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MULTI-CRITERION OPTIMIZATION OF SITUATIONAL MANAGEMENT OF MARITIME TRANSPORTATION UNDER CONDITIONS OF UNCERTAINTY

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A methodology for multi-criteria optimization of maritime transport under conditions of uncertainty in the external environment is proposed. It is noted that in the practice of maritime transport management, complex manifestations of uncertainty are observed in the form of various specific situations, obscured by possible interactions and uncertainties of the external environment. It is shown that the most rational way to solve transport problems under conditions of uncertainty is multi-criteria optimization. Based on the consideration of real situations along the Turkey-Germany transport corridor, it is shown that reducing uncertainty in determining the conditions for navigating transport routes can be achieved both through the rational use of the vessel's operational parameters and by taking into account the external conditions of the route. The parameters for optimizing transport for a specific transport route are proposed and studied in detail. A transport matrix is formed, whose optimization parameters include vessel loading, delivery duration, transit speed, load on the main engine, fuel consumption, route deviation, and transportation cost. Practical cases of route passage are considered. The influence of external disturbances on the vessel's controlled operational parameters is established, which has allowed the development of recommendations for decision-making based on the ranking of priorities among the optimization parameters of transport matrix strategies, the convergence of various generalizing functions, and the possibility of predicting the consequences of decision-making on the selected optimal management strategy under specific conditions. The diversity of various manifestations of the external environment's influence on the functioning of transport facilities, global changes in the supply structure, evolving environmental requirements for waste disposal, and other causative factors that are not subject to strict regulation significantly complicate the information support necessary for decision-making under conditions of uncertainty. The adaptation of existing sea transportation technologies to changing operational conditions, driven by fluctuations in the external environment, constitutes the essence and direction of ongoing transformational changes aimed at modernizing the industry.

Key words: *maritime transportation; development trends; management; logistics; intellectualization; transport technologies.*

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Introduction. The problem of situational management of transport under conditions of uncertainty requires taking into account the quantitative and qualitative characteristics of maritime transport, knowledge of the ranges of their changes, orientation and effectiveness on the overall process of transport transition. Most of these characteristics are poorly formalized and poorly structured. In the general formulation, situational management belongs to the class of searching for optimal process characteristics in conditions of multi-criteria evaluations and uncertainty of judgments and expert conclusions.

Denoting the parameter of the process dynamics by *t*, and the set of its values by *T*, we have $t \in T$, where $y = y(t)$. The process of the system transition from a state with the value of the time parameter t_0 to a state *S* with the value $t > t_0$ is

$$S_{t_0 t}(y(t_0)) = y(t), y \in Y, t \in T \,. \tag{1}$$

Denoting by the controlling influence on the course of the transport process from the entire possible set of controls *U*, we have

$$S^{u}_{t_0 t}(y(t,u)) = y(t,u), y \in Y, t \in T, u \in U \,. \tag{2}$$

To describe the variability of the process with an indication of the goal, it is necessary to introduce decision-making criteria. Then each individual management alternative can be evaluated by a certain number or value of the corresponding criterion and the comparison of alternatives will be reduced to comparing their corresponding numbers.

Optimization of management of the development of maritime transport in conditions of multi-criteria and uncertainty of input information is one of the unsolved problems of information theory, solid mechanics, and physical acoustics.

Statement of the problem. The functioning of maritime transport logistics and transportation is carried out under complex conditions in the external environment, involving multi-criteria and uncertainty of input information. The nature of such uncertainty lies in the fact that the parameters of uncertainty are not uniquely defined, their manifestations appear in specific situations, and it is necessary to make management decisions under conditions of risk. Modern transport systems face the need to simultaneously consider a set of factors when making management decisions while also satisfying various multi-criteria criteria. This is especially important in transport logistics, where it is necessary to balance the cost of transportation, delivery time and operational parameters.

Transport strategies are formed by taking into account the specifics of the cargo, transportation conditions, risks, and available resources. Within the framework of the multi-criteria approach, strategic transport parameters should be flexible and adaptable to different situations.

The solution to the scalar optimization problem is considered to be an element of a transport transition strategy that maximizes or minimizes the objective function. The integration of multi-criteria optimization methods into situational management allows for a significant increase in the efficiency of planning and implementation of transport operations. Real-time decisions can be based on algorithms that take into account the weighting coefficients of various criteria.

The most important advantages of multi-criteria optimization in the system management of maritime transport logistics are:

– stability of system characteristics, performance indicators and evaluation metrics;

– continuity of information flow;

– processing and aggregation of calculation results;

– integration of the multi-criteria optimization function of transportation into the system for monitoring the progress of cargo along the route.

Situational management determines the possibilities of adapting transport strategies to changing external and internal conditions. This approach is based on an operational assessment of the current situation and the selection of management influences that correspond to specific conditions. The use of situational management in transport logistics allows for flexibility in the event of failures, changes in demand or disruption of routes.

The main purpose of management decisions is to promptly detect deviations of controlled parameters from the values established by the regulations, identify and localize the vehicle’s position on the route, and, if necessary, adjust the modes and technologies of operation.

An important issue for increasing the effectiveness of management decisions in conditions of uncertainty is the development of means, methods and techniques for obtaining and processing information about the state of vehicles during their operation, the search and implementation of organizational and technological tools and transportation parameters at any time and at any point in the transport process.

The purpose of the work is to search for alternatives to the management of sea transportation in the conditions of uncertainty with the use of multi-criteria optimization.

The tasks of the work are:

– construction of a transport matrix based on expert information;

– establishment of the necessary optimization parameters that determine the specific situation of the cargo on the route;

– determination of optimization criteria, necessary convolutions and limits of variation of the matrix parameters;

– performance of calculations and adoption of recommendations for the implementation of sea transportation according to the compiled situation.

Analysis of recent research and publications.

Situational traffic management has been developed in a number of fundamental works on situational awareness [1].

Considers the role of awareness in situational management of synchromodal transportation between different modes of transport in real time in dynamic and compressed situations [2]. Presents a situational awareness system of the road situation based on neural networks and cloud computing, integrated into peripheral roadside surveillance devices for automatic recognition of vehicles, their speed and license plates. Similar problems of intelligent vehicle tracking based on deep learning of traffic in different scenarios are considered in [3]. The Fractals Coati algorithm with bidirectional long-term memory is used.

A system for controlling, detecting, navigating, and locating aims for air transport objects using electronically scanned array radars to increase situational awareness with the integration of artificial intelligence and machine learning for routing and resource optimization is presented in [4]. In [5], the Frank-Wulf approach and neural networks are used to assess road conditions, detect potholes, and track road accidents. In [6], solutions to situational control problems are presented to ensure real-time situational awareness and optimize logistics systems with a combination of simulations and software components of digital twins of multimodal freight transportation. In the generalizing work on situational awareness and its use in maritime transport [7], great importance is attached to the analysis of the risk of collision of vessels, their spatial compactness, and scenarios of possible manifestations with tuning for maritime traffic segmentation.

Modern vehicle monitoring and control systems with route optimization, based on the transmission of information messages using discrete situational network devices for route information correction, are used in vehicle traffic management [8].

A separate cycle of work on situational management is represented by combinatorial optimization of operational management in simulation models of marine transport systems with alternative solutions for local resource selection [9], digital transformations [10], computer optimization of routes [11], intelligent situational awareness with temporal and spatial orientation [12].

In the development of situational transport management, it is worth noting the work [13], which presents a decision support system for situational awareness and discrete support using multi-objective evolutionary optimization. Increasing the situational awareness of ship operators, captains and senior engineers when interacting with shore organizations through the development of interfaces and transformations of control influences is described in [14].

In [15], monitoring of the evolution of the state of sliding bearings of turbochargers of ship power plants is presented, in which the features of the trajectory of the main diagnostic feature when the material approaches the state of degradation are selected as the optimization parameter. The modernization of this methodology for determining the residual resource of ship bearings during their operation is presented in [16, 17]. In [18], the main types of architecture for building support and decision-making systems based on the creation of prototypes are considered. In [19], models for optimizing expert evaluation and methods of subjective assessments are considered: based on ranking, pairwise comparison of direct assessments and sequential comparison. Methods for multi-criteria decision-making tasks under conditions of linguistic uncertainty and fuzziness are considered. Based on the analysis of recent achievements in the field of maritime transport logistics, trends and critical development problems such as information processing algorithms, adaptive strategies, and decision-making methods under conditions of uncertainty and risk are identified. In [20] typical solutions of the situation problem, group ordering of alternatives, decision-making methods in the presence of many criteria are considered. However, the proposed information does not have methodological unity and is some aspects that are used for different purposes. The complexity of choosing optimization criteria and the objective function lies in the fact that in practice, optimization and management tasks have to deal with a set of criteria that are most often mutually contradictory. Since the studied management objects are constantly influenced by the external environment, which changes stochastically, the most acceptable method for implementing transport management tasks under conditions of uncertainty is multi-criteria optimization.

Decision-making on the choice of an alternative variant of a similar situation from a set of possible arsenals of a similar situation is carried out in conditions of multi-criteria input information, which takes into account both operational factors and navigational conditions of the route, including uncertain, unpredictable conditions of the external environment. Such input information is an additive set of multi-scale components localized in specific conditions of their possible manifestation. The main task of identifying and determining the necessary strategy for maritime transport in the existing and predicted conditions of their implementation is to analyze possible situations, adapt them to the conditions of the route and make adequate management decisions.

In known similar models, such a statement becomes possible when there is a database and a corresponding expert system. Uses complex signal processing and filtering algorithms. For multi-criteria optimization of situational management of maritime transport in conditions of uncertainty, it is necessary to develop new approaches to assessing operational parameters and parameters of the external environment with the development of appropriate mathematical models, which are based on the construction of physical and predictive models.

Presentation of the main material. The main operational parameters of the transport vessel and the conditions of the route transition were considered as research materials. Multi-criteria optimization methods were used as research methods.

The input information of the situational management optimization task under conditions of uncertainty caused by the influence of the external environment is the determination of optimization parameters. which include vessel loading, delivery duration, transition speed, main engine load, fuel consumption per day, transportation cost. Below are the optimal values of these parameters, which are tried to be observed throughout the voyage.

Vessel loading. A practical example of vessel loading is considered in the activities of the merchant vessel FULDATAL (IMO 996 2988) with a deadweight of 3804 t, which makes the transition from Turkey to Germany for three weeks. After deducting the weight of fuel and oil, the maximum volume of cargo carried is 3650 t. Recommended loads are 50–70% of the maximum value and determine the parameter of transportation restrictions in tons. Another limitation is the performance of transportation in miles. The maximum time the vessel can be in the open ocean is 40 days.

Duration of delivery. It is determined through the interaction of transport agents. This interaction involves the activities of the charterer, who acts as the customer for transportation, and the captain. The charterer's desire is explained by economic considerations to deliver the cargo as quickly as possible. The captain's actions take into account the real situation of the route, the capabilities of the vessel and the crew. After consensus is reached, the date of passage of the cargo and its passage to the destination is set, which determines the duration of delivery.

Transition speed. The estimated values of the transition speed in the normal operation of the vessel are 10 knots.

Main engine load optimal load on the main engine is considered to be a load that provides a vessel speed of up to 10 knots. This value is 75% of the maximum.

Fuel consumption. Fuel consumption is calculated from its use per day. At a load on the main engine of 75%, which provides a speed of 10 knots, this consumption is 3.5 tons per day.

Deviation from the route. This value is determined by the specific features of the cargo being transported. The cases considered concern the transportation of general cargo: bulk, bulk, container. However, there are frequent cases of sea transportation of specific cargoes that are easily ignited, that enter into chemical reactions with the metal of ship equipment, fuel and oils. This requires strict routing, taking into account the approach to ports that have such protective safety measures in accepting cargo. In the event of sudden changes in weather conditions with a full load of the vessel and the influence of other factors that are difficult to take into account, a maximum deviation from the route of up to 500 miles is possible.

Transportation costs. When crossing in 21 days, the costs for fuel and lubricants are 3 thousand US dollars per day and 63 thousand US dollars for the crossing. Operating costs for the shipowner during transit are 7 thousand USD per day. The ship's crew receives an average of 165,095 USD per voyage. Thus, the cost of the transition during the analyzed period is 235,095 USD and may fluctuate depending on the specific conditions of the route and its activities.

The matrix of situational management of transport operations and information support of transportation technologies is presented in Table 1. Numerical values of the matrix, optimization parameters, situational characteristics are represented by real situations, operational and organizational parameters collected by one of the authors of the article during similar transport transitions of the ship and the experience of implementing situational transport transitions in difficult conditions. These results were discussed and published in [21].

Table 1 – Transport matrix of the vessel FULDATAL (IMO 996 2988)

The current situation	***Optimization parameters***						
	vessel loading, tons	***delivery time, day***	***transition speed, knots***	***load on the main engine, %***	***fuel consumption, t/day***	***deviation from route, miles***	***transportation cost, thousand USD***
S_0	2920	20	13	95	5,8	200	228
S_1	3420	19	10	80	3,6	300	222
S_2	3150	19	11	60	4,2	400	230
S_3	2555	19	11	70	3,5	150	230
S_4	2555	19	11	85	4,1	350	235
S_5	2400	20	10	70	3,6	400	230
S_6	2220	20	10	70	4,1	350	240
S_7	2372	20	10	65	5,0	500	240
S_8	2485	19	11	60	4,1	200	220
S_9	2015	20	11	55	3,6	200	220
S_{10}	1825	19	12	50	3,5	300	238
S_{11}	1930	19	11	60	4,1	100	220
S_{12}	2900	20	12	80	5,6	150	222
S_{13}	3650	19	10	75	3,5	200	220
S_{14}	2935	19	12	80	5,6	100	218
S_{15}	2190	20	13	80	5,7	400	232
S_{16}	2140	21	12	80	5,6	350	235
S_{17}	2120	20	12	85	5,4	350	232
S_{18}	3650	19	10	70	3,4	250	220
S_{19}	3245	21	10	50	4,1	500	238
S_{20}	3300	20	11	60	4,3	450	226

The difficulty in determining the values of transport optimization parameters lies in their situational interaction when developing strategies for responding to disturbing influences.

Situation S_0 is characterized by the intensity of the influence of navigation conditions on the route and the sharp unpredictability of the direction of hurricanes. This forces us to resort to extreme measures of increasing the load on the main engine to 95%, which requires fuel consumption of up to 5.8 tons/day and a speed of 13 knots. Vessel loading 2920 tons. In this case, the increase in the duration of cargo delivery increases to 20 days.

Situation S_1 is characterized by some reduction in the vessel's load and a route duration of 19 days, but additional uncertain transportation characteristics appear, associated with the deviation of the route for incidental cargo, which is reflected in the cost of transportation of 222 thousand US dollars and in forcing the main engine to operate up to 80% at 60% with a load on the main engine of up to 80%.

Situation S_2 is characterized by the approach of the load to the maximum permissible level and is 86 /3% of it, i.e. 3150 t. Since no serious navigational obstacles are expected during this time, this requires normal functioning of the operational parameters of the main engine load of 60%, fuel consumption of 4.2 t/day. However, since there is a reserve in loading to the maximum value, a course deviation of 400 miles for incidental cargo is possible. To maintain the planned arrival time, the route speed will have to be increased to 11 knots. Deviation from the route causes an additional increase in the cost of transportation up to 230 thousand USD.

Situation S_3 is characterized by the fact that the cargo is transported below the permissible mark. Transportation conditions are normal. Taking into account favorable weather conditions, it is possible to increase the speed to 11 knots, reducing fuel consumption to 3.5 tons/day and arrive at the port of destination on time.

Situation S_4 is characterized by a decrease in the tonnage of the cargo being transported, which has a favorable effect on the operational parameters of the vessel, but at the same time, strong headwinds are observed on some sections of the route and storms and hurricanes are expected. This forces an increase in the speed of passage of sections with normal functioning of the vessel parameters to 11 knots in order to compensate for difficult sections of the transitions and reach the planned estimated arrival time of 19 days.

Situation S_5 is characterized by an incomplete loading of 2400 tons, which requires an additional call to other ports for passing cargo, an increase in the deviation from the route to 400 miles and an increase in the delivery time to 20 days.

Situation S_6 is characterized by normal parameters of the cargo passage to the destination, however, in the section of passage through the locks, forced delays are possible due to their low throughput, possible collisions and damage to equipment. Removing this section from the route requires an increase in such an indicator as a deviation from the route to 350 miles. At the same time, fuel consumption increases, the duration of delivery increases to 20 days, and the total cost of transportation increases to 240 thousand US dollars.

Situation S_7 is characterized by the fact that it differs little from the situation S6. The difference is a slight increase in cargo volumes, an increase in deviations from the route for passing cargo up to 500 miles and a decrease in the load on the main engine up to 65%.

Situation S_8 is characterized by the possibility of increasing the total volume of cargo transported to 2485 tons, which is achieved by increasing the load on the main engine to 60% and increasing the speed of passage to 11 knots, despite some deviations from the route for passing cargo of 200 miles. The cost of transportation is 220 thousand USD.

Situation S_9 is characterized by a stable load on the main engine of 55% of the maximum, low fuel consumption of 3.6 tons/day and a slight increase in the speed of delivery to 11 knots, which, when deviating from the route by 200 miles, is achieved by increasing the intensity of the equipment used and maximizing operational factors.

Situation S_{10} is characterized by a change in the direction of the vessel's movement to eliminate ballast crossings and an increase in the deviation from the route while maintaining the planned cargo delivery times. A tailwind on the crossing with a low load on the main engine of 50% of the maximum value in total ensures fuel consumption at minimum values, i.e. 3.5 t/day.

Situation S_{11} is characterized by an incomplete load of up to 1930 t and relatively calm operating modes of the equipment: a load on the main engine of 50%, fuel consumption of 4.1 t/day and the possibility of deviation from the course for passing cargo by 100 miles. However, to meet the planned cargo delivery times of up to 19 days, an increase in speed to 11 knots is required.

Situation S_{12} is characterized by a sudden change in the navigation situation; in addition to known head currents, storms and hurricanes are expected to complicate the crossing. This requires the formation of a load on the main engine up to 80%, which will require fuel consumption of 5.6 tons/day to ensure a possible deviation from the route of 150 miles. In such difficult conditions, the route of the load should be reduced to 2900 tons. The terms and duration of delivery will increase to 20 days.

Situation S_{13} is characterized by the parameters of the vessel loading of 3650 t, delivery duration of 19 days, passage speed of 10 knots, main engine load of 75%, fuel consumption of 3.5 t per day.

Situation S_{14} is characterized by the need to maintain a high passage speed of up to 12 knots to ensure the possibility of a deviation of 100 miles for passing cargo. This requires 80% load on the main engine and fuel consumption of 5.6 t/day to ensure the planned delivery times of cargo. Due to the short duration of the route of up to 19 days, the cost of transportation will also be minimal and is 218 thousand USD.

Situation S_{15} is characterized by a decrease in cargo volumes to 2190 t and an urgent need to reduce ballast passages. To implement these intentions, a deviation from the planned route of up to 400 miles is expected for additional cargo, which is provided by a fuel consumption of 5.7 tons/day at a load on the main engine of 80%. To maintain the cargo delivery time of up to 20 days, it is necessary to carry out cargo transportation at a speed of 13 knots in order to arrive at the destination port on time.

Situation S_{16} is characterized by the longest duration of the transition of 21 days. Due to the small load of 2140 tons, this situation requires measures to other ports located on deviations from the route of up to 400 miles. To do this, it is necessary to increase the load on the main engine to 80%, increase fuel consumption to 5.6 tons/day and increase speed to 12 knots in order to maintain the planned arrival time.

Situation S_{17} is characterized by countercurrents and natural disasters of long duration. The multidirectionality of the accompanying and counterflows forces the load on the main engine to increase to 85% with a fuel consumption of 5.4 t/day. Calling at other ports to replenish cargo in such a difficult situation is not required, however, due to possible deviations from the route trajectory, its deviation up to 350 miles is allowed. The average speed is 12 knots; the cost of transportation is 232 thousand USD.

Situation S_{18} is characterized by a small tailwind. In this case, the load on the main engine can be reduced to 70%, reducing fuel consumption to 3.4 t/day.

Situation S_{19} is characterized by the need to follow the route with a load of 3245 t with a call at the most distant port for replenishment, which is located 500 miles from the main route. Weather conditions are normal, so economical modes of main engine load of 50%, fuel consumption of 4.1 t/day are used. This allows to achieve a speed of transition of up to 10 knots. The duration of the transition under such conditions is 21 days, and the cost of transportation is 238 thousand USD.

The S_{20} situation is characterized by almost the same route situation. Loading 3300 t requires a call at a port 450 miles away from the main route. Favorable weather conditions and a slight tailwind allow the transition to be carried out at a speed of 11 knots, which requires a load on the main engine of 60% with fuel consumption of 4.3 t/day. These modes of route passage allow to reach the final points of the route in 20 days. The cost of transportation will be 226 thousand USD.

The obtained data can be used to build multi-criteria optimization models that will help find the best compromise between conflicting goals, for example, between cost and quality of service. The considered situations of maritime transport can be characterized by stable states of operation of transport objects, variable states caused by changes, adjustments, changes in operational parameters and new transformation states as a reaction to external disturbances.

Research methodology. Knowing the possible situations and the full set of possible decision outcomes, it is possible to construct a matrix whose elements can be interpreted as a numerical assessment of the advantage of the *i*-th alternative, provided that the situation has arisen j.

$$R = \begin{pmatrix} & \Pi_1 & \Pi_2 & \cdots & \Pi_n \\ \hline q_1 & \delta y_{11} & \delta y_{12} & \cdots & \delta y_{1n} \\ q_2 & \delta y_{21} & \delta y_{22} & \cdots & \delta y_{2n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ q_m & \delta y_{m1} & \delta y_{m2} & \cdots & \delta y_{mn} \end{pmatrix}, \quad (3)$$

where $q_1 \ldots q_i$ – components of transition characteristics (current situation S_i in table 1);

$\Pi_1 \ldots \Pi_j$ – optimization parameters in table 1;

i – line number;

j – column number;

δy_{ij} – relative deviation j – th parameter has the optimal value.

The matrix is the basis for a reasoned choice of a transportation strategy. In maritime transport logistics, it is a tool that allows you to systematically evaluate different logistics solutions and identify the most optimal options for many criteria and situations. It shows how different transport strategies or routes correlate with key criteria: delivery time, cost, reliability, transport load level, etc. This allows you to compare alternatives and choose the most balanced solution. If an alternative shows low results for one or more criteria, the matrix will help to identify this. It indicates areas that need improvement, for example, delays on a specific section of the route or a high level of transport operating costs.

To achieve the same goal, depending on the choice of strategy and a specific criterion, different optimal solutions can be obtained. To eliminate uncertainty, it is necessary to take into account the impact of all situations. Each type of strategy can be matched with a set of criteria for choosing the optimal solution.

Decision-making is the process of selecting the most preferential solution from a set of permissible solutions or their ordering. It is carried out on the basis of knowledge about the management object and can occur over time in the presence of a set of indicators characterizing the effectiveness of the decision made.

Formalization and meaningful filling of solutions consists in choosing the most successful alternative from a set of existing ones. The task is described by a pair (Ω, C), where Ω – multiple alternatives, C – the principle of optimality.

To determine the elements of the matrix, the evaluation of a scalar vector is used. This requires a transition from the evaluation of a vector to a scalar of objects. The functions used in solving a multi-criteria problem are the convolution function of vector arguments $y_i = (y_{i1},\ldots,y_{ij},\ldots, y_{in})$ in scalars $\delta y_{ij} = f(y_i)$.

The convolution of the vector argument serves to reduce the number of criteria. Its purpose is to replace the original criteria with general criteria. The convolution operation is called aggregation of partial criteria. It is used if the partial criteria can be ranked in order of decreasing importance so that the importance of each pair of neighboring criteria does not differ significantly. Their normalization is used to compensate for small values of some criteria with large values of other criteria.

To define elements δy_{ij} matrices, one of the methods of scalarization of vector estimates is used – the method of selection by ordering objects according to the standard.

By standard we mean a class of objects characterized by a generalized goal $h = (c_1,\ldots, c_j,\ldots, c_n)$. Let us introduce a measure of generalized deviation from the aim, which allows us not only to find the object closest to the standard, but also to order the objects by distance from the target. Let us consider a standard whose properties are formed by equality constraints ($y_j = c_j$). Deviation of the j-th feature in any direction from the point c_j ($c_j \pm \delta y_{ij}$) determines the degree of remoteness of the object from the aim by this feature. Then the relative deviation of the j-th feature from the aim is determined as

$$\delta y_{ij} = \frac{\left| y_{ij} - c_j \right|}{c_j}, \tag{4}$$

where i – line number; j – column number in matrix.

As parameters c_j it is necessary to choose the best (optimal $c_{j\,opt}$) from the point of view of the problem being solved, the values of the analyzed parameters can be maximum, minimum or intermediate values from the experimental sample. With this approach, the formula δy_{ij} will convert dimensional values into relative ones. However, with such a choice of parameters c_j will necessarily be observed coinciding with the magnitude c_j the corresponding elements of the matrix, which will lead to $\delta y_{ij} = 0$. When using additive convolution, this leads to the corresponding feature falling out of the overall assessment of the object, and when using multiplicative convolution, to its zeroing. An obvious way to eliminate such situations is to expand the limit of each feature c_j in the same percentage ratio. Below are the optimal values of each of the analyzed parameters $c_{j\,opt}$ were increased by 1%.

$$c_j = c_{j\,opt} + 0.01 c_{j\,opt}. \tag{5}$$

In this case, the principle of optimality in the problem of maritime transport logistics is implemented according to priorities. Optimization is carried out according to the rule.

$$Opt\ y_i = extr \sum_{i=1}^{n} \alpha_i y_i\ , \tag{6}$$

where α_i – optimization parameter.

Under the result of decision a_{ij} we will understand its numerical assessment, corresponding to the situation S_i and option x_i.

$$Y = \max_i \min_j a_{ij} + \max_i \min_j f(x_i, S_i)\ . \tag{7}$$

The efficiency of decision-making E can be formalized using the formula of the multiplicative combination of the decision-making factor Q and the decision-making factor A [9].

$$E = Q \cdot A\,. \tag{8}$$

If one of these factors decreases, the effectiveness of the solution decreases.

The technology model for the selection of logistics solutions with diversity and ambiguity of the principles of multi-criteria optimization of situational management of maritime transport transportation under conditions of uncertainty of the influence of the external environment is presented in Fig. 1.

This is a new scientific result in the research work: the model of situational logistics management of maritime transport under conditions of uncertainty has been further developed, consisting of their aggregation of criteria and coincidences of generalizing objective functions, which differs from existing ones by additional operations of establishing and ranking priorities of multi-criteria optimization strategies with the combination of objective assessments with subjective preferences of consumers. This increases the reliability and efficiency of transport.

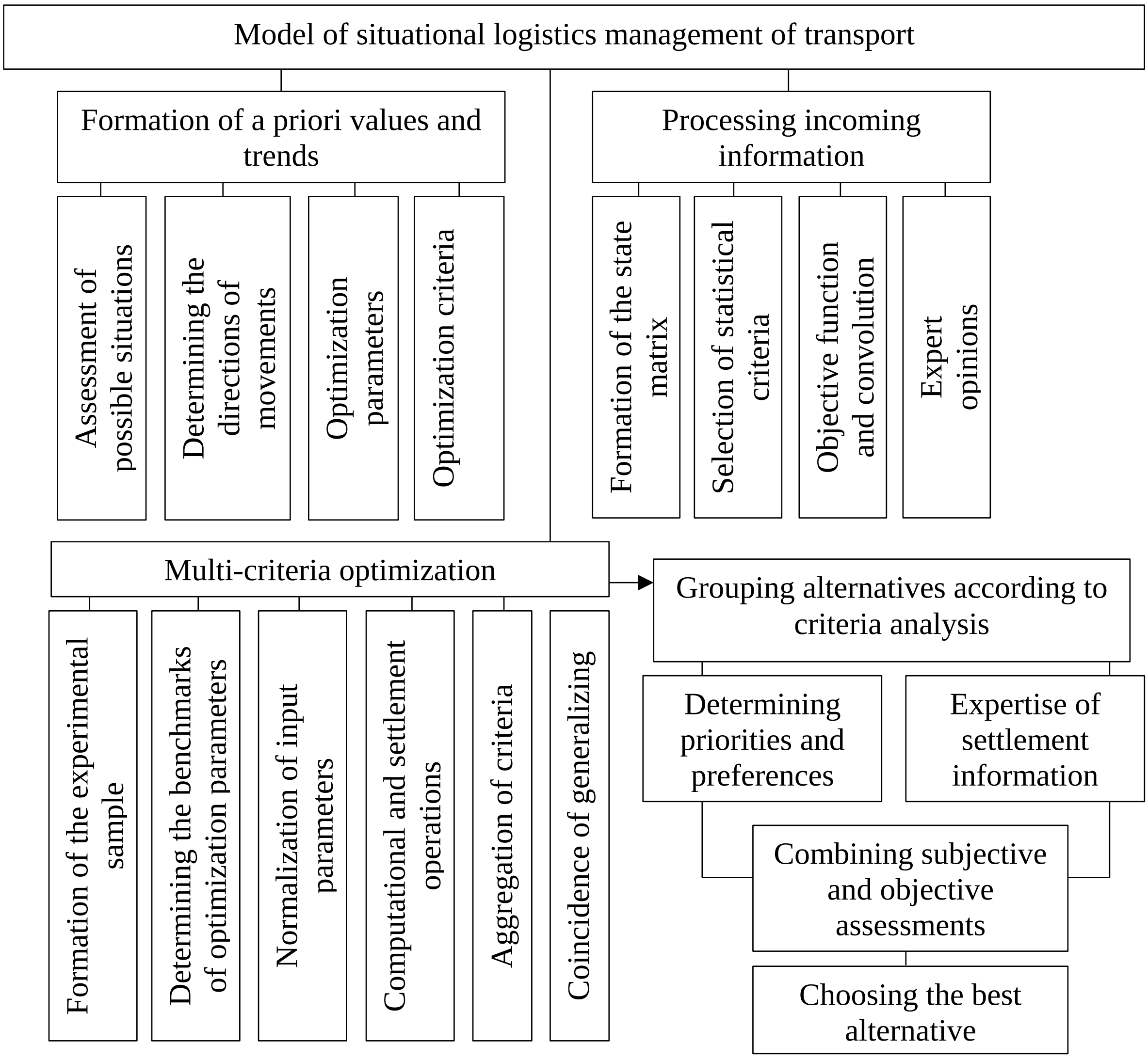

Figure 1 – Model of situational logistics management of transport

The following generalizing multi-criteria utility functions were used in the theoretical analysis.

Additive package

$$y_a = \sum_{j=1}^{n} \omega_j \delta y_{ij} \,, \tag{9}$$

where ω_j – importance (weight coefficient) of the j-th attribute,

$$\sum_{j=1}^{n} \omega_j = 1 \,. \tag{10}$$

Step multiplicative convolution

$$y_{ms} = \prod_{j=1}^{n} \left(\delta y_{ij}\right)^{\omega_j} \,. \tag{11}$$

Additional multiplicative convolution

$$y_{md} = 1 - \prod_{j=1}^{n} \left(1 - \omega_j \delta y_{ij}\right). \tag{12}$$

The best object is considered to be the one with the minimum values of the additive convolution, exponential multiplicative convolution, and additive multiplicative convolution functions.

Wald criterion (minimum maximum)

$$Z_v = \min_i \max_j \delta y_{ij}. \quad (13)$$

Laplace criterion (minimum minimum)

$$Z_L = \min_i \min_j \delta y_{ij}. \quad (14)$$

By comparing the weight and significance of the criteria, it is possible to determine from the conditions which parameters will be the most critical for the transition (for example, reducing delivery time may be more important than increasing costs during intensive operation of transport equipment).

One of the problems in decision-making in the presence of several criteria that are not always consistent with each other is their formalization using multi-criteria optimization models. In their practical implementation, they use the principle of reducing a multi-criteria problem to a single-criteria function through scalar optimization.

Scalar optimization requires additional knowledge about the properties of generalized objective functions, the scale of characteristics and weight coefficients. Since this knowledge depends on the subject area, the order of objects in n-dimensional space can be explicitly determined. Therefore, it is relevant to study the influence of the properties of generalized objective functions, characteristic scales and weight coefficients on the optimization results.

The additive generalizing function (9) synthesizes the "volumetric" indicator of the object. It reflects the total value of individual indicators, considering their importance. The direct multiplicative function (11) prefers objects with uniform estimates for all indicators, reflecting the uniformity of individual indicators. The additional multiplicative function (12) has the inverse property. The advantage of the additional over the multiplicative functions is the admissibility of zero values of the features. For direct multiplicative functions, special measures should be taken to avoid scalar estimates of vectors that have a component with a zero value.

The Wald criterion (13) is a reinsurance criterion which consists of obtaining the maximum guaranteed result under the worst conditions. Assuming the maximum negative development of the situation, the strategy chosen is not so much winning as losing. The minimum value of the worst option is taken into account (the strategy of fatalism). It can be used in cases where errors in choosing a strategy can lead to catastrophic consequences when decisions are made only once and cannot be changed in the future.

Laplace's criterion (14) determines the strategy that gives the maximum gain with an unknown state of the environment. The alternative with the lowest score according to the Laplace criterion is considered the best. This is a criterion of extreme optimism. In this case, no possible result except the best is taken into account. The degree of risk from the negative impact of changes in the external environment is not taken into account. It should be noted that situations requiring the use of such a criterion are not limited only to incorrigible optimists but also to people put in a hopeless situation when they are forced to follow the principle of "win or lose". The main disadvantage of this criterion is that when finding the average gain, the effect of compensation of small gains by large ones may occur.

The main stages of the multi-criteria approach to choosing the optimal strategy for implementing maritime transport under conditions of uncertainty are working with numerical representations of experimental information, mathematical calculations, storing and exchanging information, and interpreting results.

Main results and discussion. To ensure transparency, orderliness and compliance with the requirements for the use of multi-criteria optimization of maritime transport, a system of regulatory management procedures has been developed. Regulatory management systems are based on laws, rules, internal regulations used to organize and manage various aspects of the activities of maritime transport logistics entities.

Prospects for further research are as follows. The information obtained can be used as the basis for a computer-aided automated system designed to assist and support decision-making in solving poorly structured problems through an intelligent interactive management model (Fig. 2).

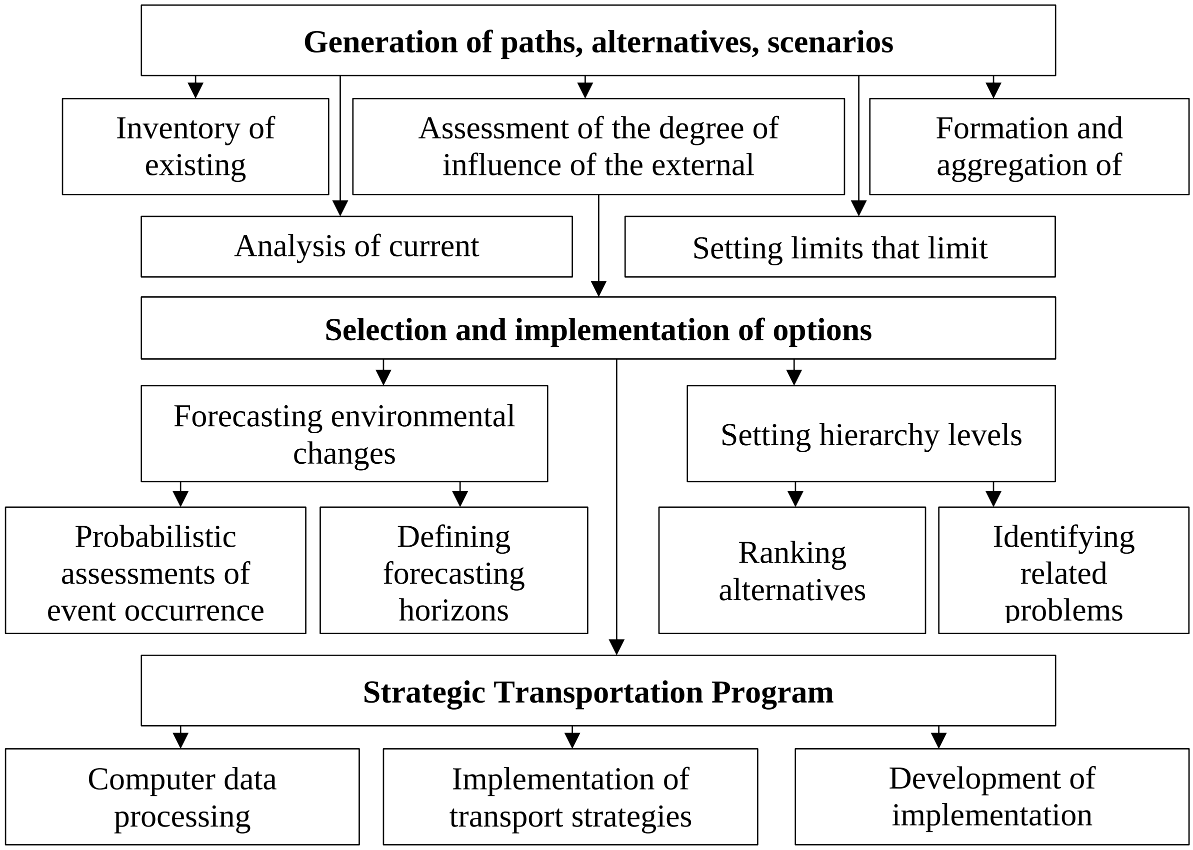

Figure 2 – Intelligent interactive model of transport management

Information management systems help reduce uncertainty in the volume of cargo flows, which allows attracting additional volumes of cargo. Digitalization allows you to control not only the cargo flow, but also to identify the time and zones of arrival, as well as the places of loading and unloading. Situational management provides flexibility and adaptability in managing transport processes. It allows you to quickly respond to changes in the environment. Modern transport systems are faced with the need to take into account a variety of factors, such as economic efficiency, equipment stability, reliability and timeliness of delivery, and others.

Multi-criteria optimization involves the simultaneous consideration of several, often conflicting, criteria after making decisions. In transport logistics, this may include minimizing costs, reducing delivery time, reducing emissions, and increasing the reliability of transport. The use of such methods allows finding compromise solutions that satisfy various stakeholders. This approach allows for the formation of adaptive strategies that simultaneously take into account a variety of factors and provide a balance between economic efficiency and service quality. Thus, the integration of multi-criteria optimization and situational management into the practice of planning and implementing transport allows for more effective achievement of goals, adaptation to changes in situations, and greater resilience of logistics networks to external influences and internal failures.

To perform calculations using the proposed method, knowledge of the weight coefficients of optimization parameters, their recommended values, directions and trends of possible changes is required. This information is presented in Table 2. The optimal values of the parameters are represented by the results of the generalization of the long-term experience of one of the authors, who is carrying out a transition along a given route. Weight coefficients were determined by expert evaluation.

Table 2 – Optimal values of parameters of the transportation process

No. s/n	***ship loading, t***	***ship loading, t***	***transition speed, knots***	***load on the main engine, %***	***fuel consumption, t/day***	***deviation from route, miles***	***transportation cost, thousand USD***
optimal value $c_{j\ opt}$	3650 (max)	19 (min)	10 (min)	75	3.4 (min)	100 (min)	218 (min)
weight factor ω_j	0.20	0.15	0.20	0.10	0.10	0.10	0.15

Calculated by the formula δy_{ij} (4). The matrix of dimensionless values of parameters, as well as the values of convolutions and criteria are presented in Table 3 (highlighted in gray). The calculations were performed using the Maple 2018 computer mathematics system. The calculations were performed assuming that all parameters have different importance.

Table 3 – Matrix of dimensionless (relative) values of process parameters, as well as the values of convolutions and criteria

No. s/n	***loading of a ship***	***delivery time***	***transition speed***	***load on the main engine***	***fuel consump-tion***	***deviation from the route***	***transporta tion cost***	***min***	***max***	y_a	y_{ms}	y_{md}
0	0.2079	0.0422	0.2871	0.9966	0.7993	0.9802	0.0355	0.0355	0.9966	0.3883	0.2093	0.3328
1	0.0722	0.0099	0.0099	0.0561	0.0483	1.9703	0.0082	0.0082	1.9703	0.2266	0.0339	0.2205
2	0.1455	0.0099	0.0891	0.9972	0.9350	2.9604	0.0446	0.0099	2.9604	0.5443	0.1456	0.4566
3	0.3069	0.0099	0.0891	0.0759	0.0192	0.4851	0.0446	0.0099	0.4851	**0.1454**	0.0739	**0.1382**
4	0.3069	0.0099	0.0891	0.1221	0.1939	2.4653	0.0673	0.0099	2.4653	0.3689	0.1223	0.3349
5	0.3489	0.0422	0.0099	0.0759	0.0483	2.9604	0.0446	0.0099	2.9604	0.3932	0.0798	0.3629
6	0.3978	0.0422	0.0099	0.0759	0.1939	2.4653	0.0900	0.0099	2.4653	0.3748	0.1028	0.3397
7	0.3565	0.0422	0.0099	0.1419	0.4560	3.9505	0.0900	0.0099	3.9505	0.5479	0.1222	0.4828
8	0.3259	0.0099	0.0891	0.2079	0.1939	0.9802	0.0008	**0.0008**	0.9802	0.2228	0.0614	0.2060
9	0.4534	0.0422	0.0891	0.2739	0.0483	0.9802	0.0008	**0.0008**	0.9802	0.2452	0.0729	0.2253
10	0.5049	0.0099	0.1881	0.3399	0.0192	1.9703	0.0809	0.0099	1.9703	0.3851	0.1387	0.3392
11	0.4764	0.0099	0.0891	0.2079	0.1939	0.0099	0.0008	**0.0008**	**0.4764**	0.1559	0.0418	0.1489
12	0.2133	0.0422	0.1881	0.0561	0.6307	0.4851	0.0082	0.0082	0.6307	0.2050	0.1060	0.1894
13	0.0099	0.0099	0.0099	0.2541	0.6889	0.9802	0.0008	**0.0008**	0.9802	0.1979	0.0228	0.1860
14	0.2038	0.0099	0.1881	0.0561	0.6307	0.0099	0.0099	0.0099	0.6307	0.1510	0.0588	0.1433
15	0.4059	0.0422	0.2871	0.0561	0.6598	2.9604	0.0536	0.0422	2.9604	0.5206	0.2092	0.4418
16	0.4195	0.0943	0.1881	0.0561	0.6307	2.4653	0.0673	0.0561	2.4653	0.4609	0.2207	0.3960
17	0.4249	0.0422	0.1881	0.1221	0.5725	2.4653	0.0536	0.0422	2.4653	0.4529	0.2029	0.3909
18	0.0099	0.0099	0.0099	0.2079	0.2230	1.4752	0.0008	**0.0008**	1.4752	0.1961	**0.0207**	0.1884
19	0.1197	0.0943	0.0099	0.3399	0.1939	3.9505	0.0809	0.0099	3.9505	0.5006	0.1093	0.4563
20	0.1048	0.0422	0.0891	0.2079	0.2521	3.4554	0.0264	0.0264	3.4554	0.4406	0.1194	0.4054
	Laplace criterion		Wald criterion									
	0.4764		**0.0008**									

In table. 3, the values of the used criteria corresponding to the optimal rows of table 1 are highlighted in bold and in color.

For the final derivation of the relatively optimal row of process parameters in table 1, it is necessary to take into account the coincidences of various generalizing functions, the degree of adequacy of each generalizing function of the problem being solved. S_8, S_9, S_{11}, S_{13}, S_{18}. Wald's criterion clearly indicates S_{11}. (Laplace criterion and additional multiplicative convolution).

Key parameters of management strategies include the level of priority of goals. Limit values of performance indicators, permissible limits of deviations from the established transition plan.

This structuring of solutions allows us to highlight the main optimization parameters in the recommended strategies. This is a common priority in the strategies. S_3, S_{11} and S_{18} have a delivery time of 19 days and fuel consumption within the permissible norm of 3.5 t/day, 4.1 t/day, 3.4 t/day. Other parameters of these strategies are considered of little importance to users and are considered as additional. Among them, the greatest interest is the vessel loading, which for strategy S_{18} is the maximum among all three considered strategies and is 3245 t. Based on these considerations, this strategy should be preferred.

The next group of ranking priority strategies, according to the calculations, is represented by strategies S_8 and S_9, in which the general priority position is the lowest transition cost, which is 220 thousand USD. Other parameters of these strategies are considered insignificant for users.

Ranking by priorities for users and organizers of crossings is a practical implementation of the proposed multi-criteria optimization method for situational management of maritime transport in conditions of uncertainty of the external environment.

Conclusions.

1. Multi-criteria optimization of situational management of sea transport is proposed, which consists of an analysis of complex manifestations of specific situations, hidden by possible interactions and uncertainties of the external environment, which differs from existing ones in the formation of a transport matrix, optimization parameters, as which the duration of delivery, load on the main engine, fuel consumption, deviation from the route, and the cost of transportation are selected. These parameters directly depend on the situation, the transition from a vector to a scalar representation and the ranking of criterion estimates of objective functions. This allows for intelligent support for decision-making regarding the choice of transportation strategies.

2. An intelligent interactive model of decision-making regarding the choice of transport management alternatives in conditions of uncertainty of input information, which includes internal regulations, standards and rules for transportation, is proposed, which differs from existing ones in that it takes into account the effects of the external environment and the probability of situations of route passage, the formation and aggregation of criteria. This allows for transparency and streamlining of procedures for implementing transport strategies.

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Шарко О. В., Степанчиков Д. М., Шарко А. О., Мовчан П. В. БАГАТОКРИТЕРІАЛЬНА ОПТИМІЗАЦІЯ СИТУАЦІЙНОГО УПРАВЛІННЯ МОРСЬКИМИ ПЕРЕВЕЗЕННЯМИ В УМОВАХ НЕВИЗНАЧЕНОСТІ

Запропоновано методологію багатокритеріальної оптимізації морських транспортних перевезень в умовах невизначеності впливу зовнішнього середовища. Зазначено, що у практиці управління морськими транспортними перевезеннями спостерігаються їх комплексні прояви у вигляди різних конкретних ситуацій, прихованих можливими взаємодіями і невизначеностями впливу зовнішнього середовища Показано, що найбільш раціональним способом вирішення завдань транспортних перевезень за умов невизначеності є багатокритеріальна оптимізація. На основі розгляду реальних ситуацій транспортного переходу Туреччина-Німеччина показано, що зниження невизначеності при визначенні умов проходження маршрутів перевезень може бути досягнуто як шляхом раціонального використання експлуатаційних параметрів судна, так і урахуванням зовнішніх умов проходження маршруту. Запропоновано та докладно досліджено параметри оптимізації транспортних перевезень конкретного транспортного маршруту. Виконано формування матриці транспортних перевезень, параметрами оптимізації в якій є завантаження судна, тривалість доставлення, швидкість переходу, навантаження на головний двигун, витрата палива, відхилення від маршруту, вартість перевезень. Розглянуто практичні ситуації проходження маршрутів. Встановлено вплив зовнішніх збурень на керовані експлуатаційні параметри судна, що дозволило виробити рекомендації щодо прийняття рішень, виходячи з ранжирування пріоритетів оптимізаційних параметрів стратегій матриці транспортних перевезень та збігів з різних узагальнювальних функцій та можливість прогнозування наслідків прийняття рішень про обрану оптимальну стратегію управління в умовах конкретної ситуації, що склалася. Запропоновано інтелектуальну інтерактивну модель прийняття рішень щодо вибору альтернатив управління транспортом в умовах невизначеності вхідної інформації, що включає внутрішні нормативні акти, стандарти та правила перевезень, яка відрізняється від наявних тим, що враховує вплив зовнішнього середовища та ймовірність ситуацій проходження маршруту, формування та агрегування критеріїв. Це дозволяє забезпечити прозорість та оптимізувати процедури реалізації транспортних стратегій.

Ключові слова: *морські перевезення; тенденції розвитку; управління; логістика; інтелектуалізація; транспортні технології.*

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