first fit and the strongest fit) and improve the solution iteratively (such local search algorithms as tabu search, simulated annealing, hill climbing search, etc.). It is declared that OptaPlanner finds a good solution in reasonable time for different NP-complete planning problems by using and automatically selecting the most proper advanced optimization algorithm for any particular case. Its current software implementation also includes the multithreaded solving ability that preserves incremental score calculation, but speeds it up dramatically and interacts with the few dozen out-of-the-box optimization algorithms based on different metaheuristics and construction heuristics (De Smet and Wauters, 2021).

The main task to be solved in order to bind OptaPlanner and simulation model is to create a special adapter, i.e to present the model entities in the terms of the application program interface (API) of the applied solver. It should be noted that the OptaPlanner library is a high-level add-in over the standard Java syntax, which permits describing a particular problem in usual terms of the considered subject area. The essence of the optimization problem is technically expressed in a special annotation of certain model classes, i.e. specifying what associative links (planning variables) for what instances of entities (planning objects) should be varied and selected from the pre-defined sets to achieve the optimal value of given quality criterion (fitness or score).

2.1. Icebreaker fleet management problem

Firstly, we consider the problem of icebreaker fleet management. This task was described in detail in (Topaj et al, 2023), therefore only a brief description is given below. According to the common theory of agent and discrete-event simulation, icebreakers can be considered as resources seized by agents (cargo vessels) during their movement through the process diagram. However, icebreaking assistance has a number of fundamental features that do not allow it to be unambiguously described in the terms of standard procedures for the capture, utilization and release of a regular resource. These features are as follows:

1. An icebreaker is a moving resource; it can move independently to its place of use according to its own movement pattern.
2. An icebreaker is a shared resource; thus, one icebreaker can support the operation of several cargo vessels (caravan) on the same voyage section.
3. An icebreaker is an optional resource. Most of modern cargo vessels with high ice class are capable of moving independently in a fairly wide range of ice conditions.
4. An icebreaker is a limited and expensive resource.

> Icebreaking assistance can significantly increase the speed of passing through heavy ice, but this service is quite expensive (Xu and Yin, 2021). At the same time, the limited number of powerful icebreakers (e.g., in 2025 there should be from 6 to 8 Russian nuclear icebreakers in operation) together with an expected explosive increase in the Arctic cargo traffic will inevitably lead to the escorting of each vessel only on a limited part of the route (Wang et al, 2021).

Therefore, any simulation model of the NSR transport system should include a certain intelligent algorithm for operational planning of icebreakers operation, which would adequately reflect the logic of real icebreaking fleet management (Babich, 2011). While executing the simulation model within the selected planning time horizon, this algorithm should provide answers to the following questions:

What is the optimal order of vessel voyages to be escorted by an icebreaker?
Which vessels will join each icebreaker caravan?
Where should the points of caravan forming and disbanding be located?
Which vessels are able to pass the whole route or its part independently, at what time and with what fuel consumption?

Figure 1 presents the object information model for the above-described combinatorial optimization problem of icebreaker management in terms of OptaPlanner framework.

The objects of optimization (i.e. the variables that need to be iterated over and searched for their best combination) are the links of voyage sections to the *Support Task* exemplars, which are the ordered list of icebreaker tasks to escort cargo vessels. If the corresponding link in the *Route Section* entity class is set to null, it means that the vessel passes this voyage segment without icebreaker assistance. On the contrary, if several segments of different voyages indicate the same icebreaker task, then this means that one icebreaker is leading a caravan. The minimized criterion of optimization task is the weighted sum of the durations of all considered vessel voyages.

Communication between the simulation model and the external module of operational planning is realized by means of special proxy-class. Limitation on the number of iterations in the guided search algorithms is defined by setting the total calculation time, so the best plan found during this time is issued as current quasi-optimal solution. It allows us to avoid critical slowdown of the simulation model during its running.

The result of the planning module is a formal description of voyage tasks for cargo vessels and assistance tasks for icebreakers. This plan is executed in the simulation model in a directive way until the next call of the rescheduling procedure, after which all incomplete and new voyages are carried out in accordance with the updated plan.

2.2. Offshore transshipment planning problem

The second problem that requires application of operational planning instruments inside the simulation model is the transshipment management.

The structure of the transshipment port often contains several offshore transshipment complexes (OTC), i.e. transit storages for transferring the cargo from Arctic shuttles to feeder ships. In the case of intensive cargo flow, the transshipment port may become a bottleneck of the entire transport system. Therefore, this element needs to be modelled in detail and OTC-agent to be added to the logic of simulation model. The aim of planning in this case is to choose for each incoming vessel the optimal transshipment complex among several others that are formally free at the moment. The latter assumes that the model should reflect some kind of sound logic for managing berthing places, such as an attempt to minimize the number of used OTCs or exclude long demurrages of ships and OTCs with available cargo reserves.

The standard business logic usually implemented by default in the simulation models (i.e. capturing the first suitable resource) turns out to be insufficient in this case.

We used the optimization algorithm and external planning engine OptaPlanner to solve the problem of assigning a specific transshipment complex for unloading from an Arctic shuttle or, conversely, for loading to a feeder vessel. The designed information model for the transshipment planning problem is shown in Fig. 2.

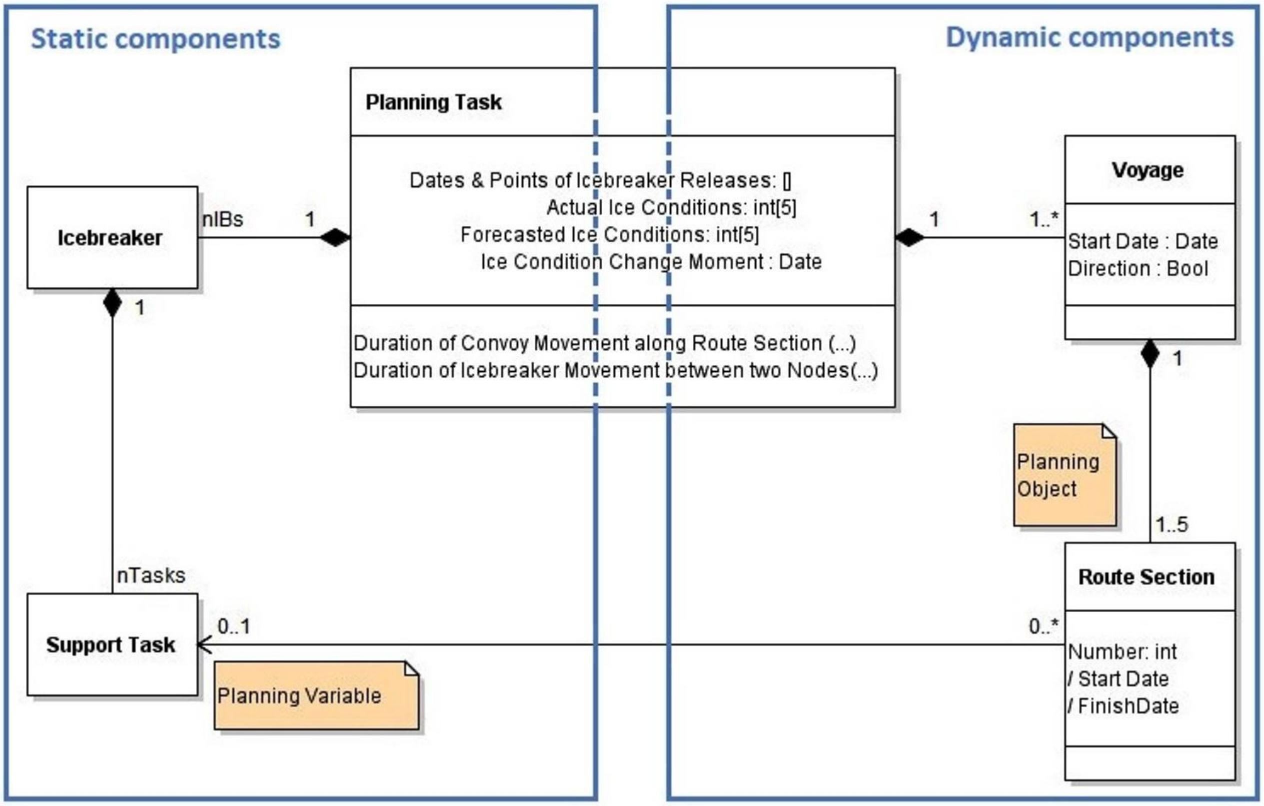

Figure 1. Object model of the data domain for planning icebreaker assistance of cargo vessels in the OptaPlanner solver

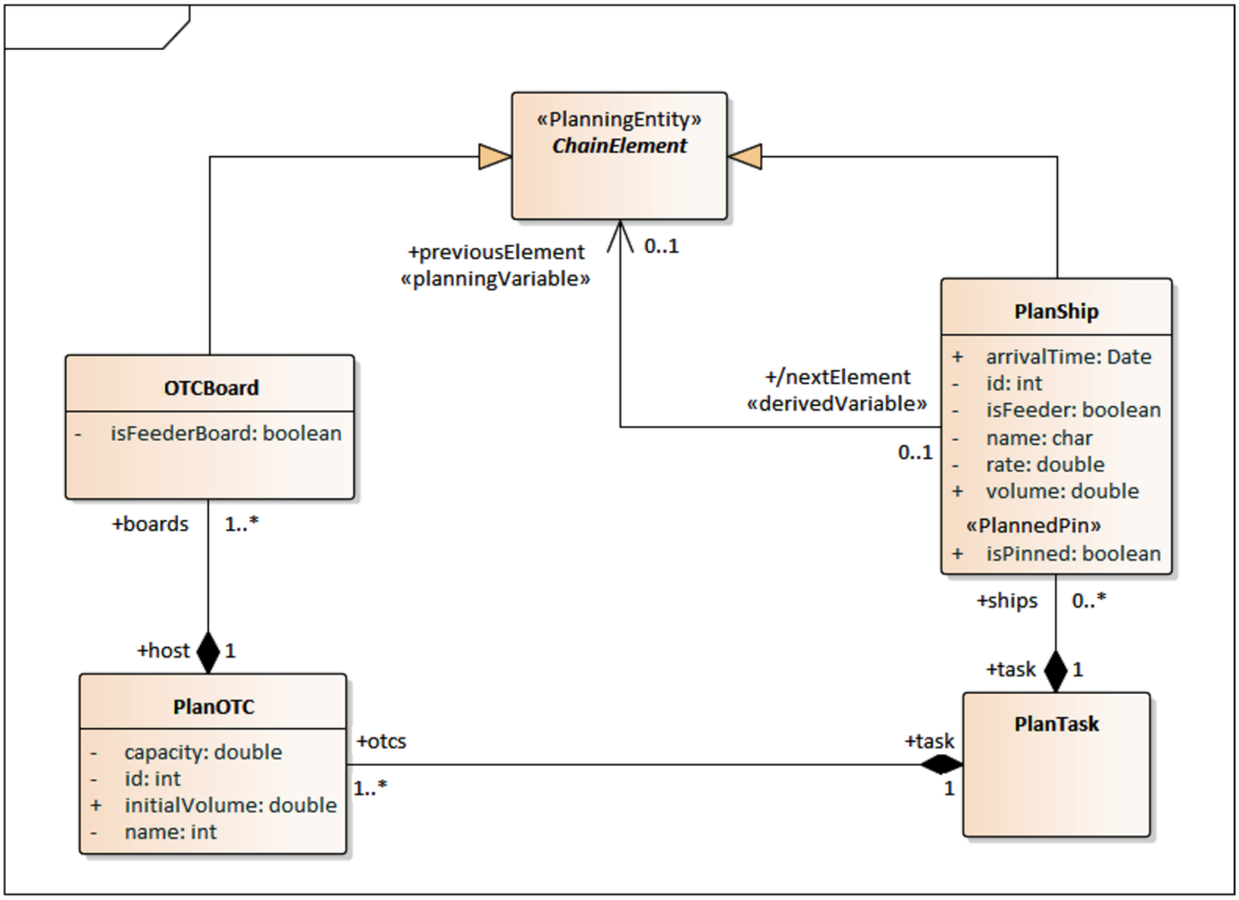

Figure 2. Class diagram for the transshipment planning problem

The main component of the considered information model is the *PlanTask* class. It encapsulates all informational description of the subject entities and static links between them (that are assumed to be fixed and are not varied). It also determines the dynamic links that are the variables in the optimization problem. These variables need to be found in such a way as to provide the best value of optimization criterion. The entities of the solved task are as follows:

1. The list of cargo vessels (both Arctic shuttles and open-water feeders), i.e. instances of the *PlanShip* class, to which transshipment complexes should be assigned and the sequence of processing on them determined;
2. The list of offshore transshipment complexes of the given transshipment port, i.e. instances of the *PlanOTC* class;
3. Each instance of the *PlanOTC* class contains a list of berths (nested array of objects of the *OTCBoard* class) on which cargo handling of ships can be carried out with the restriction formulated as "no more than one ship at the berth at same time". The role of these berthing places can be played by the boards of the offshore transshipment complex, i.e. each OTC has one board for mooring Arctic shuttle ships and the other board for feeder ships. In more general case, the semantics and the number of berthing places can be arbitrary.

Thus, a specific transshipment plan establishes the links between berths and incoming vessels, and describes the sequences in which the vessels should the berths that they are assigned to. To formalize this in the described information model, we used the concept of chains of elements that is shown in the upper part of the diagram in Fig. 2. We have assumed that both ships and berths are the inheritors of the abstract class *ChainElement*. In turn, each instance of the *PlanShip* class contains a link only to the previous element of the chain, i.e. *ChainElement* instance. If predecessor element is a ship, it means that the current ship must be serviced after the predecessor and at the same berth as the predecessor. Only the first ship in the queue for service at a specific berth links to an object of the *OTCBoard* class. The reverse end of the described associative link *nextElement* is derived. It points, on the contrary, to the next element of the chain. Therefore, each chain must always start at the instance of *OTCBoard* and is an ordered queue of ships to be serviced at this mooring place. Each variant of correct plan consists of several such chains of elements (see demo Fig. 3). Some ships may not belong to any chain (it means that they have to be served out of time horizon of the current plan), and some berths may not generate any customer chains (this means that they are not involved in the current plan).

Formalization of the cargo operation plan as a queue of ship service at a specific berth strongly resembles the formulation of the classical Vehicle Routing Problem (VRP) or the traveling salesman problem (Toth, Vigo, 2002). It can be said that the shuttle and feeder berths (sides) of each OTC construct their own routes through the customers (transport vessels of the appropriate type) in order to minimize the total time of their service. The difference with the classical VRP here is that customers are actually moving, while service vehicles are static. Another difference is that the individual routes of the berthing places of one transportation complex (OTC) cannot be considered independently of each other, but it is necessary to take into account the limited capacity of the shared storage to which they belong to.

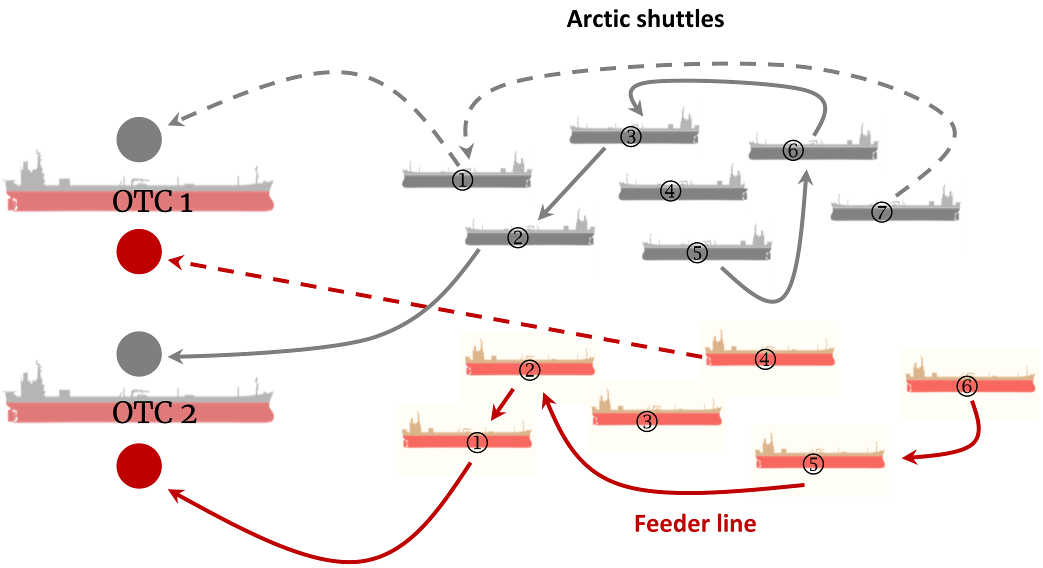

Figure 3. An example of the ship service chains in the information model of transshipment plan

The last step of the problem statement is overriding a special method that calculates the optimality criterion of current solution in *PlanTask* proxy-class. We realized the two-level structure of this criterion, which is calculated by "unfolding" (predictive playback) of ordered events that change the state of the transport system according to the current plan variant. Such events (i.e., the benchmark points on the time axis) for each OTC are the start or the end of the processing of the next shuttle or feeder ship, as well as cargo storage overfilling or emptying that cause the interruption of the unloading or loading operations. Mentioned predictive playback of the transshipment dynamics allows estimating the times of the start and the end of cargo handling operations for all vessels in the chain, as well as checking the fulfillment of logical constrains. The first-level criterion component estimates the logical consistency of the solution (e.g., absence of looped contours in the chain of serviced vessels, matching the type of the vessel and the type of berth, etc.). The second one is the quality value itself that is inversely proportional to the weighted sum of the processing times of all ships, while the weight of each vessel depends on the time of its expected arrival.

3. Results and Discussion

To demonstrate the usefulness of the approach that integrates the operational planning into the simulation model, we compared it with other methods of assigning a resource to an agent. The first alternative method is the absence of any logic, i.e. random handling of the simulated entity. In case of icebreaker planning, such approach corresponds to the independent movement of ships. In case of transshipment planning problem, the OTC is randomly assigned to each ship. The second method is some situational or greedy algorithm of best resource choice. Such an algorithm is based on some sound priority rules in handling of any coming agent and can be explicitly realized in the model code.

3.1. Icebreaker fleet management problem

For the task of icebreaker fleet management, the comparison was carried out for a simplified transportation system, where the geographical environment for ship movement is a one-dimensional graph containing six nodes and five consecutive edges. The length of each section is 300 nautical miles, and the total length of a single voyage is, respectively, 1500 miles. Ice conditions in each separate section change at a specified update rate, and are assumed to be the same within the section. Vessels can pass voyage sections either independently or under icebreaker assistance. The achievable ship or convoy speed depends on ice severity by a simple table dependency. Average voyage time of all ships was selected as a quality factor to compare variants of the plan.

Further we considered several scenarios that describe the dynamics of ice conditions on the route sections and predefine schedule of cargo vessel voyages:

- Scenario 1. Regular vessel arrivals (1 voyage per day); uniform random distribution of the severity of ice conditions on the route sections with no temporal and spatial correlation of this random process. 150 voyages of cargo vessels in total. Two icebreakers in operation.
- Scenario 2. Random schedule of vessel arrivals according to Poisson flow of requests with the intensity of 1 voyage per day. Dynamics of ice

conditions has significant temporal coherence and high value of average severity. A total of 156 cargo vessel voyages, 2 icebreakers in operation.

- Scenario 3. Random schedule of vessel arrivals according to Poisson flow of requests with the intensity of 1 voyage per day. Relatively light ice conditions having significant spatial correlation. A total of 141 cargo vessel voyages, 2 icebreakers in operation.

Obtained results are presented in Table 1. They prove that the use of operative planning algorithms for icebreaker fleet operation in the logic of Arctic marine transportation systems simulation significantly increases model performance of this transportation system. In fact, the more complex both the structure of the system (the number of cargo vessel voyages and the volume of icebreaker support) and the external conditions of its functioning (the severity of ice conditions in various parts of the route) are, the higher the effect is.

Table 1. Comparison results of the icebreakers management algorithms

Management algorithms	Average voyage time (hours)		
	Scenario 1	Scenario 2	Scenario 3
Independent movement of vessels	603.4	792.0	358.5
Greedy situational algorithm	427.7	717.8	350.5
Combinatorial optimization	324.6	547.6	286.3

More detailed description of the statement, assumptions and results of the icebreaker planning problem can be found in (Topaj et al, 2023).

3.2. Offshore transshipment planning problem

The test transportation system to compare the transshipment management methods is based on LNG delivery from Sever Bay to Rotterdam with the transshipment in Murmansk. The fleet consists of twelve Arctic shuttles with a capacity of 170,000 m^3 and eight feeder LNG carriers with a capacity of 250,000 m^3. The LNG storage in Sever Bay was assumed to be always filled without limit, i.e. the transport system was able to transport the maximum possible amount of cargo for a given configuration of cargo ships. This should clearly illustrate the impact of the transshipment planning method on the achievable cargo flow of a system. The comparison was made for various configurations of the transshipment port in Murmansk - from 1 to 10 transshipment complexes with a capacity of 520,000 m^3 each. Main performance indicators of the test transport system are shown in Table 2. They are the total LNG cargo flow, number of port calls, average (Ave), minimum and maximum durations of port call, as well as the standard deviation (St.Dev.) of the latter parameter.

Table 2. Comparison of three methods for managing the transshipment process in the LNG export simulation model (CP – operational planning, SA – situational algorithm, RA – random assignment of the transshipment complex)

Number of OTCs	Method	Performance indicators					
		LNG cargo flow (ton/year *10^6)	Number of port calls	Port time (hours)			
				Ave	Min	Max	St. Dev.
1	CP	21.8	494	112.8	24	450	69
	SA	22.2	501	109.5	24	878	84
	RA	21.9	493	112.2	24	639.2	75
2	CP	27.4	620	49.1	24	449	47
	SA	28.3	638	43	24	434	40
	RA	27	612	50.7	24	381	49
3	CP	27.9	633	44.9	24	248	32
	SA	28.6	645	39.2	24	218	26
	RA	26.7	601	50.6	24	3617	155
5	CP	29	650	37	24	328	30
	SA	28.7	643	37	24	457	38
	RA	25.2	566	61.7	24	4838	284
10	CP	30.1	671	30	24	244	15
	SA	29.2	654	31.7	24	578	41
	RA	23.8	530	75	24	5435	321

It can be noted, that when compared with situational algorithm (SA), the efficiency of a complex and resource-consuming algorithm for combinatorial planning (CP) turns out to be not high in terms of improving total cargo flow and average time of port call. For the system variants with a small number of OTCs (from 1 to 3), when the intensity of transshipment operations is the highest, the situational algorithm gives no worse and sometimes even better results. The reason for this is that ships approach OTCs very frequently, so the system becomes close to the queue system. The latter is proved by the fact that even random assignment (RA) of the transshipment complex gives the results close to CP and SA in case of 1-3 OTCs. An increase in the effectiveness of combinatorial planning is observed with an increase in the number of OTCs (up to 5-10) and a decrease in the overall intensity of their use. In this case, a smart approach for operations planning is required. It is interesting to note that in case of 5-10 OTCs, RA provides much worse results than CP and SA, since such a system configuration ceases to look like a queuing system.

However, when using CP approach, the stability of the port operations always increases. The maximum duration of port call decreases when compared with both SA and RA; this effect is the more noticeable the greater the number of OTCs. Also in case of using CP the standard deviation of port call duration becomes significantly less than for the alternative methods. These data show that CP approach allows avoiding long downtime of ships, which is possible in the case of using SA and RA.

4. Conclusions

Certainly, in order to make more profound conclusions about the effectiveness of the compared approaches, it is necessary to bring the considered test simulation models closer to the real practice of the Arctic shipping and intermodal cargo transportation. This requires considering additional factors both in transport system description (adequate modelling of ice conditions and actual navigation geography) and in stating of optimization criterion in solved planning tasks. The latter means taking into account limitations on the time of cargo vessels arrival to destination ports, requirement for the regularity of voyages, the cost of icebreaking assistance, details of transshipment operations, and other factors (Wang et al, 2021).

Anyway, solutions for both planning tasks described above (icebreaker fleet management and transshipment planning) are already implemented in the form of JAVA libraries and ready for the integration into arbitrary simulation models. They were successfully used in several applied studies carried out by LLC Bureau Hyperborea for different stakeholders, e.g. the model of logistic supply of Ob-Taz Bay region, the model for the prospective development of the Murmansk Bulk/Fertilizer Terminal, the model of the transport and technological system for exporting oil and LNG from the Sever Bay sea terminal. The experience of practical applications allows us to conclude that incorporation of optimal planning engine into simulation models (or development integrated platforms that combine simulation modeling and operations research functionality) appears to be the most proper and sometimes the only tool for adequate predictive and pre-design analysis of the complex prospective transportation systems.

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