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CARGO-FLOW-ORIENTED DESIGN OF SUPPLY VESSEL OPERATING IN ICE CONDITIONS

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ABSTRACT

Due to the dynamic development of the oil and gas fields in the Arctic, the challenges of supply fleet sizing and composition in this region are becoming relevant. In most studies, the Arctic is mainly associated with ice conditions, but it is not the only factor that influences the design of platform supply vessels (PSV) and corresponding marine transport systems (MTS) for this region. The structure of cargo flow (i.e. its distribution by cargo types) affects the supply system significantly. It defines the level of utilization of vessel capacity that determines transport efficiency. At the same time, the literature represents this aspect poorly.

This paper describes an approach to optimize supply fleet configuration by the criterion of total cost considering both non-stationary ice conditions and structure of cargo flows. The cargo-flow-oriented design concept incorporates the detailed calculation model of PSV and the special tactical planning algorithm. PSV model allows considering the influence of cargo spaces on the main characteristics and operational parameters of the ship. It covers the main design aspects of PSVs: general arrangement; lines plan; resistance in open water and ice; engine and propeller characteristics; hydrostatics; capacity and mass calculation. The pseudo-optimal tactical planning algorithm is intended to build the plan of voyages and to set the size of fleet considering the structure of cargo flow.

As the test example, we examine a task of servicing the group of platforms in the Kara Sea. The case study shows that cargo flow structure has a high influence on the efficiency of PSVs in case of high-load operation; while a widespread “deck-cargo” approach is unable to consider this aspect because it ignores the vessel’s carrying capacity and payload. The conclusion about a higher efficiency of PSV compared to AHTS with the same displacement was drawn.

1. INTRODUCTION

Supply ships provide a necessary service for uninterrupted operation of offshore platforms [1], an unplanned shutdown of which may cause significant financial losses. These ships are one of the most expensive elements of the upstream chain [2] and that fact determines the need to solve the fleet sizing and planning tasks precisely. At present, a considerable experience in these fields has been accumulated for the case of open water operation. At the same time, oil and gas offshore industry gradually moves to the regions with harsh weather conditions, in particular – to the Arctic, where there is no significant experience available. The existing supply vessels usually have an icebreaking capability of 1.0-1.3 m that allows their year-round operation only in the western arctic seas with the mildest arctic ice conditions (Barents and Pechora seas). Therefore, the problem of supply vessel design optimization and fleet composition in the arctic waterways is the actual task that requires considering various technical and logistical issues.

PSV is one of the few classes of ships that have cargo spaces for simultaneous transporting of different types of cargo. At the same time, upstream cargo flows of offshore platforms have a specific structure in different geographical regions. The climate-, organizational-, technological- and logistical features cause it. For example, typical structure of supply cargo flows on the Russian Arctic shelf is characterized by the absence of drilling mud and brine. Due to the remote location and harsh weather conditions, these essences are fabricated directly on the offshore platform from necessary liquid and bulk components. Additional bulk cargoes are transported on cargo deck in specialized offshore containers, while the traditional drilling mud/brine tanks become useless and lead to unreasonable cargo load of PSV in the voyage. Therefore, we should analyze the influence of vessel capacity distribution between different cargoes on its effectiveness.

Modern supply vessels are often designed to carry out several transport and non-transport functions. The most popular type of multipurpose vessel for offshore operation is the anchor handling tug supply vessel (AHTS). Such vessels are widely used as supply ships to deliver cargoes to the platform. However, it is well known that like any multipurpose tool, AHTSs are at a disadvantage compared with the specialized analogues in specific narrow aspects of the latter ones. For example, AHTSs have lower efficiency in cargo transportation than PSVs. Along with that, the literature poorly represents the task of comparison of the transport efficiency of equivalent PSV and AHTS.

Thus, we consider all the mentioned issues as the study objectives. This paper describes the approach to analyze and optimize the supply fleet composition considering the structure of cargo flow and non-stationary ice conditions. We also made the comparison of transport efficiency of PSV and AHTS.

2. STATE OF THE ART

There is a variety of studies that focused on the problem of initial ship design in general. A comprehensive review of this field is given in [3]. We may note that the most of modern attempts to increase ship efficiency during the design process are connected with the consideration of ship operation in the frame of MTS [4-6]. Therefore, most studies related to PSV optimization and fleet sizing treat vessel as a part of the marine supply system. The existing approaches may be conditionally subdivided into three specific groups: design models, logistic planning models and dynamic simulation models.

The first group focuses on PSV design optimization. These studies contain parametric models of the vessel, enabling to search for the optimal solution by means of continuous variation of main ship parameters. The study [7] presents a calculation model of the offshore support vessels that covers a wide range of their types; the vessel is represented as a complex system that has the capacity, stability, resistance, functionality, etc. Deck area and deadweight are considered as the main capacity characteristics. The article [8] presents a framework for parametric design and optimization of ships in arctic conditions; it considers the design and operational aspects. An optimization model that considers the modular principles in offshore ship design is described in [9]. We also took some general ideas of initial ship design for the current study from the detailed optimization model of container vessel given in [10]. It incorporates hull geometry, stability, propulsion, weights, various loading conditions, etc.

The second group of studies focuses on optimization of PSV-fleet composition with the use of tactical planning algorithms. Its distinctive feature is the absence of specialized ship calculation models and the use of variants of ships for fleet optimization. Particulars of supply vessels are the input data that is presented by a small set of parameters. At the same time, the task of tactical and operational planning involves a number of specific features, such as temporal constraints on deliveries, the need for servicing a number of facilities, different types of cargo, etc. Therefore, specialized methods are created to solve such problems. The problem of PSV tactical planning was first defined as an integer programming problem in [11] using the example of servicing a set of offshore installations in the Norwegian Sea. This algorithm answers the question which vessel, when and in what order will serve each of the considered offshore installations. The planning horizon is set to one week, and the main assumption is that the supply fleet operates year-round by one regular weekly schedule. Also, the specific assumption on the cargo flow is made based on the real practice: only the deck-cargoes are taken into account, while other cargoes are assumed to have an insignificant effect on system's performance. As noted by the author, the main weakness of this approach is the resource-intensive computational process. Most of the subsequent studies [12-15] are based on this concept, supplementing and improving it. However, in the most of logistic-oriented studies of PSV operation, the basic assumption about deck-cargoes remained constant due to the troubles in calculation when considering multiple types of cargoes.

The third group of methods has no detailed model of the vessel, the same as the second one. However, instead of the deterministic optimization planning algorithm, they use the discrete-event stochastic simulation model as a logical core of the approach. A discrete-event simulation model of supply fleet operation is described in [16]. Modeled weather conditions include significant wave height, mean wave direction, and wind speed. These parameters influence vessels speeds and weather windows of drilling units. The cargo flow is described by deck-cargoes. The paper [17] presents a discrete-event simulation model for determining a sub optimal configuration of PSV fleet using the example of Kharg district, Persian Gulf. The article focuses on the comparison of two alternative approaches to solve the problem of planning: a regular weekly schedule and a non-regular demand-based voyage planning. The main conclusion of this study is the statement about the increased efficiency of fleet operation upon irregular schedule in comparison with the alternative weekly-oriented one. The cargo flow is represented by the number of visits of each platform per week. A discrete-event simulation model to optimize supply fleet in the Kara Sea is developed in [18]. The probabilistic model of weather is used to evaluate the platform accessibility for cargo operations and it includes significant wave height, wind speed, visibility and polar lows. The platform needs are represented by a statistically-based flow of deck cargoes. Ice conditions in the Kara Sea are out of the investigation.

Each group of methods has its field of practical application: optimization of a ship under given assumptions; implementation into the practice of fleet management; "what if" analysis and supporting decision making. However, we did not found a direct link between the structure of cargo flow and a ship design process and recognized this as a knowledge gap and a research target.

This article offers an approach for PSV and offshore supply system conceptual design, which distinctive feature is a consideration of multiple types of cargoes. Most of the existing studies ignore the structure of cargo flow and carrying capacity of PSVs because they are not important when there is a large margin of MTS capacity. At the same time, at high-load MTS-configurations (in particular – in the Arctic) these factors can play a significant role. As far as we expand beyond the assumption of a single "deck-type" cargo, we have a need to use the elements from each group of methods: the detailed parametric model of the vessel; irregular pseudo-optimal planning; modeling of the weather- and ice-conditions; describing storage filling dynamics on the platform.

3. MAIN PRINCIPLES OF THE APPROACH

Fig. 1 represents the main stages of calculation process. Input parameters (step 1) are the data on cargo flows, PSV variants, ice conditions and the distance between shore base and target customer. The description of cargo flows contains the types and quantities of cargoes to be carried within the investigated period. This data may be set with an arbitrary time discretization. The information model of PSV describes all the necessary parameters of the ship for further investigations. Generation of the information model is carried out based on nine key parameters, which are preset for each vessel and represent its main design- and operation characteristics. Such models are generated for each variant of the vessel before running the search algorithm (step 2). Parameters of the serviced object are represented by capacities and areas to arrange cargoes of all considered types.

In this study, the ice cover is described as a set of equivalent ice thicknesses and percentages of lanes for each month of the year. The lanes in ice cover are the water openings or areas with thin ice that were formed during the movement of ice fields. The ice data was provided by Arctic Antarctic Research Institute based on archive ice charts from the period 1960-2014 [19]. Equivalent ice thickness is calculated as a function of the ice age, form, concentration, the degree of ridging, snow cover and melting stage.

The influence of winds and waves is considered indirectly by the weather coefficient that increases the duration of PSVs operations in ports. The impact of these factors on vessel speed is not taken into account due to weak influence compared with ice. The percentage of lanes in the area of vessel navigation should be considered as an important condition for reliable estimation of vessel speed. It results from the modern practice of ice navigation when vessel routes are optimized based on data from satellite monitoring and remote sensing of actual ice state allowing minimizing the voyage time.

Generation of information models for all variants of PSVs is undertaken at step 2 with the use of the vessel calculation parametric model (see item 3.1). This model has a high level of detail, which is typical for ship optimization models. This is due to the fact that only a quite detailed model allows considering the distribution of ship capacity taking into account all other ship design aspects, while the capacity distribution is the principal feature of the cargo-flow-oriented design concept. We consider a ship to be a number of sub-systems that interact and influence each other. As a result, the impact of certain properties of the ship on an overall efficiency of MTS could be analyzed. The detailed ship model also gives a possibility to estimate the effect of vessel type reliably, ice class and icebreaking capability on the efficiency of MTS. These factors influence the transport system through the cargo capacity, payload, open deck area, and fuel consumption.

There is a popular approach, according to which the characteristics of existing vessels are used to avoid the need for a detailed vessel model [16, 18]. In our case, it cannot be applied due to the limited number of constructed PSVs and AHTSs capable of arctic navigation.

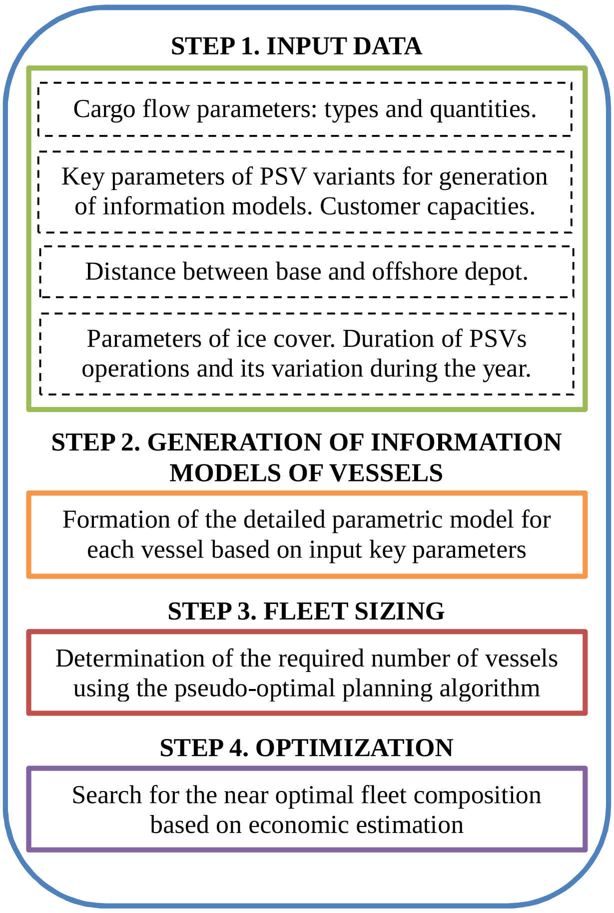

Figure 1. The main stages of the design process

The obtained information models of ships are delivered to the step 3 for determining the required number of vessels. To solve this task we developed the original pseudo-optimal algorithm (see item 3.2) to build the voyage plan governing fleet operation. There are two reasons that motivate the creation of a new planning tool: 1) the existing planning approaches are oriented on the single type of cargo (i.e. deck cargo), while we need to analyze the several types; 2) most of the existing approaches utilize the concept of regular weekly schedule, but it is not applicable in arctic conditions due to the significant change of voyage time even in two consecutive weeks.

For each fleet configuration, we made the economic assessment of system efficiency; after that, the selection of near optimal solution is done. Main limitations of the approach are presented in section 6.

3.1. Holistic calculation model of the supply vessel

At the first step of model development, the large volume of statistic information on built ships was collected and analyzed. As a result, a database, holding over 100 parameters for 115 modern (1997 – 2017 years) original projects (without sisterships) of PSVs and AHTSs, was created. It contains a large amount of statistical information and includes vessel characteristics related to all significant design and operational aspects. Based on the obtained data, we conducted a system-oriented analysis, which resulted in the structure and principles of generation of the vessel information model.

The main principle for vessel generation is the use of typical ship design parameters (see Table 1) as initial key data in design procedures. For most of the logistic-oriented studies, it is typical to use the operational parameters of the ship (deadweight, cargo capacity, etc.) as the initial input data to generate vessel particulars.

The other principle is that the requirements of safety and environmental protection are taken into account in the model in an indirect manner. As it is noted in [20], the direct optimization of ship hull weight and other parameters by cost criterion can lead to an increased risk of hull damage. Therefore, hull form, freeboard and required power are taken in accordance with the requirements of Russian Maritime Register of Shipping (RMRS) and all weight calculations are based on the statistical data on ships designed in accordance with RMRS rules. The necessity to minimize a negative impact on the environment is also taken into account indirectly by adding fuel consumption value into cost criterion.

Fig. 2 represents the main calculation modules of PSV model. The model enables to generate vessel hull geometry and to calculate propulsive characteristics, required engine power, payload, capacities and areas for various cargoes, speed in open water and in ice based on input key parameters. Table 1 represents the list of key parameters and the ranges of their variation. Two alternative types of vessels having the same key parameters could be generated: PSV and AHTS. Restriction of the maximum speed in open water corresponds to a Froude number (Fn) 0.35. The ice classes *C* are taken in accordance with RMRS. For each ice class, the specific range of possible values of icebreaking capability is set.

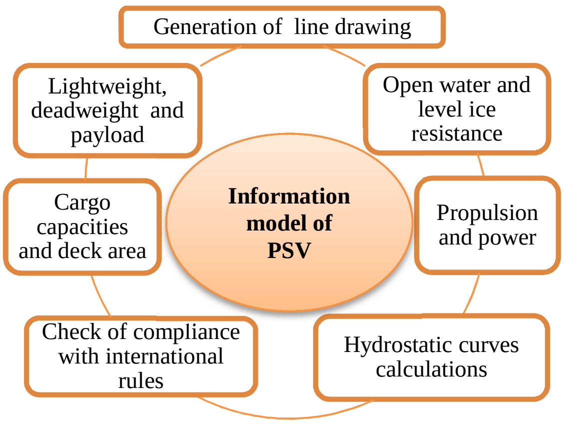

Figure 2. Simplified scheme of PSV calculation model

Minimum and maximum values for main dimensions of the vessel are selected based on statistical information. The relations of main dimensions are checked for the correspondence to the permitted values. Vessels with smaller dimensions will have lower economic efficiency. In turn, the vessels with larger dimensions are limited by the need to ensure high maneuvering ability and safety during an operation near offshore platforms. In addition, the linear dimensions of PSVs and AHTSs are restricted by the corresponding dimensions of serviced objects; therefore further increase of ship size may lead to difficulties in mooring and loading operations.

RMRS requirements are checked in the model and calculation of minimum permitted freeboard is done.

Vessel geometry is formed by means of interpolation between five specific prototype line drawings. The range of considered C_b values depends on the vessel ice class:

No ice class…Arc 4 – C_b vary from 0.68 to 0.78;

Arc 5…Arc 8 – C_b vary from 0.58 to 0.7.

Table 1. List of key parameters of PSV information model

Parameter	Symbol	min	max
1. Vessel type		PSV / AHTS	
2. Length, m	L_{pp}	50	100
3. Breadth, m	B	13	25
4. Draft, м	d	4	9
5. Depth, m	D	5	13.5
6. Open water speed, kn	Vs	8	$\frac{0.35}{0.5144}\sqrt{L_{pp}g}$
7. Ice class	C	-	Arc8
8. Icebreaking capability, m	h_{lim}	0	2.5
9. Block coefficient	C_b	0.58	0.78
10. Distribution of cargo spaces by the cargo types			

The selected basic line drawings cover all the range of specific C_b values. Figure 3 presents the basic line drawings for vessels of ice classes Arc 5…Arc 8.

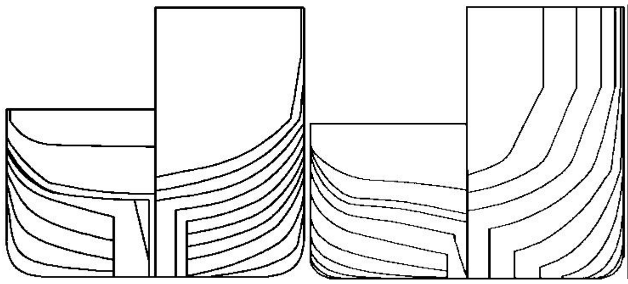

Figure 3. Base ship hulls for generation of geometry towards vessels with high ice class

The basic line drawings are stored as the tables of relative ordinates for 22 (0 - 21) transverse sections and 12 waterlines (5^{th} waterline is the design WL). The coordinate system is the following: origin corresponds to the intersection of the fore perpendicular to the base plane. The positive direction of the *x* axis is directed in the stern, the ordinate (*y*) is on the starboard side, the applicator (*z*) is up. Ordinates of the required drawing are determined according to formula (1) [21].

$$y = \left(y_2 - \frac{(C_{b2} - C_b)}{(C_{b2} - C_{b1})}(y_2 - y_1) \right) \frac{B}{2}, \text{m} \quad (1)$$

where C_{b1} and C_{b2} – are the closest smaller and nearest larger block coefficients, y_1 and y_2 – relative ordinates of the first and the second line drawings. Contours of the stem and the stern in the form of relative *x*-coordinates are also taken into account in order to increase the accuracy of geometry modeling and hydrostatic calculations. Hydrostatic curves as well as specific volumes and areas are calculated by means of numerical integration by trapezoid method (2 – 6) based on a calculated table of ordinates. Nomenclature:

n number of transverse section;
m number of waterline (WL);
$W_{n,m}$ area of n transverse section up to m WL (m^2);
S_m area of m waterline (m^2);
V_m volume of hull up to m WL (m^3);
L_n perimeter of n transverse section up to the design WL (m);
S_{ws} area of wetted surface up to the design WL (m^2).

$$W_{n,m} = 2\int_0^{z_m} y_n dz\,;\; S_m = 2\int_{x_{min}}^{x_{max}} y_m dx\,;\; V_m = \int_0^{z_m} S dz; \qquad (2-4)$$

$$L_n = y_{n,0} + \sum_{m=1}^{5}\sqrt{(z_m - z_{m-1})^2 + \left(y_{n,m} - y_{n,m-1}\right)^2} \qquad (5)$$

$$S_{ws} = \int_{x_{min}}^{x_{max}} L_n dx \qquad (6)$$

In a similar way, the coordinates of buoyancy center are identified, as well as the transversal and longitudinal metacentric radii for each waterline.

Calculation of ship resistance in open water is done by various methods for ships with different hulls forms. For the vessels of ice class up to Arc4, we apply the multipurpose method proposed by J. Holtrop and J. Mennen [22]. However, this method is not applicable for ice-going supply vessels; the obtained results of residual resistance are 15-25% lower than the values from tank tests. For the vessels with Arc5…Arc8 ice classes, the more accurate results could be obtained using the method of O.V. Dubrovin [23]. It is based on the principle of residual resistance re-calculation using the prototype vessel and considering the impact of L_{pp}/B, B/d ratios and C_b value. This method was created during an analysis of residual resistance for the range of icebreakers with various hull form parameters. Boundaries of the applicability of this method agree nicely with the dimensions of supply ships.

Residual resistance is calculated by the formula (7), C_{R_0} – residual resistance coefficient of prototype vessel from the model tests (see Fig. 4); χ – auxiliary coefficients.

$$C_R = C_{R_0} k_{C_b} k_{B/d} k_{L_{pp}/B} \qquad (7)$$

$$k_{C_b} = \frac{\chi_{C_b}}{\chi_{C_{b_0}}};\; k_{B/T} = \frac{\chi_{B/d}}{\chi_{B/d_0}};\; k_{L_{wl}/B} = \frac{\chi_{L_{pp}/B}}{\chi_{L_{pp}/B_0}} \qquad (8-10)$$

In formulae (8-10), index “0” means that this parameter is related to the prototype vessel. Auxiliary coefficients χ in the original study [23] are given in a graph form (Figure 5). In the current study, we made their regression approximation by the least square method. Calculation of the total vessel resistance in open water is made by supplementing the residual resistance with missing components as in [22].

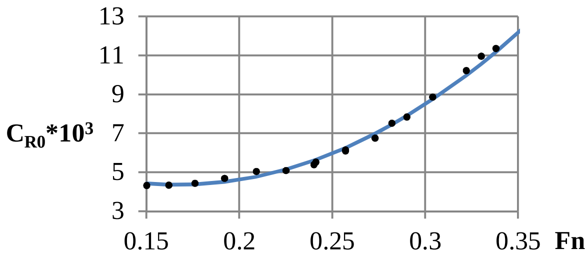

Figure 4. Residual resistance data from the model tank tests of the prototype supply vessel

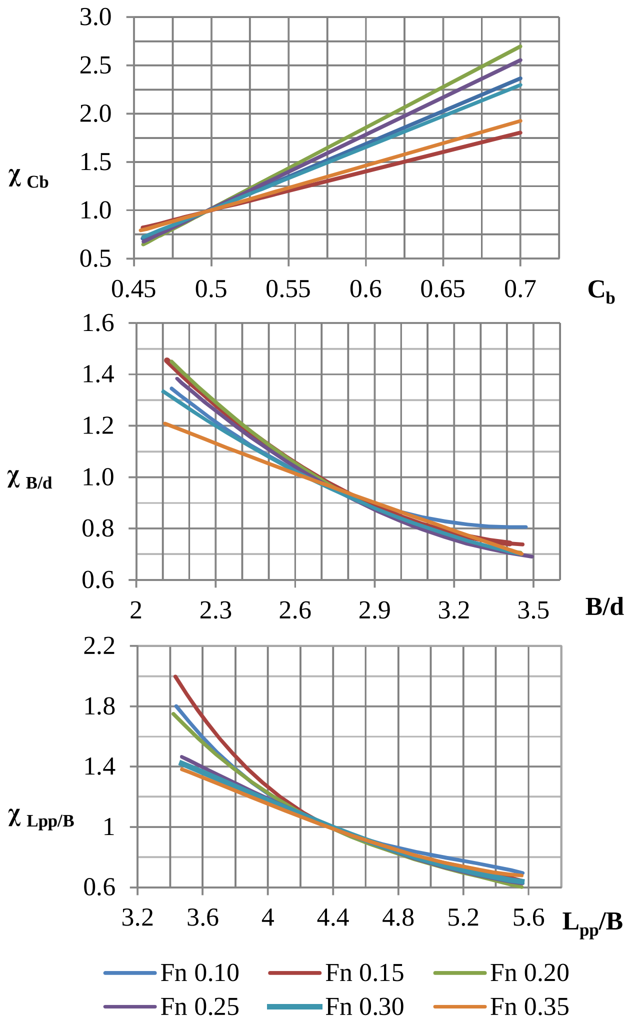

Figure 5. Graphs for determining the auxiliary coefficients χ depending on the number of Froude [23]

To calculate the vessel resistance in level ice, we applied the method proposed by G. Lindquist [24]. In all calculations, the speed V_{lim}, which corresponds to the icebreaking capability of the ship, is 2 knots.

The algorithm for the automated selection of appropriate four-blade propellers is realized based on two series of model propellers designed in Krylov State Research Centre (KSRC). One series is designed for ice-going vessels (Arc5 and higher), the other one – for conventional transport ships. The calculation mode for propeller selection in both cases is the open water design speed. The mandatory condition in propeller selection is the absence of the second stage of cavitation at maximum thrust and design speed (Arc4 and lower) or zero speed (Arc5...Arc8).

The required power to be delivered on propellers (P_d) is identified as the maximum value from a number of regimes: movement in open water; icebreaking mode; anchor handling (for AHTS); towing a standard customer (for AHTS). The P_d value is taken in accordance with RMRS requirements. The alternative variants of the propeller-rudder system are considered during P_d calculation: azimuth thrusters; screw propellers (FPP/CPP); nozzles. The type of propulsion system is either diesel-electric or mechanical, depending on ice class and the type of ship. Hotel loads and auxiliary generators are also considered when estimating the power plant.

To create an algorithm for calculating the cargo capacity and deck area, we analyzed 25 general arrangement drawings of PSVs and AHTSs. As the result, we obtained the statistic equations to identify vessel's cargo areas and capacities. Calculation of hull capacity and deck area is made directly by means of the lines plan. After that, the main features of general arrangement (bulkheads, double bottom) are identified and all the capacities below upper deck that do not intend to arrange cargo are estimated based on statistical data (engine room, thruster room, steering room, the stern roller of AHTS, etc.). The remained capacity is distributed among the cargoes by the preset percentage ratio considering the statistical utilization coefficients for each of cargo type. The following cargo spaces are modeled: ballast/drill water, fuel cargo, ship fuel, fresh water, drilling mud/brine, bulk.

Special attention is given to calculation of the upper deck area, accessible to arrange general cargoes. For this, the calculated total deck area is decreased by the areas occupied for other purposes (forecastle, double bulwarks, hull gears). The deducted areas are identified depending on the vessel type and the region of operation (for example, arctic PSVs and AHTSs are characterized by approximately two times higher area of forecastle compared with non-arctic ships). The obtained area to arrange cargo is multiplied by decreasing coefficient that allows considering the practical restrictions of the close-by arrangement of cargo units.

Ship lightweight is estimated by 10 components. Each of them is identified separately by statistical formulas, based on the experience of supply vessels design in Baltsudoproekt bureau (the part of KSRC). Ice reinforcement's weight is calculated based on the regression formula obtained in the separate research. This weight depends on ice class, main dimensions and hull shape parameters. The final phase of vessel weights calculation is the identification of deadweight and payload values. The coordinates of gravity center are calculated for all lightweight and deadweight components.

3.2. Pseudo-optimal planning algorithm

The main idea of the pseudo-optimal voyage planning algorithm is to meet the critical supply needs by means of so called approach "from A to Z". The algorithm plans voyages based on the given cargo flows and chooses the best vessel-executor. Planning algorithm is organized in a way to maximize the time T_{crit} till the overflowing/depleting (depending on the direction of cargo flow) of storages on the platform. For this end, it simulates the dynamics of cargo spaces filling. The instruments of maximizing the time T_{crit} are: 1) choosing of vessel-executor and 2) vessel loading in each voyage. The vessel-executor is chosen from the pool of alternative vessels based on the cargo capacity for the type of cargo that determine T_{crit} and considering the time, that vessel needs to deliver the critical cargo. The vessel loading is done in an optimization way by successive adding of cargo amounts of various types to maximize T_{crit} taking into account cargo consumption rates on the platform, restrictions on volumes of platform storages and vessel capacities, durations of voyages and cargo operations. Fig. 6 shows the main logic elements of the algorithm.

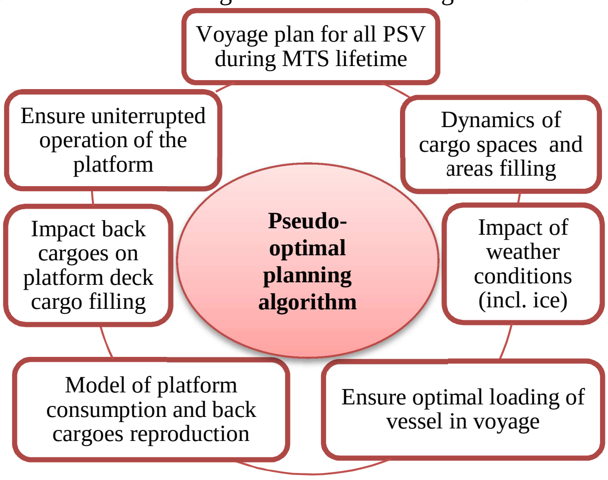

Figure 6. Elements of the pseudo-optimal planning algorithm

Ship voyage time is calculated under an assumption that it runs at maximum achievable speed in all natural conditions. As the ice parameters, we have taken the equivalent ice thickness h_{ice} (m) and percentage of lanes p_{Lane}. Maximum speed in ice V_{LI} (kn) is identified under the formula (11), and the speed in lanes V_{Lane} (kn) – under (12). Maximum open water speed V_{max} (kn) is identified from the resistance curve. Coefficient p_{red} sets the relative ice thickness in lanes, which is accepted to be 20% of h_{ice}. The average vessel speed, that determine the voyage duration, is calculated under the formula (13). Parameter p_{util} is the percentage of used lanes; it is taken as 50%. The p_{red} and p_{util} coefficients reflects the modern practice of ice routing; their values were taken with the help of special calculations by the ice routing algorithm in [4].

$$V_{LI} = V_{lim} + (V_{max} - V_{lim})(h_{lim} - h_{ice})/h_{lim} \quad (11)$$
$$V_{Lane} = V_{lim} + (V_{max} - V_{lim})(h_{lim} - h_{ice}p_{red})/h_{lim} \quad (12)$$
$$V_{Fin} = V_{LI}(1 - p_{Lane}p_{util}) + V_{Lane}p_{Lane}p_{util} \quad (13)$$

3.3. Feasibility evaluation

Economic efficiency of MTS variants is evaluated by the total cost criterion. To identify the cost of vessel acquisition, we collected statistic data on the sales cost (USD) of over 50 supply vessels during the period from 1998 to 2017. All prices were driven to 2017 considering the values of US consumer price index. The cost of vessel acquisition C_{av} (M$) is evaluated under the obtained formula (14) depending on the lightweight LWT (t).

$$C_{av} = 0.0172 \cdot LWT - 9.2 \quad (14)$$

The detailed list of vessel operations resulted from the planning stage (movement, platform- and port operations), enables to calculate the total time for various types of operations t_i (hr) for each vessel. Fuel consumption F_{cons_i}(t) for each operation is identified under the formula (15), where i – type of operation, q – specific fuel consumption (t/kWh), N_i – average power to execute operation (kWh),

$$F_{cons_i} = qN_it_i \quad (15)$$

The values of N_i are identified under the formula (16), where P_i(kWh) – consumed power, K_{tr_i} – power transmission ratio. The values of q, P_i and K_{tr_i} are shown in Table 2, where P_{hl}(kWh) – hotel load at moving regime.

$$N_i = P_i/K_{tr_i} \quad (16)$$

Hotel loads are calculated using [25], while consumed shaft power is known from earlier calculations. The value of K_{tr} for ship movement depends on the type of power transmission; it is taken 0.97 for mechanic transmission (z-drive type) and 0.87 for electric one.

Table 2. Data for fuel consumption calculation

Operation type (*i*)	**P_i, kWh**	**K_{tr_i}**	**q, t/ kWh**
Moving	P_d+P_{hl}	0.97 / 0.87	
Platform operations	3000	0.93	$0.221 \cdot 10^{-3}$
Port operations	750	0.93	

Total cost criterion (17) represents the expenses amount for fleet acquisition and for fuel, where F_{price} ($) – the cost of one ton of MDO.

$$Expenses = \sum C_{av} + F_{price} \cdot \sum F_{cons_i} \cdot 10^{-6} \quad (17)$$

4. CASE STUDY

We took the task of servicing the group of platforms in the Kara Sea as the case study. Supply cargoes are transported from coastal base to the floating storage arranged at a distance of 300 nautical miles from the shore. Capacities and areas for various cargoes on the floating storage are taken under an assumption of 10-day supply stock amount for the given cargo flow. Annual cargo flow is 160000 t that guarantees a "high-load" operation of PSVs and makes difference between various configurations more evident. We analyzed two variants of cargo flow structure (see Table 3): CF-1 ("traditional") and CF-2 ("special"). In the first variant, the drilling mud is delivered from the shore in specialized onboard tanks; in the second one, the drilling mud is fabricated on the platform, while the components are transported in deck containers. The structure of CF-2 is justified by the peculiarities of arctic operation. Poor development of infrastructure leads to an increase of a distance between the supply base and the target object. Harsh ice conditions in the Arctic may cause considerable deviations in the duration of round voyage in comparison with the average value. In this circumstances, the production of drilling mud onboard the platform increases system sustainability minimizing the probability of forced shutdown of platform operation.

Table 3. Two variants of annual cargo flow structure

Type of cargo	**Attribute**	**CF-1**	**CF-2**
Bulk (m^3)	2.0 t/m^3	3616	3616
Drilling Mud/Brine (m^3)	2.5 t/m^3	10265	0
Cargo fuel (m^3)	0.85 t/m^3	17390	17390
Drill water (m^3)	1.0 t/m^3	83320	90550
Average container (pcs.)	7.3 m^2, 3.4 t	8580	14040

The modeled parameters of ice (see Fig. 7) correspond to an average type of severity of ice conditions in the Kara Sea.

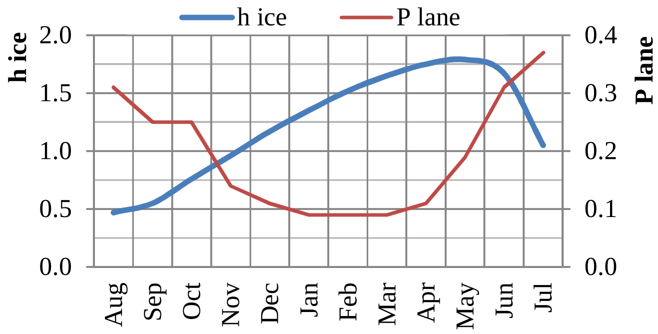

Figure 7. Parameters of ice conditions in the case study

Table 4 shows the main particulars of the alternative variants of ships; the fleet is homogeneous. The vessels are generated with two values of icebreaking capability and in a broad range of deadweights. Vessels of Arc7 ice class have a greater range of deadweight change than vessels of Arc8 class due to the limitations of ship main dimensions (see Table 1). Distribution of the total useful cubic capacity of studied vessels is done for each ship in different ways depending on the task.

Fig.8 shows the calculation results, where the graphs from *a* to *d* correspond to an average statistical distribution of vessel capacity (see Table 5), which was obtained for open-water PSVs and AHTSs from the statistical database (see par. 3.1). The space utilization coefficients in Table 5 consider the shape of tanks, passages for humans, etc. Graphs *e* and *f* show the comparison of improved distributions with average ones.

Fig. 8*a* shows the results for the first variant of cargo flow (CF-1) and the operation period of 10 years. In this case, the vessels with Arc7 ice class and deadweight within a range of 3200 – 4000 t have the best economic indicators. Increased ice capability of Arc8 vessels and corresponding speed growth do not compensate the negative impact due to a decrease in their transport capacity and payload.

In case of CF-2 cargo flow structure (Fig. 8*b*), where the containers percentage is notably greater, the picture changes significantly. In this case, the advantage of Arc7 vessels is observed not on the whole range of deadweight values, although the best efficiency is still observed for an Arc7 class at deadweight of 4500 – 5000 t. This is due to re-distribution of the numbers of engaged vessels and their voyages.

Comparing the graphs *a* and *b*, one can note that vessels of Arc8 class slightly changed their expenses, while Arc7-classed ships – significantly. This is due to that Arc8 vessels have less cubic capacity, which is determinant in case of CF-1, while their large deck is poorly utilized. As a result, when proceeding from CF-1 to CF-2, additional deck cargoes do not influence the number of Arc8 vessels. In case of Arc7 ships, the increase of number of deck cargoes leads to an increase of ships number.

Fig. 8*c* shows the expenses for CF-1 cargo flow at operation period of 20 years for four variants of fleet type: PSV Arc7 and PSV Arc8; AHTS Arc7 and AHTS Arc8. For the vessels of Arc7 class, the use of AHTSs instead of PSVs (with the similar deadweight) leads to the growth of expenses by 5% at average. For the vessels with low deadweight and Arc8 class, the expenses of AHTSs considerably exceed the expenses of PSVs. The best results showed the PSVs of Arc7 class with the deadweight of 3500 – 5000 t.

Table 4. PSV variants for fleet optimization

Dwt PSV / AHTS	Deck area, m^2 PSV / AHTS	Ice class	h_{lim}, m	$L_{pp} \times B \times D \times d \times C_b$
1670 / 1540	590 / 470	Arc7	2.0	73.3×18×11.2×8.3×0.59
2280 / 2160	622 / 500	Arc7	2.0	78×17.82×10×8.25×0.6
2780 / 2680	900 / 830	Arc7	2.0	79.5×20.95×11×8.5×0.6
2800 / 2700	1070 / 990	Arc7	2.0	88×21×11.2×8.29×0.59
3080 / 2980	1100 / 1020	Arc7	2.0	95×19.5×10.3×8.05×0.6
3470 / 3360	1170 / 1080	Arc7	2.0	95×21×11×8.4×0.6
3830 / 3720	1410 / 1310	Arc7	2.0	94×23.8×11.2×8.5×0.59
4050 / 3940	1450 / 1350	Arc7	2.0	100×23×11.2×8.43×0.6
4240 / 4140	1470 / 1360	Arc7	2.0	88.8×21×11.2×9×0.64
4630 / 4520	1510 / 1400	Arc7	2.0	97×23×11×8.7×0.62
5280 / 5170	1600 / 1490	Arc7	2.0	100×25×11×8.7×0.62
1960 / 1860	1070 / 990	Arc8	2.5	88×21×11.2×8.29×0.59
2250 / 2150	1100 / 1020	Arc8	2.5	95×19.5×10.3×8.05×0.6
2550 / 2450	1170 / 1080	Arc8	2.5	95×21×11×8.4×0.6
2850 / 2750	1410 / 1310	Arc8	2.5	94×23.8×11.2×8.5×0.59
3050 / 2940	1450 / 1350	Arc8	2.5	100×23×11.2×8.43×0.6
3610 / 3500	1490 / 1380	Arc8	2.5	100×23.4×11.2×8.7×0.61
4070 / 3960	1570 / 1455	Arc8	2.5	100×24.5×11×8.7×0.62

Table 5. Average distribution of PSV and AHTS capacity

Type of cargo space	The part of the useful cubic capacity	Coefficient of space utilization
Bulk cargoes	0.05	0.37
Mud / Brine tanks	0.20	0.95
Cargo fuel + ship fuel	0.22 + 0.02 = 0.240	
Drill + Fresh water	0.35+0.135 = 0.485	
Other non-cargo tanks	0.025	

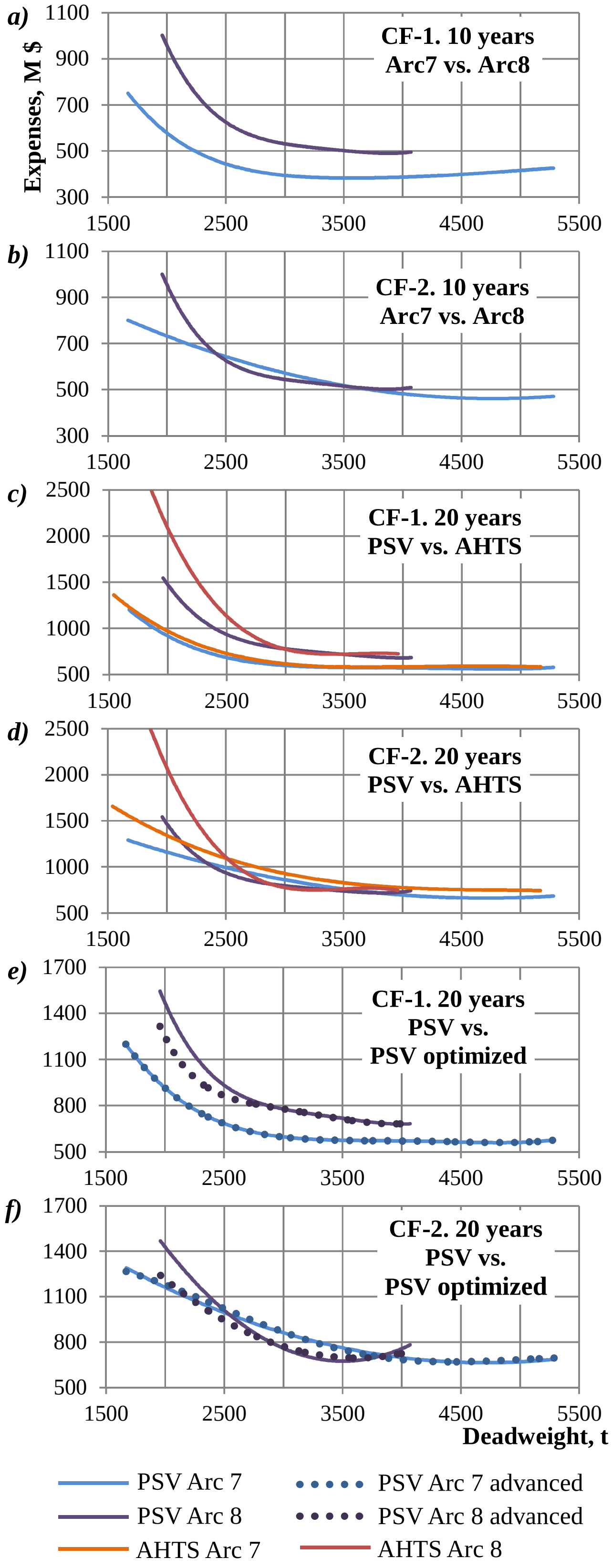

Figure 8. Expenses for various variants of the supply system

Fig. 8*d* presents the data similar to Fig. 8c, but for the alternative structure of cargo flow (CF-2). The increase in the percentage of general cargoes in CF-2 leads to the growth of PSVs and AHTSs expenses of Arc7 class on the whole range of deadweight values, while vessels of Arc8 class slightly changed their expenses. At this cargo flow, PSVs are 10-15% more efficient that AHTSs. PSV Arc7 configuration with a deadweight of 4000 – 5000 t shows the best results.

Fig. 8*e* (CF-1) and Fig. 8*f* (CF-2) represent the comparison of PSV Arc7 and PSV Arc8 fleet: 1) with an average statistical distribution of capacities by the types of cargoes (see Table 5); 2) with the more appropriate distribution of cargo spaces in accordance with cargo flow structure. The latter one is obtained by dividing the total useful cubic capacity in proportion to the volumes of corresponding cargoes in the cargo flow, considering not only cargo fuel but a ship fuel as well. This type of adaptation of cargo spaces is correct in case of a deterministic model of supply system operation; in case of stochastic modeling question is the subject for optimization.

As it is seen from Fig. 8*e* and 8*f*, the change of cargo capacity distribution insignificantly affects the Arc7 vessels at all types of cargo flow. The influence of this factor is observed only for Arc8 class vessels having low deadweight; it enables to decrease the expenses by over 10 %. In Table 6, we give an example of capacity distribution for PSV Arc8 Dwt 2250 in case of CF-1 cargo flow. The nature of the influence of capacity distribution on system expenses is related to the fact that this factor is significant only on high-load configurations of the supply system. We found out that ratio (18) could serve as a kind of marker for the preliminary definition of a need to consider the capacity distribution of a vessel.

$$K_C = \frac{\text{total useful cubic capacity}}{\text{useful deck area}} \leq 4.5 \ldots 4.7 \quad (18)$$

Vessels with K_C less than 4.5…4.7 were found to be affected by capacity distribution; the exact limiting value of K_C depends on the structure of cargo flow. The lower the K_C, the greater the effect of capacity distribution. Indeed, existing PSVs are characterized by K_C = 5.1…9.5 (the middle value is 6.5), while arctic vessels could have K_C down to 4.0 due to the influence of ice class.

Table 6. Distribution of capacities for PSV Arc8 Dwt 2250

Cargo space	Average	Designed for CF-1
Bulk cargoes (m^3)	220	106
Mud / Brine tanks (m^3)	885	305
Cargo fuel (m^3)	105	655
Ship fuel (m^3)	955	955
Drill water (m^3)	1547	2470
Fresh water (m^3)	600	0
Deck area (m^2)	1000	1000

5. HANDLING UNCERTAINTIES

As known, MTS operation in the Arctic is characterized by a variety of uncertainties caused by different internal and external factors of different scale [26]. They are, for example, the increase of ice severity, the breakdown of vessels, the change of factual cargo flows, etc. It is quite difficult to represent such factors as the stochastic variables in an optimization model due to several reasons. Firstly, there is a trouble in the parametric identification of the stochastic variables responsible for the uncertainties because of the lack of operational data. Secondly, the stochastic optimization model has a computational complexity 200-1000 times higher than deterministic one due to the fact that it needs multiple running the model to obtain stochastically proven results.

On the other hand, the relevant practice of platform supply system management in open water regions has formed in a way to treat uncertainties at the operational level. This practice is based on the long- and short term freight contracts. The base part of the fleet is long-term contracted and this part is chosen on the assumption of average operating conditions. When some unpredictable events occur, the additional ships are chartered under short-term contracts. In case of operation in ice covered waters, the picture is basically the same. The difference is that there are fewer possibilities in short-term contracting due to the lack of appropriate ships, but at the same time there are some additional measures of local increase of system robustness (for example, an icebreaker may serve as a measure to increase ice performance of a system). Thus, when determining the fleet composition the task is to find the main part of the fleet. Treating of uncertainties could be done in stochastic-based models or under a “what if” principle simulation-based models. Such kind of research is out of the scope of the current study and could be done in the future.

6. LIMITATIONS OF THE APPROACH

Limitations of the described cargo-flow-oriented approach could be divided into two parts: principal restrictions and the constraints of the current technical implementation.

The first group of principal restrictions is the limitations of an applied planning algorithm. It is quite difficult to consider several platforms located in various areas by means of such an algorithm. In addition, its pseudo-optimal nature makes it difficult to compare various variants of supply system strictly, because each of the variants has a different level of “optimality”. At the same time, typical logistic algorithms fail to consider multiple types of cargoes together with other restrictions (platform capacity, voyage time deviation, etc.). In these circumstances, we prefer to move in the direction of improvement of pseudo-optimal concept by adding some elements of formal optimization to the algorithm.

The second group of principal restrictions is connected with considering the stochastic factors when modeling supply system, because they may have a significant influence. Using of stochastic simulation would be preferable, while it is connected with troubles described in section 5.

The constraints of the current technical implementation are the following: 1) wind-and-wave conditions are not considered; their impact should be evaluated; 2) long term variations of ice conditions are out of investigation; 3) icebreaker assistance of supply vessels is not considered; 4) it is assumed that arctic supply vessels have the same main dimensions as the open water ships, but it needs an additional design analysis; 5) vessel geometry is limited by prototypes; parametric CAD model would be preferable; 6) fuel consumption identified under an assumption that vessels run at maximum speed; consideration of the actual maritime practice would benefit.

7. CONCLUSION

The proposed approach and investigations conducted in the case study allowed making a number of applied conclusions:

1) The use of AHTSs instead of PSVs with the similar deadweight leads to the growth of expenses more than by 5% for all analyzed cases. This is resulted from the lower transport capabilities of AHTSs compared with PSVs.
2) Regarding the structure of cargo flow, it could be concluded that the lower the part of deck cargoes in total cargo tonnage, the more efficient the transportation is.
3) The influence of vessel cargo capacity distribution on system expenses is significant only on high-load configurations of the supply system. We found an empirical criterion for the preliminary estimation of a need to consider the capacity distribution of supply vessel. Vessels with the ratio “useful cubic capacity / useful deck area” less than 4.5…4.7 were found to be affected by capacity distribution. The lower this value, the greater the effect of capacity distribution on transport efficiency.

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