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IMPROVING THE METHODOLOGY FOR OPTIMIZING MULTIMODAL TRANSPORTATION DELIVERY ROUTES AND CYCLIC SCHEDULES IN A TRANSNATIONAL DIRECTION

Summary. This study considers the task of planning the routes of multimodal transnational cargo transportation. Due to the extremely long length of such routes, delivery times and costs per cargo unit are extremely important. Delays in various types of transport and in the case of cargo transshipment are associated not only with the growth of cargo flows but also with the inconsistency of vehicle schedules. The purpose of this study is to improve the previously developed methodology for optimizing multimodal cargo transportation, taking into account the need for its application to transnational transport corridors. The content of the formulated network problem is reduced to a modification of the traveling salesman problem with an unknown number of transport points the route should pass through. Such a problem is NP-hard due to the time complexity of the algorithms. A modified algorithm has been developed, according to which the general problem with the number of *N* points is divided into several sub-problems. Transport points are grouped into consecutive subsets that are related by only one non-alternative way of transportation. This way can be any “bottleneck” of the transport network or an artificially created one. Such a decomposition of the problem gives a set of partial solutions, which were combined into the final optimal solution. The obtained solution to the routing problem of multimodal routes takes into account the cyclical schedules of the transport operation and gives a guaranteed exact optimum for calculations performed within the permissible time. In addition to determining the optimal route, the algorithm makes it possible to determine the required number of vehicles and their work schedules depending on the total cargo flow on the route.

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1. INTRODUCTION

With the continuous development of the global economy and the level of prosperity of society, the volumes of international trade are growing significantly. At the same time, the requirements of modern logistics regarding timeliness, cost-effectiveness and reliability continue to grow as well. Due to the limitations of the traditional single type of transport, it cannot fully satisfy the growing logistics needs in the advantageous transportation distance and organizational form. As a cargo transportation system that can integrate multiple types of transportation, multimodal transportation is widely promoted in many countries. With the development of multimodal transport networks, there may be several routes from the beginning to the end of the cargo transportation process.

Since different routes have certain restrictions for different types of transport, the optimization of the route between the two trade hubs of Eurasia has been analyzed in this article to further improve the economic and time advantages of transportation. We first used a nonlinear planning model to define a multimodal transportation route optimization problem. At the same time, multi-objective optimization was considered as a goal, and a genetic algorithm to select the appropriate route was used. Finally, a case was used to illustrate the applied model. The present study can solve the problem of multi-objective planning and route selection of multimodal transportation. It also has a certain reference value for logistics practice.

Modern multimodal transportation is expanding to transnational in scope. This happens when information flow capacity increases and accompanies the exchange of goods. The desire to reduce the cost of transportation leads consumers to increase the volumes of cargo delivery batches. If cargo flows are powerful, then it makes sense to look for more profitable routes for them, choose less expensive and more reliable methods of transportation, and form more convenient delivery schedules. At the same time, such tasks become the prerogative of individual logistics companies that serve specific orders of a transnational nature.

The content of the problem of organizing more profitable routes and goods traffic schedules is that such tasks are more complex than the optimization of intercity transportation by one or several types of transport. The task is complicated by the increasing importance of the time factor at long distances, meaning its calculation must be more accurate. On the other hand, the increase in the length of the route, the number of transshipment points, and alternative routes make it difficult to find an exact guaranteed solution. Therefore, improving the methodology of multimodal transportation routing on transnational routes is an urgent research problem. Its solution is useful for logistics companies that carry out periodic or single orders for the delivery of goods in international communication involving various types of transport. The maximum effect from the application of the improved methodology can be achieved with the constant, periodic delivery of goods in reasonable batches.

2. LITERATURE REVIEW

In order to strengthen economic ties and trade cooperation between China and Europe, as well as between other neighboring countries along the Silk Road Economic Belt, Asian governments and private equity have invested heavily in the far-reaching Belt and Road Initiative (BRI) [1]. As a result, maritime shipping has assumed a dominant role in the cargo transportation market, carrying 93% by weight and 59% by cost of China-Europe cargo in 2020 [2]. However, these decisions were rather one-sided, as the focus was made on the slowest way of transportation. This is an example of insufficiently substantiated decisions that lead to the congestion of bottlenecks in international transport corridors.

Liner shipping, rail transportation, road transportation and air transportation are the four options for shippers to transport goods in the transnational transport route corridor. Each of them has constant advantages and disadvantages. For instance, air transport is much more expensive than the other two types of transport and only takes a small part of the total trade volume. Road transport is characterized by high efficiency, but it is complicated in terms of delivery schemes and has limitations on the capacity of transport points. Railway delivery has significant limitations on the place of delivery and road capacity [3].

In the context of the BRI, the intensive development of various types of transportation has greatly improved and reconfigured the cargo transportation network of the Great Silk Road, providing China-Europe shippers with a better cargo transportation option. Moreover, an overall China-Europe cargo transportation network was created by integrating the domestic highway network in China and the multinational highway network in Europe to provide origin and terminal services, connecting cargo origin and destination points with adjacent seaports and railway stations. Given that the multimodal cargo transportation network is built to include the above components, a large number of multimodal routes, each defined by a combination of selected transportation types and routes, will be generated to provide sufficient coverage for the various options that shippers may choose [4, 5].

The behavior of individual shippers regarding the choice of combined transportation method and route is characterized by the widely used multinomial logit model; the time value for different categories of goods is included in this model's utility functions. Transshipment effects arising from bottlenecks along shipping lines and cargo railway lines (i.e., seaports, waterways, and break stations) are first captured by bulk service models and then approximated by polynomial delay functions. While the accommodation capacity of individual service lines is clearly built into the model as hard constraints. This equilibrium model of the supernetwork is implemented using a subgradient algorithm in a Lagrangian relaxation system that includes a disaggregated simplicial decomposition algorithm. Computational experiments are performed on a multi-layered heterostructured supply and demand dataset collected from multiple data storage systems, government agencies, cargo carriers, and research articles and reports. Preliminary results demonstrate the computational performance of the solution procedure and reveal variations in bottleneck overload levels, service line capacity utilization profiles, and the conditions of competitiveness between the services of liner shipping and cargo rail transportation under different models of monthly demand [1, 2].

New multimodal logistics programs must address various problems, including complex traffic conditions and time constraints. In the article [6], the problem of vehicle routing with time-dependent travel times and time windows was considered in the context of urban logistics. The goal was to minimize the total specific costs per unit of cargo, including transportation, waiting times, and the fixed costs associated with each vehicle. The problems in this direction are characterized by a low level of solution quality [7].

Recently, society has been paying more and more attention to the problem of increasing emissions of harmful gases from transport. First of all, this applies to road and air transport. Also, as a result of accidents, the water environment of the planet is suffering. Transportation methods and transportation routes should be chosen wisely to improve transportation efficiency while reducing carbon dioxide emissions. The publication [8] is based on these aspects and is a starting point for studying the choice of transport routes and methods of multimodal transportation. However, the optimization criterion in the article is reduced to monetary costs, which is a subjective choice.

The use of various mathematical models makes it possible, at present, to solve the problem only by heuristic or mega-heuristic methods [1, 4, 9-12]. However, the increases in the lengths of common routes and in time loss against this background are the result of approximate solutions. Therefore, there is a need to improve the quality and accuracy of the methodology.

Attempts to increase the accuracy of solutions to the multimodal routing problem were made, taking into account the dynamics of the process (changes in external conditions). The use of the entropy method in the optimization and forecasting of multimodal transportation in terms of risks – which can be simultaneously deterministic, stochastic, and uncertain values – is examined in the article [11]. This allows one to change the transportation route optimally in real time with an unacceptable increase in risk at one of its subsequent stages and to predict the redistribution of loads of transport hubs. However, the solution methods remain heuristic.

There have been known attempts to formalize the processes of cargo delivery by multimodal routes as an optimization model of the total time of cargo delivery with the constraints of rational and reliable (failure-tolerant) loading of transport fleets. Such optimization takes into account the stochastic arrival of transport flows, the duration of technological operations, and the consistency of delivery schedules in each of the supply chains. However, the model is presented in an implicit form, so the scientific and applied problem can be solved only experimentally. This approach makes it possible to implement a systematic approach in the optimization of the entire supply chain in an operational plan [13].

In work [14], at first, the problem of optimizing the combination of transport routes and types for a container multimodal transport system is formulated as a problem of mixed integer programming. Then, a dynamic programming algorithm is proposed to obtain an optimal strategy for combining types of transport. Finally, a real problem is solved to show the feasibility and effectiveness of the proposed model as an approximation. It is quite logical to improve the practical limitations of the model and make the task of optimizing the combination of transport routes and types of visualization.

The article [15] presents TIMI-Plan as a software tool that successfully solves certain multimodal and unimodal transport problems of a large company. Multimodal transportation usually involves a combination of a large number of resources along with time constraints, resource consumption, cost functions, etc. It is obvious that the bottleneck in this problem is the combinatorial explosion, which makes it impossible to obtain optimal solutions within the time limit. Thus, the company uses only classical planning or disjunction methods. Instead, the problem was split into two different subproblems, combining the use of a linear programming method for automated scheduling. This new way of combining allowed us to balance the obtained total cost (quality), the time required to compute the solution, and the time to simulate different optimization problems. The results show that the modified Multi-Objective Ant Colony System algorithm successfully solves the company's unimodal transportation problems using various optimization criteria. However, in international communication, a similar problem cannot be solved by this method due to the instability of the solutions, which must take into account the dynamics of the delivery process.

In the work [16], the problem of the coordination of the individual stages of the multimodal delivery process is considered while taking into account the fact that the process is a discrete material flow in its nature. Methods for determining indicators of periodic processes, such as a tact, group size, front of a discrete flow, and their interdependence, have been developed. It was shown that the efficiency of delivery of a certain volume of goods in batches depends on the number and volume of batches. The article is devoted to identifying the conditions for the effective use of multimodal transportation. At the same time, the efficiency of competing routes is relative, depending on the volume of delivery. However, the task of choosing a route for given volumes, in the presence of several alternative ways between nodal points, is NP complex and can be solved in polynomial time. With a significant number of transit points and alternative routes, the exact solution is not guaranteed by deterministic methods. One of the possible admissible methods of solving the routing problem is the decomposition of the routing problem with a large amount of data into several simple ones in which a guaranteed exact solution can be found in an admissible time using a deterministic method [6]. Due to the difference in cost and time consumption between different modes of transportation, the path planning of multimodal transport is different from that of single-mode transport. Moreover, planning uncertainty arises due to the need to overload and coordinate schedules of modes of transport. Fuzzy, heuristic, and other approximate methods are used in known methods. At the same time, the presence of rhythmicity of cargo deliveries in transnational communication is not taken into account. In this regard, the known methods need to be improved because they do not satisfy the need for calculation accuracy.

3. RESEARCH PURPOSE AND OBJECTIVES

The purpose of the studies carried out in this work is to improve the previously developed methodology for optimizing multimodal cargo transportation while taking into account the need for its application in transnational transport corridors. That is, the problem of using deterministic routing algorithms and drawing up schedules with a big data array is considered. Such a modification of the methodology will take into consideration the following factors: the significant length of the route, which affects the importance of time delays; a large number of transit points, including nodal ones, as well as alternative ways of traveling along the route, which affects the multivariate nature of the problem; and the algorithmic complexity of finding the optimal solution.

Achieving the goal is possible by solving the following research objectives:
1. To improve the well-known method of developing a multimodal, transnational route while taking into account the presence of transit nodal points, as well as bottlenecks in the transport network (e.g., customs points).
2. To analyze the organizational and technological parameters of the multimodal transnational transport network using the example of the southern Trans-Caspian transport corridor: China-Dostyk-Aktai-Batumi-Istanbul. To determine the signs of expediency of dividing the route into clusters when transporting cargo in a fixed direction.
3. To apply the methodology for partitioned data as well as for the global route. To establish the feasibility conditions for the decomposition of the global routing problem.

4. RESEARCH METHODOLOGY

A transport network, which consists of terminals and nodal transport points, is given. Transport points are located in several countries along which the trans-national corridor runs. From θ=1 to Θ_{max} types of transport can pass through the transport points, taking into consideration the geographical features of the area and the economic development of the countries. Here, by the type of transport, we understand not only the type of mover and the way of movement (car, rail, water, air) but also a significant difference in terms of technical and operational indicators. For example, different types of transport also include vehicles of the same type, which have different load capacities (e.g., large-, medium-, and low-tonnage cars). Similarly, we classify railway carriages, for example, covered with a load capacity of 55-69 tons, and platforms with a load capacity of 60-75 tons. If transport containers are used on some part of the route, they are classified as a separate type of transport, taking into consideration the method of transporting the containers.

Within the borders of one country, transport corridors can have a diverse configuration, which was developed under the influence of political, economic, and geographical circumstances. Thus, in the territory of China, the government plans to focus on the development of the transport system, which, in the future, should become an international transit transport hub for various Chinese provinces in the direction of the western border of the PRC and further through the countries of Central Asia to European markets. "Chanan" international cargo trains will be launched on a regular basis along the Xi'an – Central Asia route (Kazakhstan, Uzbekistan, Kyrgyzstan, Turkmenistan). There are plans to continue the route, with one branch going to the north and the other to Rotterdam (the Netherlands). In recent years, there has been a rapid increase in the trade volume of Shaanxi province with Central Asia countries (the main trading partners are Kazakhstan and Uzbekistan). The provincial government plans to intensify work on the establishment of the "Xian Free Trade Zone," focusing on the Central Asia region and Europe.

Thus, the number of alternative variants of the multimodal transport and technological scheme depends on the possibility of using different types of transport, the configuration of the multimodal transport network (i.e., the availability and location of transport hubs and terminals and the connecting routes between them), the capacity of individual sections of the network, and the political and economic situation. Given the largest transport corridors of Asian countries (trade cargo flows), it can be assumed that the average number of intermediate hubs where transshipment occurs and through which the desired route can be built is quite large and is approximately 75–300 per route. The routing of one group of goods on a multimodal transnational network is reduced to a modified traveling salesman problem, where the number of transport points that the route should pass through is not set in advance. Such a problem is recognized as difficult in terms of discrete optimization and is considered NP-complete due to the time complexity of the algorithms [17]. The exact algorithm of the full search has factorial complexity. Well-known classical algorithms capable of solving the traveling salesman problem work effectively only when the problem is of low dimensionality (i.e., the number of points does not exceed 20). In this regard, the problem of choosing the appropriate methodology that allows one to solve this problem in an acceptable time has matured.

The physical meaning of the problem is that two transport points belonging to different states are specified. Both points can be terminals or hubs, but one of them must declare a certain amount of K_{sum}

unit cargo that needs to be delivered to the final point ready for shipment. Cargos can be transported by several types of transport, transshipping at other transit nodes of the transport network. They can also be divided into groups of an arbitrary size according to the load capacity of vehicles. It is necessary to develop a delivery route for the entire K_{sum} group such that the indicators of the duration and/or cost of delivery of one package are minimal. It is necessary to take into consideration the periodic nature of the operation of all types of transport on the project route.

We will now formalize the problem. A graph displaying a network of alternative routes $G(Q,U)$, where $Q=\{q_1, q_i, ..., q_j, ..., q_N\}$ is a set of vertices that display N of transport points. U is the set of arcs between the given vertices Q. Any vertex q_i of the graph G, except for q_i and q_N, which are the points of initial dispatch and final delivery of some batch of goods K_{sum}, is connected to other vertices by at least two arcs; one of these arcs must be $u_{x.i}$, and the other must be $u_{i.y}$, where $x,y \in G$. That is, any point q_i that belongs to Q when $i \neq 1$, N also belongs to at least one alternative way from q_1 to q_N. A graph G is directed, strongly connected, and may contain cycles. Any arc $u_{i.j}$ of the graph G corresponds to an available connection between the vertices q_i and q_j, taking into account the corresponding type of transport. If several connections of different types of transport pass through the point qi, then the graph G contains several vertices $q_{i.\theta}$, which are equated to the vertex q_i. Arcs $u_{i.\theta+1.i.\theta+2}$ can be found between the identified vertices $q_{i.\theta}$ in the form of loops in the graph G. Such loops reflect operations of transshipment from one type of transport to another. If such a transshipment is impossible at point q_i, then the corresponding loops are absent. If nodal transport points can serve several types of transport, then they are also connected by multiple arcs ($u_{i.j}$, $u_{i.j+1}$, … $u_{i.j+\theta}$) with other vertices of the graph. Here, θ is the total number of available types of transport at the vertex q_i. The number of arcs U depends on the real geographical data, which represent the routes of communication between transport hubs available in practice.

The initial unordered model of the multimodal transportation process is a graph $H(E,Y)$ that displays a graph G, where $E=\{e_1, e_i, …, e_j, …, e_N\}$ is a set of vertices that represent the starting moments of the corresponding elementary logistics operations, Y is a set of arcs that correspond to the practical information about the parameters of the movement between given vertices of the graph G. In this case e_1 is the initial vertex of the graph H, the one to which no arc enters, e_N is the final vertex from which no arc from Y departs. If the graph G contains multiple arcs that connect vertices, for example, q_i, q_j, with the help of n arcs, then n such vertices $e_{i.1}$, … $e_{i.n}$, $e_{j.1}$, … $e_{j.n}$, are entered in the graph H, between which n corresponding arcs are drawn. All other vertices of the graph H have at least one input arc and at least one output arc. On such a graph, it is necessary to find all possible ways from the vertex e_1 to the vertex e_N such that in one way, any vertex occurs only once. And the subgraph H_x of the graph H, which represents one multimodal transport process, and that is a simple chain. In the chains of all routes to each vertex, except e_1, e_N has one entry arc and one exit arc. Considering the restrictions imposed on the graph H, there will be a finite number of ways that reflect alternative processes. Searching for routes on the graph H with the number of vertices N is a combinatorial problem, the dimension of which significantly affects the complexity and duration of the algorithm's execution.

Although there are many partial cargo flows on international transport corridors, these studies consider one that must originate at a predetermined transport point q_1 and end at point q_N. The number of points that can be in the optimal way is the set $E \leq Q$. However, the cargo flow that passes along such a way is discrete, as determined by its execution schedule. This means that there is such a group of goods $K_{sum} \geq k_1$ at the initial point of departure for which k_1 is the size of the group of goods transported by the first vehicle from the initial point of the route.

If the inequality sign is fulfilled, then the shipment of goods along the searched route is, in general, periodic. This means that in the task, in addition to the route configuration, it is necessary to select the following parameters of the cargo dispatch schedule, which achieve the optimal performance of the multimodal route:

• total duration of movement of vehicles with cargo:

$$T_{\Sigma} = \sum_{i=1}^{N} \sum_{j=2}^{N} n_{c.i.j} \cdot t_{i.j}\,, \; i,j \in M_s, \tag{1}$$

• maximum possible duration of the project:

$$T_{\max} = \sum_{i=1}^{N}\sum_{j=2}^{N} t_{i.j} + \tau_{\xi.N} \cdot \left(n_{c.\xi.N} - 1\right),\ i,j,\xi \in M_x \tag{2}$$

where:
N is the total number of transport points the selected route passes through;
$n_{c.i.j}$ is the number of cycles that need to be completed in order to transport goods on the section of the route i-j;
$t_{i.j}$ is the average duration of movement on section i-j;
$\tau_{i.j}$ is the tact of the transportation process that takes place on the section
i-j is the time between the departure of another group of cargo $k_{i.j}$ from point i;
M_x is the set of vertices of the graph H that belong to the route x under consideration;
$\tau_{\xi.N}$ is the tact of the last operation in the chain of the multimodal route;
$n_{c.\xi.N}$ is the number of cycles of operation performed as the last in the chain [17].

The transportation schedule is given by the set of tact values $T=\{\tau_{1.i},\ \tau_{i.j},\ldots\ \tau_{\upsilon.i},..,\tau_{z.N}\}$ – time windows for the operation performance. Therefore, the task includes finding the optimal set T in addition to finding the shortest route. The schedule in such a transport scheme is periodic and consists of a finite number of cycles. The required number of cycles is determined from the expression:

$$n_{c.i.j} = \frac{K_{sum}}{k_{i.j}} \tag{3}$$

We calculate the cost per unit of the moved product using the expression:

$$c_k = \left(\sum_{i=1}^{N}\sum_{j=2}^{N}\left(C_{c.r} + C_{l.r} \cdot t_{i.j} \cdot n_{c.i.j} + C_{t.r} \cdot T_{\max}\right)\right) \cdot \frac{1}{K_{sum}} \tag{4}$$

where:
$C_{c.r}$ is the constant cost of transportation on one section of the route, which does not depend on the volume, distance, or time of transportation but only on the type of vehicle;
$C_{t.r}$ is a component of costs that depend on the time of transportation on this section, regardless of whether the vehicle is moving or idle (in practice, these are the so-called conditionally constant costs that depend on the time of employment of this type of transport r);
$C_{l.r}$ is the variable cost for one hour of movement when moving cargo.

Of the three parameters (1), (2), and (4), the one that best meets the quality conditions of multimodal transportation is taken as the criterion.

Since, with N>20, the problem cannot be solved by any available method, including the one outlined in [15], in an acceptable time, we proposed revising the general formulation of the problem in the given dimensionity N. To solve the problem with a complete sorting out of the options, we divide the total set of transport points—respectively, the set of vertices Q=1…N–into subsets $Q1, Q2, ... QY$, such that

$$\forall a,b = 1..Y, Q_a \cap Q_b = \varnothing. \tag{5}$$

In this case, there must be an arc $u_{i.j}$ that connects the subsets Q_a and Q_b and is the only possible arc of all those available in the graph G. Since the graph Q is connected, the arcs satisfying condition (5) must be at least one. If there is more than one such arc in the graph G, then it is possible to introduce a fictitious arc with the help of a fictitious vertex q_{0i} without a loss of generality, assuming that the arcs that come from the subset Q_a all enter the vertex q_{0i} and come out into the subset Q_b. The fictitious vertex q_{0i} is a kind of trigger between the subsets Q_a and Q_b.

Thus, the transport points are divided into consecutive subsets, which are connected by only one non-alternative connection way. This way can be any "bottleneck" of the transport network or an artificially created one. Based on the Ford-Falkerson algorithm, such a way always exists on any connected network [18]. Practically, such roads connect customs control points on the border of two countries, seaports, and transport terminals. If the set Q is divided into subsets so that the number of vertices in any of the subsets formed does not exceed the admissible dimension of the traveling salesman problem, which is solved by the method of complete search, then the problem can be solved by performing a sequential optimization search for routes in each of the subsets and then combining the found local routes into one global route. However, it is necessary to follow the condition of compatibility of partial transport cycles. Thus, the application of decomposition of the general problem is possible if the parameters of the arcs between the vertices of each subgraph Q_a are mutually independent. If these parameters are the travel time and the distance traveled along each section $u_{i.j}$ of the route, then this condition is fulfilled. However, if we take into account the intensity of the cargo flow, then the parameters of the tact τ and the size of the group k should be such that the principle of the continuity of the discrete material flow is maintained:

$$\mu = \frac{k_{1.i}}{\tau_{1.i}} = \frac{k_{i.j}}{\tau_{i.j}} = \ldots = \frac{k_{b.N}}{\tau_{b.N}} \tag{6}$$

where μ is the material flow intensity.

Since the tact and the actual size of the group of partial flows on each section of the route can be varied within the permissible limits, the intensity parameter can also be kept constant.

The material flow from vertex q_1 до q_N is direct without branching. Therefore, the material flow with the shortest duration of the process, based on the admissible optimal schedule T, can take only one route. Hence, a necessary condition for the decomposition of the graph Q into subgraphs is the constancy of the material flow intensity on each way of the route q_1–q_N.

Since the search for routes on a graph is a combinatorial problem, recursive search procedures were applied.

5. CASE STUDY

The present study was carried out on the example of the delivery of unit cargoes in the direction of Shanghai–Istanbul. Delivery volume was considered a research variable. The volume change range is K_{sum}=100...5000 units. The unit of volume measurement is a transport package. Each transport package can be delivered by a consolidated delivery with a group of other goods that need to be transported in several trips on a periodic schedule. Also, such a volume of delivery can be performed in several batches, the size of which is not larger than the entire specified volume of K_{sum}. In previous studies, we found that the total volume of delivery affects the choice of the optimal route. In this task, the conditions are complicated by the fact that the optimal route can pass through three to five countries (China, Kazakhstan, Uzbekistan, Georgia, and Turkey) or, by water, through the Indian Ocean, the Suez Canal, and the Black Sea. Air transportation is also possible. Increasing the length and complexity of the potential route configuration complicates the algorithm for its optimization. In general, the following types of transport were used: 1 – heavy-duty vehicles (over 20 tons of load capacity), 2 – medium-duty cars (7–20 tons of load capacity), 3 – railway transportation, 4 – marine dry cargo vessels, and 5 – air transportation. On a route, it is possible to name the mutual advantages and disadvantages of different types of transport, which generally lead to the desired result: availability, frequency, cost, duration, size of a one-time batch, and number of free means of transport [1]. We evaluated the efficiency of transportation using the following indicators:

$T_{\max}$ – the maximum duration of delivery of one batch of goods (there may be several batches, depending on the load capacity of the vehicle);

T_{sum} – the total time spent performing the given transportation.

The following initial data were used:

Fixed costs depending on the type of transport (all costs are in Euros) – Cn_1=76.5; Cn_2=35; Cn_3=153; Cn_4=0.8; Cn_5=200 [19].

Road costs (Euro per 1 km of transportation) – Cl_1=0.58; Cl_2=0.23; Cl_3=0.037; Cl_4=0.25; Cl_5=2.50 [19].

Time costs (Euro for one hour during which the cargo is on the way to or in the warehouse) – Ct_1=1.36; Ct_2=0.98; Ct_3=0.048; Ct_4=1.2; Ct_5=7.1 [19].

Maximum transport load capacity (in the number of transport packages on Euro pallets) – $k_{\max.1}$=10; $k_{\max.2}$=5; $k_{\max.3}$=2000; $k_{\max.4}$=11000; $k_{\max.5}$=120, where indices 1...5 mean the type of transport.

The front of vehicles is the number of vehicles that are on the route at the same time. It is accepted that there is no limit to the front for trucks, but the fronts of trains, planes, and sea cargo cannot exceed one (or, rarely, two).

The duration of the corresponding vehicle was determined using Google Maps and [20]. Maps of the network of roads and railways were obtained from Google Maps and other available maps.

Since, in practice, routes can include up to 100 transport points, choosing a route with a guaranteed minimum is not always possible. Therefore, we divided the general territory of the route into sections that are logically separated by state borders, sea ports, and other bottlenecks. In this way, three sections were obtained: Chinese, Kazakhstani, and Georgian-Turkish (Figs. 1-3).

The initial data for route search are the initial q_i and final q_j points of the way; the code of transport code r; the average duration of movement $t_{i.j.r}$, taking into account the average operational speed of this type of transport; restrictions on the maximum front $f_{\max.i.j.r}$ – that is, the number of transport units of this type which can be simultaneously involved for transportation on a given way of the route (accepted $f_{\max.1}=10$, $f_{\max.2}=10$, $f_{\max.3}=1$, $f_{\max.4}=1$, $f_{\max.5}=1$ for all routes); and minimum cycle time. Minimum cycle time – the maximum time window for dispatching the next vehicle unit, which is not limited for road transport, whereas for railway, water, and air transport, the cycle time depends on the duration of one transport cycle in the presence of one vehicle on the network connection way. The initial data is generated in separate files according to the number of sections. The numbering of transport points for each route of the network of each section corresponds to the numbering in Figs. 1-3. The starting point of each section No. 1 is a fictitious, formal beginning of the route on the section. There is such a case in which one geographical transport point can have several multiple numberings, which means that this point is a hub and there is a shipment from several types of transport. Transshipping from one type of transport to another may occur at such points. This possibility is coded in the initial data.

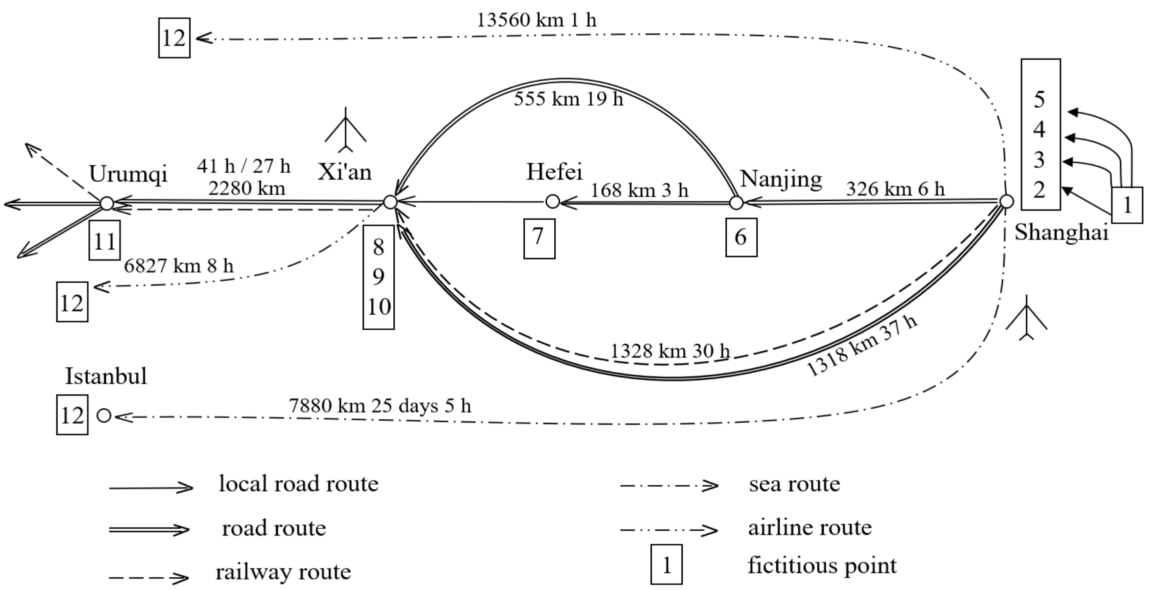

Fig. 1. Scheme of the international Shanghai–Istanbul route (Section I, China)

Using the previously compiled program and its corresponding algorithm, which contains a recursive procedure for a complete search of all the routes of the site, all possible routes for the delivery of goods that meet the given criteria and which are competitive have been found.

This resulted in six competing routes in China:

No. 1) 1 2 6 7 9 11 12 – only trucks;
No. 2) 1 2 6 9 11 12 – trucks + train;
No. 3) 1 2 9 11 12 – only trucks;
No. 4) 1 3 8 11 12 – train + trucks;
No. 5) 1 4 12 – sea ship;
No. 6) 1 5 12 – plain.

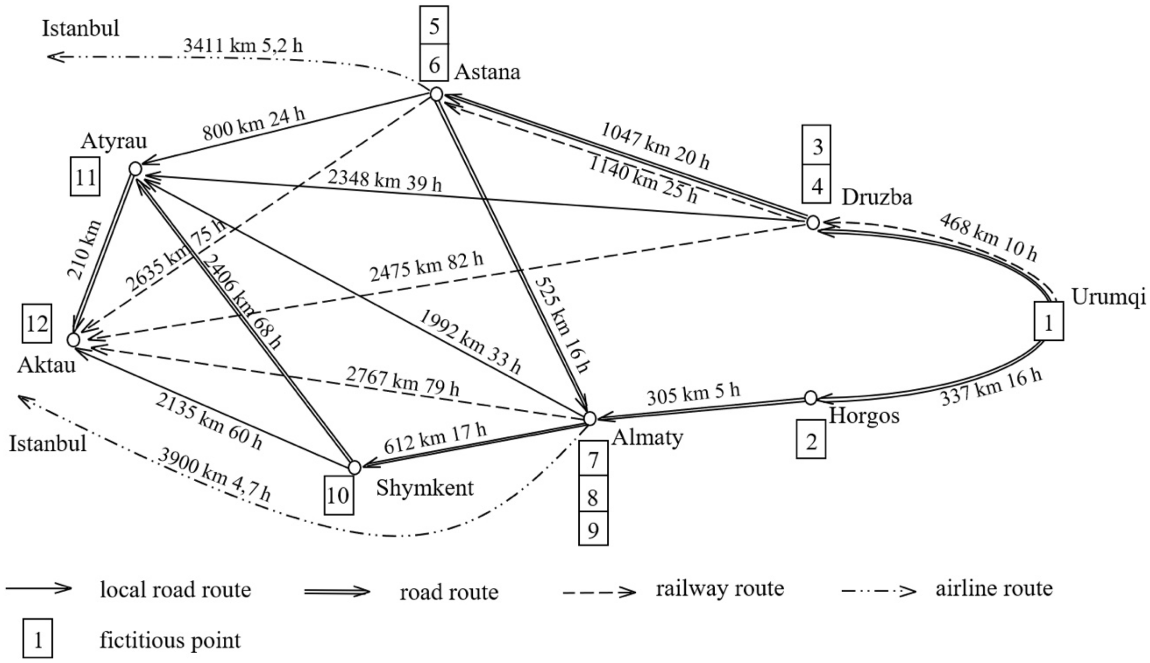

Fig. 2. Scheme of the international Shanghai–Istanbul route (Section II, Kazakhstan)

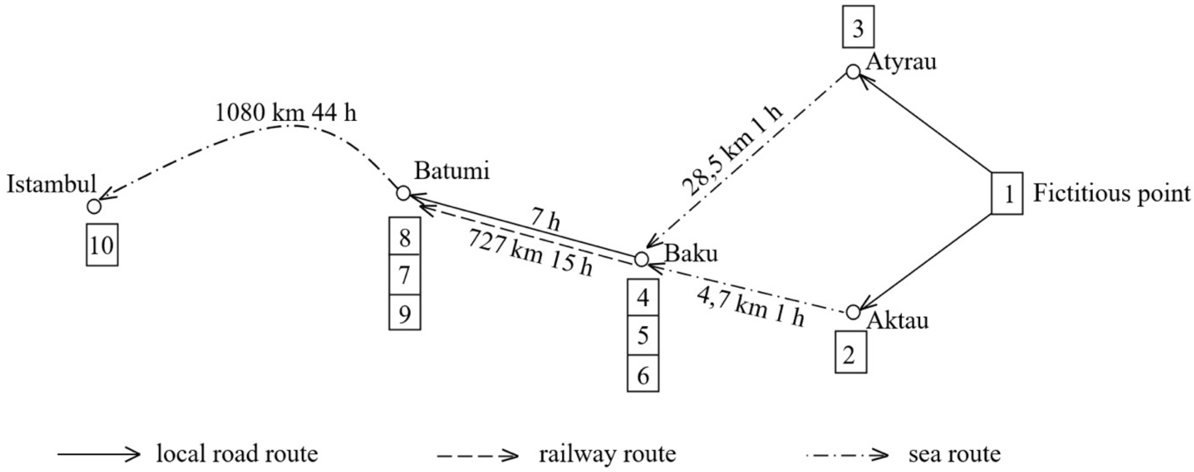

Fig. 3. Scheme of the international Shanghai–Istanbul route (Section III, Georgian-Turkish route)

It also yielded nine routes in Kazakhstan:
No. 1) 1 2 7 8 12 – trucks + train;
No. 2) 1 2 7 9 12 – train;
No. 3) 1 2 7 10 11 12 – trucks;
No. 4) 1 2 7 10 12 – trucks;
No. 5) 1 2 7 11 12 – trucks;
No. 6) 1 3 4 6 12 – train;
No. 7) 1 3 4 12 – train;
No. 8) 1 3 5 6 12 – train + trucks;
No. 9) 1 3 5 7 8 12 – train + trucks.

Finally, it generated four routes to the final destination, Istanbul, via Georgia, the Black Sea, and the Caspian Sea:
No. 1) 1 2 4 5 7 9 10 – sea ship + train + sea ship;
No. 1) 1 2 4 6 8 9 10 – sea ship + truck + sea ship;

No. 1) 1 3 4 5 7 9 10 – sea ship + train + sea ship;
No. 1) 1 3 4 6 8 9 10 – sea ship + truck + sea ship.

Some district routes are combined (road and rail), and some are mono-transport (road, sea, or air). For all routes, separate partial dependencies of the total duration, the maximum guaranteed duration, and the delivery cost of a cargo unit are constructed (a unit of cargo can be one transport standard package, one TEU, or one ton of cargo). Accepted only one transport package. The dependencies represent three separate sections of a common possible route. The optimization of routes was carried out according to the criterion of transportation cost of a unit of cargo C_n with the limitation of the maximum duration T_{max}. The guaranteed optimum was achieved in each section in particular. Route indicators depend on the size of the group of goods that are located in Shanghai and that need to be sent to Istanbul in several batches. In Figs. 4-6, the dependences of route indicators in section No. 1 are shown. Similar dependences were obtained for other sections.

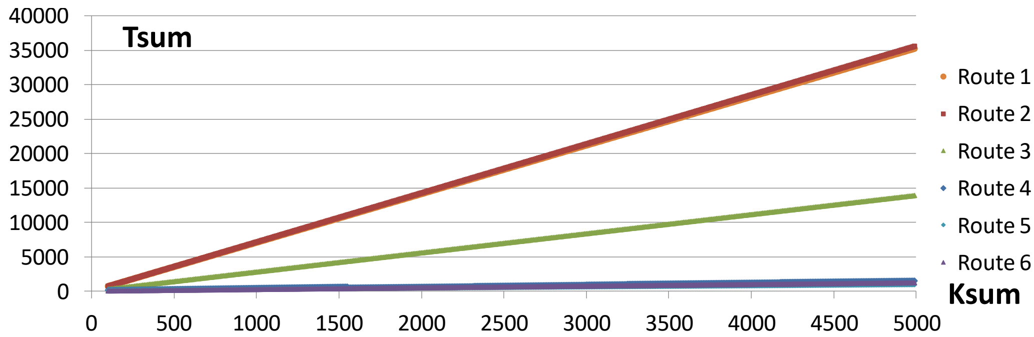

Fig. 4. Dependence of the total time spent on the delivery of the entire batch of K_{sum} cargo along the first section of the Shanghai–Urumqi route (China)

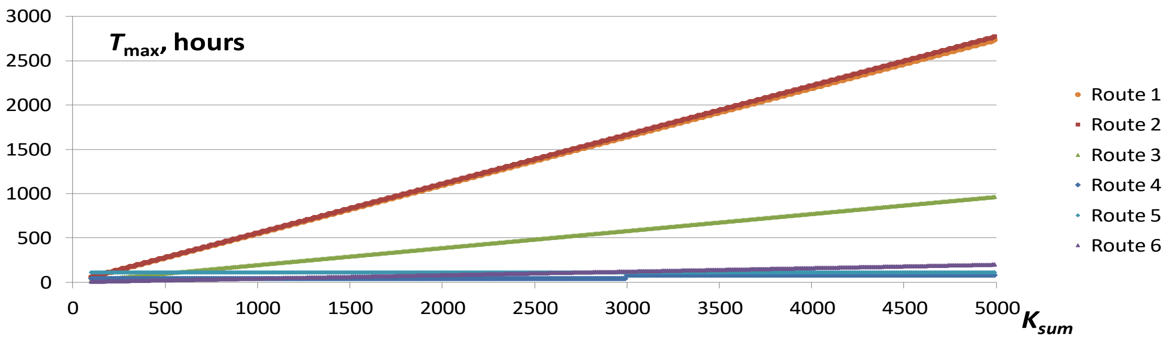

Fig. 5. Dependence of the maximum delivery duration of one package along the first section of the Shanghai–Urumqi route (China)

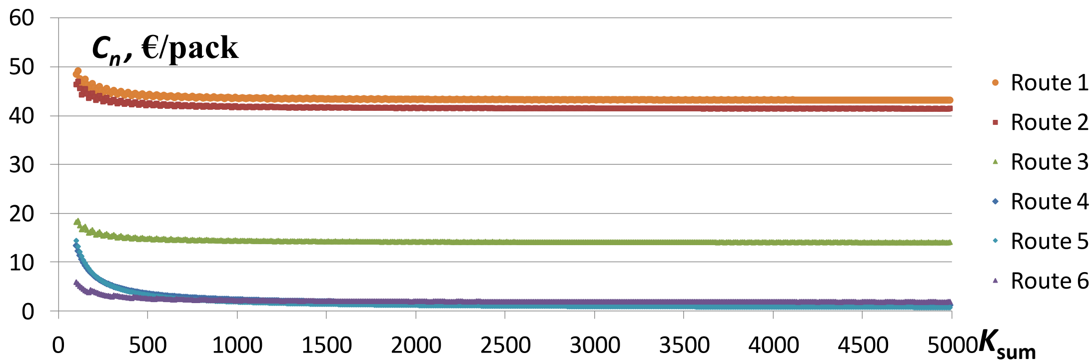

Fig. 6. Dependence of the delivery cost of one package along the first section of the Shankhai–Urumqi route (China)

The next stage of the modified algorithm is the creation of a combined global route, which consists of three sections. Expression (6)—that is, the constancy of the material flow intensity—and the selection of the best variant of the general route components (the best routes of the sections) are the conditions for the synthesis of such a route. At the same time, the global route is calculated based on the single argument K_{sum}. The corresponding algorithm consists of three steps:

1) With the given K_{sum}, check and choose the route from the first section, in which the value of the optimality criterion is the best (e.g., with $C_n \rightarrow$min). If the last non-fictitious route point q_L=q_N, then take K_{sum}:=K_{sum} +Δ K_{sum} and repeat the first step. Otherwise, go to step (2).
2) Go to the next section and choose the route with the best value of the optimality criterion for the given K_{sum}. Compare the found route with the intensity of cargo flow according to expression (6). If condition (6) is not fulfilled for this section of the route, then choose another route in this section for which the criterion value is worse. Perform the comparison according to (6). If no route of the given section fits according to expression (6), then return to the previous section and choose the next-ranking route at the given K_{sum}.
3) Combine the global route from the found sections and calculate its indicators.

Using this algorithm, three sections of the Shanghai-Istanbul route were combined, and the dependence of C_n of this global route on K_{sum} was obtained (Fig. 7). From the obtained C_n_*Sum*(K_{sum}) dependencies, it can be seen that these dependencies are inversely proportional and that they consist of separate continuous sections. Each section represents the dependence of transportation costs of one route on a given volume. Thus, the first continuous section of the dependency concerns the combined route, which has the configuration: Shankhai – Xi'an – Urumqi – Horgos (heavy-duty main cars) – Almaty – Aktau (by rail) – Baku (by sea) – Batumi (medium-duty cars) – Istanbul (by sea). C_n costs vary for this route, ranging from €64.2 to €18.3 per transport package. The maximum duration of delivery on such a route does not exceed the predetermined value of 1500 hours. Further, when the volume of transportation increases, the optimal route changes, along with the cost C_n=16.5...15.2. Such changes in cost last up to K_{sum}=600 packages, after which neither the volume of transportation nor the configuration of the route significantly affects the specific costs of delivery. However, the maximum duration of delivery by such combined routes increases significantly but does not exceed the permissible limits. Non-transshipment routes by sea on the delivery of any transportation amount by sea transport are excluded from consideration, as they exceed the permissible limits in terms of duration. Air delivery is impractical on a cost basis.

At the same time, we used the branch-and-bound algorithm to construct optimal routes under the same initial conditions without dividing the overall routing task into partial ones. The dependence of C_n on K_{sum} for such global multimodal routes is presented in Fig. 7. It can be seen from the figure that over the entire range of K_{sum}, the heuristic algorithm leads to deliberately worse results. The costs of C_n _Global are significantly higher, especially for large volumes of transportation.

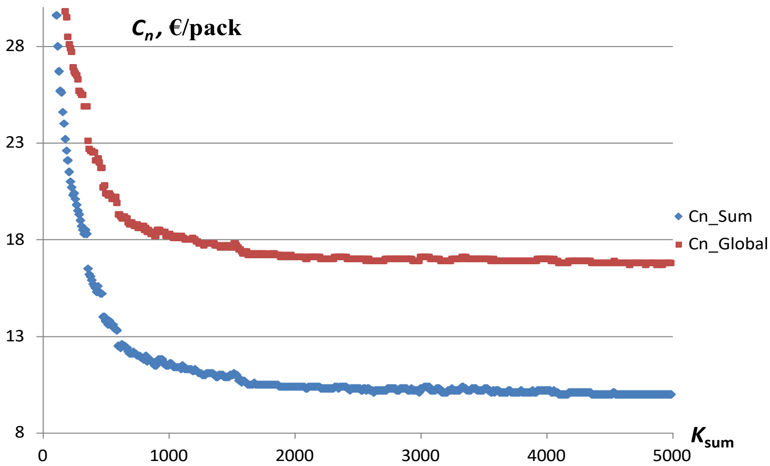

Fig. 7. Dependence of cargo delivery costs on the combined Shankhai–Istanbul routes on the volume of transportation: Cn_Sum – for the route built according to the improved algorithm with decomposition; Cn_Global – for a route that is built using a heuristic algorithm

6. CONCLUSIONS

Multimodal transnational cargo transportation is carried out within the framework of common international transport corridors but has route differences. The optimal structure of international multimodal routes connecting the same points of departure and destination of goods depends on the volume of the consignment of cargo, delivery criteria, and organizational and technological restrictions, such as the traffic schedule, cargo volume, the maximum number of available vehicles, and the maximum size of the consignments. The objective choice of the structure of the multimodal route is complicated by the presence of nodal transport points with different types of transport and different road capacities. The presence of more than 20 nodal points along the transport corridor leads to a complication of the routing problem for which, in practice, the known methods of solving it do not give an exact and guaranteed optimum in the acceptive time. At the same time, routing accuracy for long-term routes is a significant factor in the quality of planning since the absolute error in calculating the duration and cost of delivery of a cargo unit is significant. The improvement of known algorithms for the optimization of long-term international multimodal routes can be performed by decomposing the general problem without reducing the accuracy or performance of the solution. If heuristic algorithms are applied, the values of the route indicators are worse, and the errors in finding the exact optimum can be up to 3.5 times greater than those of the exact solution.

Decomposition of the general problem of routing and scheduling of multimodal transportation can be applied when considering the delivery of goods in the form of discrete material flows. In this case, it is possible to choose an appropriate conditional transport point of the transnational network, which will be its critical section and in which the condition of constancy of the intensity of the material flow will be fulfilled. Thus, the parceling of the general route into several partial routes is possible and solves the dimensionality problem of the routing problem. The practical significance of such a decision is that the accuracy of calculating the duration of delivery and costs for one transport package increases by 1.5 to 3.5 times depending on the group of goods, which allows logistics companies to reduce expected risks and gain competitive advantages. The improved technique does not depend on the length of the multimodal route, the number of involved modes of transport, or the number of transshipments.

The use of improved route optimization algorithms during their decomposition leads to improved results, as they are obtained when the options are fully sorted by the recursion procedure. Applying the algorithm for the Shanghai–Istanbul multimodal route allows savings of €6.8 to €20.4 on the delivery of one package, depending on the total volume of the delivery batch.

The structure of the optimal multimodal route, as well as its execution schedule, depends on the total volume of cargo to be transported. Such dependence is especially significant when the total volume of transportation does not exceed 600 transport packages. With larger volumes of the cargo group, the structure and indicators of the delivery cost do not change significantly. This is due to a more even distribution of fixed costs and a more stable schedule of transportation.

Further research will address the application of a wider transport network and multiple material flows along it within the framework of the South Asian Transport Corridor.

References

1. Li, X. & Xie, C. & Bao, Z. A multimodal multicommodity network equilibrium model with service capacity and bottleneck congestion for China-Europe containerized freight flows. *Transportation Research Part E: Logistics and Transportation Review.* 2022. Vol. 164. No. 102786.
2. *European Statistical System (ESS).* Available at: https://www.efta.int/statistics/european-statistical-system.
3. Kang, F. & Li, X. & Li, J. Analysis of Multi-objective Multimodal Transport Route Planning Based on Genetic Algorithm. In: *Application of Intelligent Systems in Multi-modal Information Analytics: 2021 International Conference on Multi-modal Information Analytics (MMIA 2021).* Vol. 1. Springer International Publishing. 2021. P. 30-38.

4. Song, W. Research on optimization of multimodal transport path under low-carbon background. In: *International Conference on Algorithms, Microchips and Network Applications*. SPIE. 2022. P. 626-630.
5. Oliskevych, M. & Taran, I. & Volkova, T. & Klymenko, I. Simulation of cargo delivery by road carrier: case study of the transportation company. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*. 2022. Vol. 2. P. 118-123.
6. Yao, Yu. et al. ADMM-based problem decomposition scheme for vehicle routing problem with time windows. *Transportation Research Part B: Methodological*. 2019. Vol. 129. P. 156-174.
7. Neves-Moreira, F. et al. Solving a large multi-product production-routing problem with delivery time windows. *Omega*. 2019. Vol. 86. P. 154-172.
8. Teo, H.C. & Lechner, A.M. & Walton, G.W. & Chan, F.K.S. & Cheshmehzangi, A. & Tan-Mullins, M. & Chan, H.K. & Sternberg, T. & Campos-Arceiz, A. Environmental impacts of infrastructure development under the Belt and Road Initiative. *Environments*. 2019. Vol. 6(6). No. 72.
9. Prokudin, G. & Oliskevych, M. & Chupaylenko, O. & Maidanik, K. Optimization model of freight transportation on the routes of international transport corridors. *Journal of Sustainable Development of Transport and Logistics*. 2020. Vol. 5(1). P. 66-76.
10. Boyko, N. & Muzyka, M. Analysis of Multimodal Data for Classification Problems by Using Methods of Machine Learning. In: *2021 IEEE 8th International Conference on Problems of Infocommunications, Science and Technology (PIC S&T)*. 2021. P. 525-534.
11. Bazaluk, O. & Kotenko, S. & Nitsenko, V. Entropy as an objective function of optimization multimodal transportations. *Entropy*. 2021. Vol. 23(8). No. 946.
12. Pavlenko, O. & Muzylyov, D. & Shramenko, N. & Cagáňová, D. & Ivanov, V. Mathematical Modeling as a Tool for Selecting a Rational Logistical Route in Multimodal Transport Systems. *EAI/Springer Innovations in Communication and Computing*. 2023. P. 22-37.
13. Hao, C. & Yue, Y. Optimization on combination of transport routes and modes on dynamic programming for a container multimodal transport system. *Procedia Engineering*. 2016. Vol. 137. P. 382-390.
14. Mazaraki, A. & Matsiuk, V. & Ilchenko, N. & Kavun-Moshkovska, O. & Grygorenko, T. Development of a multimodal (railroad-water) chain of grain supply by the agent-based simulation method. *Eastern-European Journal of Enterprise Technologies*. 2020. Vol. 6(3-108). P. 14-22.
15. García, J. & et al. Solving multi-modal and uni-modal transportation problems through TIMIPlan. *IFAC Proceedings Volumes*. 2012. Vol.45(24). P. 203-208.
16. Taran, I. & Olzhabayeva, R. & Oliskevych, M. & Danchuk, V. Structural optimization of multimodal routes for cargo delivery. *Archives of Transport.* 2023. Vol. 67(3). P. 49-70.
17. *A Survey on Travelling Salesman Problem.* Available at: https://micsymposium.org/mics_2010_proceedings/mics2010_submission_51.pdf.
18. Kyi, M.T. & Naing, L.L. Application of Ford-Fulkerson algorithm to maximum flow in water distribution pipeline network. *International Journal of Scientific and Research Publications.* 2018. Vol. 8(12). P. 306-310.
19. Akyüz, M.H. & Dekker, R. & Azadeh, S.S. Partial and complete replanning of an intermodal logistic system under disruptions. *Transportation Research Part E: Logistics and Transportation Review.* 2023. Vol. 169. P. 102968.
20. SEARATES by DP World. Available at: https://www.searates.com/ua/services/distances-time/.

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