Formalized model and algorithm for managing complex interaction of heterogeneous transport

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Abstract. The problem of ensuring the reliability of heterogeneous transport systems is extremely multifaceted and covers all stages of development - from design to operation. To increase efficiency, there is a need to harmonize the processes taking place in heterogeneous systems within the framework of single transport communication. The lack of appropriate theoretical justification leads in practice to the emergence of insufficiently substantiated decisions, because of which subsequent efforts made to eliminate the discovered shortcomings are, as a rule, costly and ineffective. Assessment of the system of integrated regulation of the transport system, from the point of view of its sustainability, is an indispensable condition for its operational efficiency and reliability. The efficiency of transport processes assumes that the effective functioning of local transport systems is ensured by the level of interaction between participants in the transport process, modes of transport that create positive dynamics of transit freight turnover. The paper substantiates the need for complex interaction in the management of the regional transport system, considering the interaction of adjacent modes of transport in a single information space. The method describes in detail the solution of forecasting and coordination problems in maritime transport systems, harmonization of the interests of heterogeneous transport in solving forecasting and control problems.

1. Formulation of the problem

Management of complex transport systems, the dynamics of their functioning, and interaction should be based on a system of mathematical methods, optimization of interaction, and information. In the implementation of the complex tasks of operational regulation, the methods of mathematical modeling of the sea transportation process are of decisive importance. The setting of modeling tasks depends on the level and information capabilities of the technical means used. The nature of the results of operational regulation, representing various dispatch decisions on the distribution of incoming ships to ports and berths, forwarding of ships, or adjusting the schedules of ships, requires high-speed processing of many operational data and, on this basis, in most cases enumerating a huge number of options. This problem is solved by the introduction of automated management and decision-making tools, while there is an increase in the efficiency of the production process, an increase in labor productivity based on the existing transport infrastructure.
An information management system can also be defined as a set of rationally organized automated technological processes for collecting, transmitting, and processing technical and economic data, providing information to control bodies for optimal functioning (activity) of the economic system.

The creation of automated control systems (ACS) in a single information space, it is advisable to perform in several stages (stages). In this regard, as applied to transport, we present the classification of automated systems depending on the main functions assigned to them and the forms of communication with the operator.

The first stage is information systems. These systems provide collection, accumulation, primary processing of data, as well as the issuance (on request) of the processing results in a convenient form for the operator. At the same time, primary processing consists of sorting and accumulating data according to certain indicators in storage arrays, automatic calculations of accounting and reporting and statistical data, and the development of forms of resulting documents, as well as issuing certain recommendations to eliminate distortions of the planned flow of production processes. Improvement of information systems will consist in imposing on them variant calculations for planning and resource allocation, as well as the simplest tasks of operational regulation and forecasting. Operators are expected to participate in all phases of information processing.

The second stage is information management systems. In these systems, computer technology is used for the automated solution of more complex control problems, up to the simulation of production processes. They carry out remote information exchange and automatic preparation of initial data for control tasks, most of which are solved automatically, without human intervention. However, before the transmission of the fundamental results of calculations to control objects, they are tested by the management of various levels. The complexes of technical means in these systems represent an extensive network of information and technical means connected and software-controlled in their work.

The problem of creating and implementing automated information management systems in the marine fleet is extremely complex, combining the practical implementation of the results obtained with ongoing theoretical research.

Modern trends in the development of the transport complex of the Southern Federal District urgently require the development of an automated control system. The main task facing the developers of such an automated control system should be the coordinated management of adjacent modes of transport: sea, rail, the road to increase the capacity of networks without significant capital investments in the development of the existing infrastructure.

Management systems for individual modes of transport are built on a hierarchical principle, and the coordination of the interests of transport companies is possible at various levels: road management - by shipping companies, port - port station, etc.

To create centralized control systems in the region and at the nodes, it is advisable to carry out a systematic analysis of the quality of the interaction of sea, rail, and road transport and, on this basis, develop and implement an automated control system.

Thus, it is necessary to develop methods for aligning the interests of heterogeneous transport at different levels of the hierarchy. In this paper, one of the options for the mathematical formulation of the problem of coordinating the interests of transport organizations participating in the operation of a transport hub (port-port station, shipping companies, etc.) is proposed. The ways of development of methods of coordinated control considering the hierarchy of systems are outlined [1].

2. Main part
For formalization, a heterogeneous transport system will be perceived as a port-port station system, a shipping company.

These subsystems are not legally subordinate to each other, and the management of the name is carried out independently; at the same time, there is currently a coordination center with the authority to influence the management process of individual subsystems (port - port railway station).
The coordination (logistic) center can have different completeness of power concerning the subsystems included in the united transport hub. The purpose of the coordination center is to ensure the stable operation of the entire transport system of the region; each subsystem has its own primary goals of work (for example, the fulfillment of contractual obligations, stevedoring, provision of rolling stock, etc.).

Since the subsystems in the process of interaction depend on each other, it becomes possible to centrally control them, with an increase in the effect of the operation of transport; each subsystem has its own goals of work (for example, the fulfillment of contractual obligations).

In a qualitative description of the process of coordinated management of the subsystems of the transport node, we will assume that the management of the subsystem consists of developing a certain operational plan, which includes indicators that are internal to the subsystem and indicators that characterize the connection between the subsystem and the adjacent subsystem. In addition, we will assume that the indicators characterizing the relationship between two subsystems are for each of them, i.e., are measured in the same quantities and reflect the same process.

Currently, each subsystem plans its work independently, and the indicators common for adjacent subsystems do not coincide.

The first step in improving the planning of the subsystem's work is to consider the capabilities of related organizations when implementing the plan adopted by this subsystem. It is necessary to have a model of an adjacent organization, with which it is possible to assess the feasibility of the plan adopted by the subsystem.

This approach will lead to the development of realizable plans in each subsystem. Moreover, each subsystem will plan indicators common to the system. Consequently, it is necessary to develop such plans of subsystems in which these indicators will have the same value in each subsystem.

When developing forecasts (plans) with the same values of general indicators (joint plans), the efficiency indicators of the plans of each system will decrease, since we introduce an additional requirement into consideration, but the plans will become realizable.

If there is no coordinating body, and the subsystems are independent and equal, then the principle of equal concessions will be the most reasonable; i.e., the performance indicators of the plan of each of the subsystems because the adoption of a joint plan may decrease by some amount, and this value should be minimal (preferably equal for each of the subsystems).

If there is a coordinating body, then it can demand from the subsystem’s concessions (depending on their powers) concerning independently adopted plans that may not be implemented; among the plans with such concessions, find the most effective from the point of view of the coordinating body.

The coordinating body can also change the set of admittedly agreed plans, which will lead to the choice of the desired plan.

If one of the parties is constantly forced to make a big concession, then it is necessary to have a mechanism to compensate for losses at the expense of the party making smaller concessions [2].

### 3. Formalization of the problem of reconciliation of interests

We carry the following designations: $X^Z_i$ - internal indicators of the $i$-th subsystem, $i = 1,2$; $X^\theta_i$ - indicators common to all subsystems; $F_i( X^Z_i, X^\theta_i )$ - indicators of the quality of functioning of the $U$-th subsystem.

The purpose of the agreement is to obtain a plan in which $X^\theta_i = X^\theta_i$. Therefore, the parameters $X^Z_i$ will not interest us in an explicit form, each subsystem is independently planning them.

We will assume that there is some dependence $X^\theta_i( X^\theta_i )$ i.e., with a fixed value of $X^\theta_i$ the subsystem selects the most appropriate parameter value $X^\theta_i$ from its point of view. Then $F_i( X^\theta_i( X^\theta_i ), X^\theta_i ) = F_i( X^\theta_i )$. Each subsystem has a known range of admissible values of $X^\theta_i$,
denote it by \( Y_i = \{X_i^0\} \). Thus, the forecasting of freight traffic, produced at the modern level, can be formalized as follows:

**Problem 1.** \( \max F_i^1(X_i^0), i = 1,2. \) Moreover \( X_i^0 \) may not belong to \( Y_2 \), i.e., such a forecast is certainly not realizable.

**Problem 2.** \( \max \frac{\max F_i^1(X_i^0)}{X_i^0 \in Y_1 \cap Y_2} F_i^1(X_i^0), i = 1,2. \) In this case, we get the predicted value of the cargo traffic that is guaranteed to be realized by both parties. Remarks. Indicators \( F_i^1(X_i^0) \) and \( F_i^2(X_2^0) \) are vectors. Therefore, the entry \( \max F_i^2(X_i^0) \) is not a vector, but a scalar. Thus, we get problem 2.1

\[
\max_{X_i^0 \in Y_1 \cap Y_2} \Phi_i(X_i^0), i = 1,2. \tag{1}
\]

To measure these concessions, the proposed method is as follows. Indicators \( F_i^j \) means the degree of fulfillment of one of the indicators of the plan. they can be considered a dimensionless quantity not exceeding one. If we assume that the subsystem is equally important to fulfill all indicators of the predicted values, then the efficiency of the forecast \( X_i^0 \) can be measured by the value \( \Phi_i(X_i^0) = \min_i F_i^j(X_i^0), \) where \( \Phi_i \) is not a vector, but a scalar. Thus, we get problem 2.1

\[
\max_{X_i^0 \in Y_1 \cap Y_2} \Phi_i(X_i^0), i = 1,2. \tag{2}
\]

The presence of a coordinating body, which is the bearer of strategic interests and has a certain degree of power, leads to the following task.

**Problem 4.** Find \( X_i^0 \) at which \( \max F_o(X_i^0) \) is reached, where \( F_o \) is the economic effect of plan \( X_i^0 \). In addition, the constraints \( \delta_i(X_i^0) \geq \delta_i X_i^0 \in Y_i^K \cap Y_2^K \), must be met, where \( \delta_i \) is the lower value of the concessions of the \( i \)-th subsystem, set by the coordinating body: \( Y_i^K \subseteq Y_i, Y_2^K \subseteq Y_2 \), subsets of the sets of admissible forecasts, set, if necessary, by the coordinating body. At \( Y_i^K = Y_i, \delta_i = \delta \) task 4 becomes task 3. If \( \delta = 0 \), then the task is solved, considering the recommendations of the center.

\[
\max_{X_i^0 \in Y_1 \cap Y_2} F_o(X_i^0), \tag{3}
\]
It may turn out that the values $\delta_i$ and $\delta$ are not equal. For example, a slight decrease in one of them leads to a greater increase in the value of criterion $F_0$. In this case, a mechanism should be developed to compensate one subsystem (for a large concession) at the expense of another.

Analysis of the formal setting. In order to use the formal statement of the coordinated control problem, it is necessary to describe the set of variables $X_i^0$ and $X_i^¥$; be able to find the values of indicators $F_i(X_i^0, X_i^¥)$, be able to describe the set of feasible solutions - $Y_i$; for a given set $X_i^0$ we find the best set $X_i^¥$ that is, have the function $X_i^¥ = X_i^¥(X_i^0)$; find the values of criteria $F_i(X_i^¥)$; be able to collapse the vector criterion $F_i$ into a scalar criterion $\Phi_i$; have a mathematical apparatus for solving problem 4.

To search for the value of indicators $F_i(X_i^0, X_i^¥)$ and a set of feasible decisions, it is necessary to know the current state of the transportation process and be able to predict the consequences of decisions made.

The current state can be obtained from the dynamic model of the transportation process, which is considered in detail in, and to predict the consequences of the decisions made, it is necessary to develop a forecasting system for the transportation process. One of such systems for the railway was investigated in [3].

To obtain the function $F_i(X_i^0)$, it is necessary to solve this problem by finding the optimal values of the variables $X_i^0$ for the given values of the variables $X_i^¥$. This task is currently being handled by an operator. Therefore, it is necessary to develop formalized methods for its solution and give the operator a tool for a faster solution to it, for example, an interactive planning system. In addition, each transport organization needs to know the capabilities of the subcontractor and its solutions in one way or another. These solutions, as indicated above, are often found according to an informal rule. Therefore, each transport organization should have, albeit not entirely face-to-face, formalized model of the behavior of related organizations.

The problem of convolution of criteria $F_¥$ into criterion $\Phi_i$ in the first approximation was solved above. The most difficult question is the methods for solving problem 4. It is necessary to develop how the most probable iterative such methods are, i.e., it will be necessary to work out several variants of the plan $X_i^0$. Consequently, the information collection system and the planning system in the subsystems should allow finding several plans for different values of the variables $X_i^¥$. In its simplest form, you can create an interactive system associated with the information collection system, with the help of which the dispatchers of the subsystem could find the agreed plan (an example of the application of the proposed technique).

To illustrate the proposed technique, consider the following example. We will assume that a port station and a port interact in a transport hub. The countries agree on the delivery of wagons with cargo from the station to the port for one day - $X = (X^1...X^n)$, where $m$ is the number of types of cargo. The number of wagons with various types of cargo at the station is known.

Let's enter the designation of the number of wagons with $j$-th cargo view through $Y_i^j$, $j = 1, m$. Then $0 \leq X^j \leq Y_i^j$, so $Y_i = \{0, Y_i^j\} X...X\{0, Y_i^m\}$. The port accepts wagons and processes them in two ways: wagon – ship, no more than $Y_2^j$ in total, for the $j$-type of cargo and a wagon – warehouse, no more than $Y_2^j$ for the $j$-type of cargo-$Y_2 = \{0, Y_2^j\} + Y_2^{2j}/X...X\{0, Y_2^m\} + Y_2^{2m}$. In this case, the criterion of technological optimality at the station:

$$- F_j(X) = (F_j(X^1), F_j(X^2)...F_j(X^m))$$
\[ F_2(X) = F_1^1(X^1), F_2^2(X^2), \ldots F_2^m(X^m). \]

Suppose that each of the functions \( F_i^j(X^j) \) has the form:

\[ F_i^j(X^j) = \begin{cases} x^j \in [x^j_{\min}, x^j_{\max}] & \text{if } x^j \in [x^j_{\min}, x^j_{\max}] \end{cases} \] (3)

The result of this function is the proportion of fulfilling the predicted values \( X_i^j \), where \( i = 1,2 \) (1 – station, 2 – port, \( j = \frac{1}{m} \)).

If the station and the port have total restrictions on the total number of wagons that they can handle, i.e.,

\[ \sum_{j=1}^{m} X_j^i \leq A_i; \quad \sum_{j=1}^{m} X_j \leq A_2 \] (4)

Problem 1 for the station is formulated as follows and has the form:

\[ \max F_i^j(X); \quad 0 \leq X_j^i \leq Y_j^i, \quad 0 \leq \sum_{j=1}^{m} X_j^j \leq A_1, \quad X = (X^1, \ldots, X^m). \] This is not a task yet, because \( F_i^j(X) \) - vector. To concretize the problem, we introduce the convolution of functions \( F_i^j \) of the following form: \( \Phi(X) = \min F_i^j(X^j) \) i.e., the greatest non-fulfillment of the predicted volume for one of the types of cargo.

We get the following type of problem 1.

Problem 1 tbsp. \( \max \Phi_i(X) \), where \( X \) satisfies the constraints:

\[ 0 \leq X_j^i \leq Y_j^i, \quad 0 \leq \sum_{j=1}^{m} X_j \leq A_1, \quad X = (X^1, \ldots, X^m). \] Similarly, for port 1, we have the following form.

\[ \Omega = \left\{ X : \begin{align*} 0 \leq X_j^i \leq Y_j^i, & \ldots, 0 \leq X_j^i \leq Y_j^i + Y_j^i \\ 0 \leq \sum_{j=1}^{m} \min(A_i, A_2) \end{align*} \right\} \] (6)

Problem 2 tbsp.

\[ \max_{X \in \Omega} \Phi_i(X) \] (5)

\[ \Phi_i(X) = \max_{X \in \Omega} \Phi_i(X) \]

Assigning a station when accepting plan \( X \) instead of \( X \) is optimal solutions to these problems.

Problem 3 is

\[ \max_{X \in \Omega} \left( \min(\delta_i(X), \delta_2(X)) \right)^2. \]
Problem 4 - \( \max_{X \in \Omega} F_0(X), \ldots, \delta_i(X) \geq \delta_i \) where \( \delta_i \) is the concessions recommended by the coordinating (logistic) body, and \( F_0(X) \) is the criterion for the coordinating body. We can assume that \( F_0(X) = \sum_{j=1}^{m} a_j X^j \).

Thus, of the above examples 1-4 are nonlinear programming problems of the same type. To solve them, it is proposed to apply the appropriate software. For \( j = 2 \) the problem can be solved explicitly. For simplicity, put \( A_1 = A_2 = A \); \( Y^1 = Y^1 = Y^{1,1} + Y^{2,1} \); \( Y^2 = Y^2 = Y^{1,2} + Y^{2,2} \).

The graphic solution of this problem is discussed in detail in [4].

4. Possibilities of detailing the technique
An approach to solving the problem of coordinating the interests of several subsystems with and without a coordinating body is substantiated. The subsystems were adopted as single-level ones. The methodology will be detailed as follows, the transport organizations will agree on the general provisions of the methodology – the correspondence of the qualitative description of the object to the real object, the possibility of the proposed convolution of criteria, the use of the principle of equal concessions, the possibility and expediency for the coordinating body to operate with concessions, etc.

If it is recognized that the described approach meets the requirements of related modes of transport, then it will be necessary to clarify the list of planning indicators, the vector of parameters, the method of their convolution and conduct an experiment for the case of two indicators, when calculations can be performed manually. In the future, it is advisable to develop software for solving a problem of higher dimensions.

Another direction will be considering the hierarchical structure of subsystems in the methodology. In its simplest version, it can be considered that the sets depending on the decisions of the higher levels of the hierarchy. In this case, options for coordinating the decisions made are possible.

One of them is that for fixed decisions of the upper levels, the lower levels of the hierarchy agree on their decisions. If the agreement fails, each of the subsystems turns to a higher authority, etc.

Another approach is that reconciliation is done first at the top levels of the hierarchy. The decisions of the upper levels are passed on to the lower levels, i.e., coordinate their decisions, etc. Figure 1. The expediency of using one or another coordination of the decisions made will become clear after a more detailed description of the existing control methods in subsystems and the requirements for the coordination method.

The most important direction of increasing the efficiency of the transportation process is the creation of a unified automated control system based on the optimal organization and coordination of all modes of transport in the node and region. At the same time, along with the development of existing automated control systems for individual types of transport, the problem of developing a unified automated system for coordinating types of transport complexes of regions and the country arises. The solution of these important issues should be preceded by a systematic, comprehensive study of the processes of management of transport complexes [5].
5. Results and Discussion:
The paper investigates a formalized model and an algorithm for managing the complex interaction of heterogeneous transport. The basis for improving the efficiency of management is the information-measuring system, formed according to the hierarchical principle, considering the interests of all links of the transport system, which is realized based on the proposed mathematical apparatus. The author admits the possibility of using dynamic models of the transportation process, which requires a stable information system for collecting information based on a dialogue system. This is a prerequisite for the creation of a single global dispatching system for managing complex interaction of heterogeneous transport in the region.

6. Conclusion
An automated control system should be based on the principles of territorial transport management, unite all management links of interacting modes of transport with a single information network, and be locked into regional and federal authorities.

The main effect of the introduction of automated systems can be obtained by solving operational management tasks. They require the most sophisticated methods for their solution, so the focus should be on these very tasks. The development of methods for their solution should be considered the most urgent problem.

Improving the organizational structure and management methods will undoubtedly lead to a change in the quantitative characteristics of existing information flows and will provide objective data for the creation of means of technical support for management and implement the development of ACS and transport within the framework of a unified information and transport system, especially in transport hubs and regional transport systems.

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