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INTEGRATED OPTIMIZATION MODELS FOR CARRIER SELECTION AND ROUTE PLANNING IN MULTIMODAL TRANSPORT SYSTEMS

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Summary. This paper presents a comprehensive approach to the optimization of carrier routes and warehouses within multimodal transport systems, with a focus on a localized approach that takes into account specific regional features and constraints. The study develops an economic and mathematical model that considers both operational efficiency and cost minimization by integrating different modes of transport such as road, rail, and sea. Through a comprehensive analysis of existing literature and application of advanced optimization algorithms, the study proposes a new framework that improves the decision-making process in route planning and carrier selection. The proposed model is validated with real-world examples, demonstrating its practical applicability and potential to significantly improve the efficiency of multimodal transportation systems under different scenarios.

Keywords: multimodal transportation chain, transport systems, route optimization, carrier selection, shipping, holistic approach, modes of transport, decision-making frameworks, containers, transportation efficiency, cost minimization, logistics, optimization algorithms

1. INTRODUCTION

The dynamic landscape of multimodal transportation systems has led to numerous studies aimed at optimizing various aspects of these systems, from route planning to the integration of new technologies.

Integrated optimization models are essential for improving carrier selection and route planning in multimodal transport systems [1, 2]. These models take into account various factors, including modes of transport, delivery windows and cost-effectiveness, to ensure optimal operational efficiency. The dynamic approach to studying the impact of delivery systems on infrastructure projects highlights the need for adaptive strategies in multimodal transport [3, 4]. Integrated system solutions are crucial not only for addressing logistical issues related to human factors, but also for improving efficiency through innovative, science-based approaches [5, 6].

Technological advances play a key role in optimizing delivery systems, such as the integration of trucks and drones, which increases the efficiency of last-mile delivery [7]. Optimizing production and transportation planning with a focus on prefabricated components and time windows further demonstrates how proper planning can lead to successful deliveries [8]. Neural network-based route selection models have also proven to be effective, especially during global disruptions, improving multimodal freight transportation systems [9]. The selection of optimal routes and modes of transport under conditions of uncertainty highlights the need for mathematical models to support decision-making in logistics [10, 11].

Multimodal transport routes can be further optimized using AND/OR graphs and discrete ant colony optimization, as these methods have been shown to improve both risk management and energy efficiency [12]. Genetic algorithms are widely used for multi-objective transport route planning, providing computational advantages that improve overall system performance [13]. The optimization approach for periodic multimodal transport routes takes into account the need for regularity and reliability of logistics operations [14]. In addition, the integration of key processes in work areas into route planning is crucial to maintaining efficiency and profitability [15].

A two-stage route optimization algorithm for multimodal networks offers further insight into improving transport efficiency [16]. Structural optimization of multimodal freight delivery routes demonstrates the potential to improve freight transport operational results [17]. Methodologies focused on consolidating cargo delivery provide a basis for improving overall efficiency by optimizing the use of available resources [18]. Digital delivery safety and efficiency management systems are increasingly being implemented in multimodal transport systems, helping to optimize safety and logistics operations [19].

In maritime transport, ensuring the reliable and safe operation of technical systems is a vital aspect of multimodal transport systems, especially with the integration of energy-efficient engines [20]. The interaction between rolling stock and infrastructure must be carefully managed to ensure the smooth operation of transport systems, as shown in studies of their dynamic characteristics [21]. Leadership in transport organizations, especially with regard to preventive maintenance, plays a key role in ensuring the safe and efficient operation of transport systems [22].

The role of cybersecurity in multimodal transport, especially in maritime systems, is becoming increasingly important. Risk analysis models for maritime cybersecurity emphasize the need to create secure systems to prevent potential threats [23]. Comprehensive assessments of the maritime cybersecurity landscape also provide insight into current challenges and opportunities for improving security [24]. Education and training in multimodal transport systems is important, especially in light of advances in autonomous shipping technologies, where special programmes are needed to meet the needs of the industry [25].

Energy-efficient growth in ports plays an important role in multimodal transport systems, as shown by studies focusing on the quality of port infrastructure and superstructure [26]. Port efficiency is also affected by the quality of infrastructure, which has a direct impact on logistics costs [27]. Future opportunities for the development of port cities also demonstrate the prospects for improving multimodal transport systems [28]. Blockchain technology, which is still evolving, has the potential to increase transparency and operational efficiency in maritime transport [29].

The optimization of maritime cargo delivery continues to evolve through the use of genetic algorithms [30], which have proven effective in improving route planning and carrier selection [31]. Simulation modelling techniques and improved transport route optimization further contribute to the efficiency of multimodal transport operations [32]. The integration of real-time data and the professionalization of transport operations offer further improvements in transport system management [33, 34]. Multimodal transport systems also benefit from integrated public transport and car sharing, which demonstrates the potential for more sustainable and efficient transport systems [35]. Optimizing international multimodal routes under conditions of uncertainty adds complexity, but mathematical models provide reliable solutions for managing unpredictability in logistics operations [36].

Competition in seaports and its impact on technical efficiency is another key area, as shown in studies analyzing European container ports [37]. Operational research in road transport logistics also contributes to the development of more efficient systems by optimizing route selection and carrier performance [38]. Genetic algorithms remain the main tool for improving transport route planning [39], and their continuous improvement continues to increase the efficiency of multimodal transport networks [40]. A bibliometric analysis of maritime transport trends highlights the importance of sustainable practices in multimodal transport systems [41], and research on uncertainty theory contributes to the further improvement of route optimization models for international transport [42]. Finally, the integration of sustainability and operational research continues to drive progress in the optimization of multimodal transport systems, offering practical solutions to today's logistics challenges [43].

The idea of an integrated consideration of delivery systems was considered in the above sources, where, in particular, a model was proposed that takes into account the "economies of scale" and the formation of a synergistic effect for the organizer of delivery systems (freight forwarding company). A continuation of this approach was the work where a project-oriented approach to cargo transportation orders within the project management office provided for an integrated consideration of a set of operations related to cargo transportation to ensure an increase in the volume of work to reduce their cost for the freight forwarding company. The corresponding economic and mathematical model is aimed at maximizing the synergistic effect to reduce the cost of transportation services. It should be noted that the model focuses on the set of operations of the transport and technological process, both basic and additional.

Despite significant advances in the optimization of multimodal transport systems, existing approaches often consider individual components in isolation, resulting in suboptimal solutions that fail fully to integrate carrier selection, route planning, and synergistic economies of scale. This fragmentation limits the potential for efficiency improvement and cost reduction, especially in the face of uncertainty and complex operational constraints. Thus, the research problem is to develop an integrated optimization model that integrates these aspects into a holistic framework, improving operational efficiency and minimizing costs by accounting for interdependencies, risk management, and real-world complexities in multimodal transportation networks.

2. MATERIALS AND METHODS

The development of ideas, taking into account the additional conditions inherent in multimodal transportation and the multimodal transportation model developed for the localized approach, allows us to formulate the following economic and mathematical model.

Let us consider a multimodal transportation system within a certain period of time $\{S^1, S^2, ..., S^M\}$, each of which is characterized by the following set of characteristics:

$$S^m = \left\langle Q^m, T_m*, \Delta T_m*, g_m, h_m \in \left\{A_i, i = \overline{1,n}\right\}\right\rangle, m = \overline{1,M} \tag{1}$$

where Q^m – is the number of containers (TEU) with cargo to be transported from the point of g_m to the point h_m, these points belong to the set of points (nodes) of the transport network $A_i, i = \overline{1,n}$, $T_m*, \Delta T_m*$ – accordingly, a time limit and a possible increase in this time limit.

Let us consider $x_{ij}^{mkl^k} = \{0;1\}, m = \overline{1,M}, i = \overline{1,n}, j = \overline{1,n}, k = 1,2,3, l^k \in \Omega'^k_{ij}$ – control parameter, the essence of which is the choice for the order *m* a particular carrier *l* of a certain type of transportation *k* for transportation by communication *ij,* the choice of a particular carrier corresponds to the value $x_{ij}^{kl^k} = 1$.

It should be noted that the choice of carriers for the maritime component is not made from the set of all carriers operating in this direction of transportation (communication), but from the set of $\Omega'^k_{ij} \subset \Omega^k_{ij}$ those whose schedule meets the requirements for departure times as previously established.

The objective function meets the optimality criterion, which is proposed to use the total costs of a multimodal operator, taking into account possible risks for the entire multimodal transportation system under consideration:

$$\sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{3}\sum_{l^k\in\Omega'^k_{ij}} R_{ij}^{kl^k}(\sum_{m=1}^{M} x_{ij}^{mkl^k}\cdot Q^m)+\Delta R_{ij}^{kl^k}(\sum_{m=1}^{M} x_{ij}^{mkl^k}\cdot Q^m)\to \min \tag{2}$$

This expression (2) takes into account the entire path of the cargo system, considering all modes of transport and carriers. The objective function also takes into account the dependence of the cost of transportation $R_{ij}^{kl^k}(Q)$ for each communication and each carrier of the total amount of cargo (TEU) Q.

Considering the need to meet transportation deadlines, the following restriction takes into account the total time for each multimodal transportation:

$$\sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{3}\sum_{l^k\in\Omega'^k_{ij}} (T_{ij}^{kl^k}+\Delta T_{ij}^{kl^k})\cdot x_{ij}^{mkl^k}\le T_m*, m=\overline{1,M} \tag{3}$$

where T_m* – the maximum permissible period of multimodal transportation, which is determined by the cargo owner for each order $m=\overline{1,M}$. If the "area of compromise" approach is followed, as it was before, this limitation can be adjusted:

$$\sum_{i=g_m}^{h_m}\sum_{j=1}^{h_m}\sum_{k=1}^{3}\sum_{l^k\in\Omega'^k_{ij}} (T_{ij}^{kl^k}+\Delta T_{ij}^{kl^k})\cdot x_{ij}^{mkl^k}\le T_m*+\Delta T_m*, m=\overline{1,M} \tag{4}$$

where $\Delta T_m*, m=\overline{1,M}$ – permissible increase of the specified period of multimodal transportation according to the conditions of the cargo owner.

Next, we consider two groups of constraints that ensure the formation of a scheme in which, if necessary, the sections are sequenced for each order – multimodal transportation $m=\overline{1,M}$.

The first group of model constraints takes into account the need for cargo to "exit" each intermediate point – the nodes of the transportation network:

$$\sum_{\substack{j=1\\ j\ne h_m}}^{n}\sum_{k=1}^{3}\sum_{l^k\in\Omega'^k_{ij}} x_{ij}^{mkl^k}=\sum_{\substack{j=1\\ j\ne h_m}}^{n}\sum_{k=1}^{3}\sum_{l^k\in\Omega'^k_{ij}} x_{ji}^{mkl^k}, i=\overline{1,n}, i\ne g_m, m=\overline{1,M} \tag{5}$$

i.e. for all points that are intermediate for each multimodal transportation, the number of "inbound" and "outbound" communications is the same (whether they are selected or not).

It should be noted that this model is focused on a network of any type in terms of transport links, so the constraint expressions take into account any "detour" of transport nodes from the first (departure) to the last (destination) for each transportation.

The second group of constraints reflects the specifics of the first and last points for each order, i.e. the cargo must leave the first point and enter the last (destination):

$$\sum_{j=1}^{n}\sum_{k=1}^{3}\sum_{l^k\in\Omega'^k_{ij}} x_{g_m j}^{mkl^k} - \sum_{j=1}^{n}\sum_{k=1}^{3}\sum_{l^k\in\Omega'^k_{ij}} x_{j g_m}^{mkl^k} = 1, m=\overline{1,M} \tag{6}$$

$$\sum_{i=1}^{n}\sum_{k=1}^{3}\sum_{l^k\in\Omega'^k_{ij}} x_{i h_m}^{mkl^k} - \sum_{i=1}^{n}\sum_{k=1}^{3}\sum_{l^k\in\Omega'^k_{ij}} x_{h_m i}^{mkl^k} = 1, m=\overline{1,M} \tag{7}$$

this establishes that the number of "outgoing" and the number of "incoming" communications from and to the points of departure and destination, respectively, should be one more.

The condition of the values of the model control parameters (variables):

$$x_{ij}^{mkl^k} = \{0;1\}, m=\overline{1,M}, i=\overline{1,n}, j=\overline{1,n}, k=1,2,3, l^k\in\Omega'^k_{ij} \tag{8}$$

The expressions (2)-(8) form an economic and mathematical model for determining the optimal schemes and composition of carriers for the multimodal transportation system when they are considered in an integrated manner.

It should be noted that the proposed model considers the formation schemes for each multimodal transportation separately, but the costs, taking into account the risks of their increase, are considered in total, taking into account the dependencies $R_{ij}^{kl^k}(Q), i=\overline{1,n}, j=\overline{1,n}, k=1,2,3, l^k\in\Omega'^k_{ij}$.

Let us consider the following example with a 4-modal transportation system $\{S^1,S^2,S^3,S^4\}$ by volume Q^1,Q^2,Q^3,Q^4, $g_1=2, h_1=6; g_2=1, h_2=5; g_3=3, h_3=5; g_4=6, h_4=2$ with time limits $T^*_1, T^*_2, T^*_3, T^*_4$ and a possible increase in transportation time $\Delta T^*_1, \Delta T^*_2, \Delta T^*_3, \Delta T^*_4$, considered on the transportation network shown in Fig. 1. It should be noted that, unlike the previous example, when a single multimodal transportation was considered, the transport network assumes bilateral communications, i.e., from each point to those with which there is a transport connection, it is possible to reach in one direction and in the other, taking into account the need for experimental verification of "multidirectional" shipments within the system under consideration.

It should also be added that the presence of "return" cargo is one of the sources of synergy for a multimodal operator, as carriers are inclined to make price concessions for the opposite direction, especially when it comes to cargo in containers, where there is always an imbalance between exports and imports.

3. RESULTS AND DISCUSSION

Thus, carriers working on communication A_{12}, also work in communication A_{21}. Therefore, Table 1 shows the characteristics for only one direction of communication, given that the composition of carriers in the opposite direction is the same.

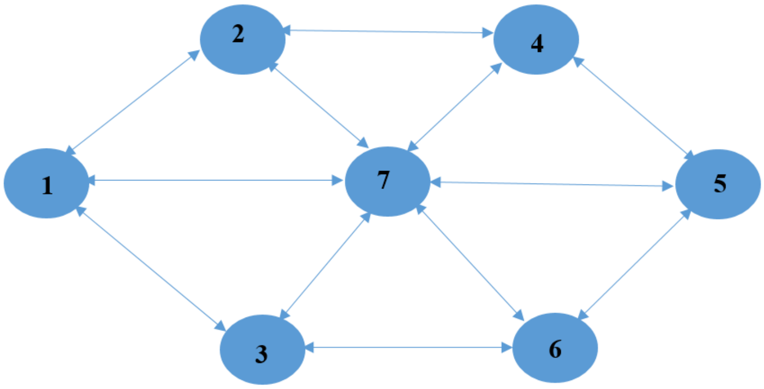

Fig. 1. Scheme of transport communications for the design example

Tab. 1

Possible alternatives for transport communications

Communication	Type of transportation	Transportation companies
A_{12}	k=1,2	l^1=1,2 l^2=1
A_{13}	k=1	l^1=1,2
A_{17}	k=3	l^3=1,2
A_{27}	k=3	l^3=1,2
A_{24}	k=3	l^3=1,2,3
A_{37}	k=3	l^3=1,2
A_{36}	k=3	l^3=1,2
A_{47}	k=3	l^3=1,2
A_{45}	k=3	l^3=1,2
A_{65}	k=3	l^3=1,2
A_{67}	k=3	l^3=1,2
A_{75}	k=3	l^3=1,2

The characteristics of transportation for alternative carriers by different modes of transport are shown in Tables 2 and 3. It should be noted that in this case, transportation costs and risks are taken as dependencies on the volume of the container batch (TEU). We assume risks as a percentage of the transportation cost. Also, for this example, it is assumed that the costs in the opposite direction are the same, but in practice, as a rule, transportation rates in the import/export directions differ. This assumption does not affect the experimental validation of the model, as it only reduces the amount of input data.

Tab. 2

The characteristics of transportation costs for alternative carriers by different modes of transport

Communication	Type of transportation	Transportation companies	$R_{ij}^{kl^k}$, m.u.	$\Delta R_{ij}^{kl^k}$, %
	k=1	l^1=1	$R = 1008 \cdot x^{-0,028}$	10

A_{12}, A_{21}		l^1=2	$R = 1230 \cdot x^{-0,11}$	5
	k=2	l^2=1	$R = 805 \cdot x^{-0,027}$	7
A_{13}, A_{31}	k=1	l^1=1	$R = 908 \cdot x^{-0,022}$	10
		l^1=2	$R = 950 \cdot x^{-0,1}$	3
A_{17}, A_{71}	k=3	l^3=1	$R = 1200 \cdot x^{-0,02}$	7
		l^3=2	$R = 1240 \cdot x^{-0,021}$	7
A_{27}, A_{72}	k=3	l^3=1	$R = 1400 \cdot x^{-0,023}$	10
		l^3=2	$R = 1530 \cdot x^{-0,028}$	12
A_{24}, A_{42}	k=3	l^3=1	$R = 2400 \cdot x^{-0,02}$	10
		l^3=2	$R = 2500 \cdot x^{-0,02}$	8
		l^3=3	$R = 2580 \cdot x^{-0,022}$	5
A_{37}, A_{73}	k=3	l^3=1	$R = 1805 \cdot x^{-0,027}$	7
		l^3=2	$R = 1900 \cdot x^{-0,02}$	5
A_{36}, A_{63}	k=3	l^3=1	$R = 1008 \cdot x^{-0,028}$	5
		l^3=2	$R = 1230 \cdot x^{-0,11}$	10
A_{47}, A_{74}	k=3	l^3=1	$R = 1905 \cdot x^{-0,022}$	8
		l^3=2	$R = 1950 \cdot x^{-0,1}$	5
A_{45}, A_{54}	k=3	l^3=1	$R = 750 \cdot x^{-0,026}$	7
		l^3=2	$R = 1250 \cdot x^{-0,02}$	5
A_{65}, A_{56}	k=3	l^3=1	$R = 1430 \cdot x^{-0,11}$	5
		l^3=2	$R = 1505 \cdot x^{-0,027}$	3
A_{67}, A_{76}	k=3	l^3=1	$R = 980 \cdot x^{-0,022}$	3
		l^3=2	$R = 1000 \cdot x^{-0,022}$	10
A_{75}, A_{57}	k=3	l^3=1	$R = 1280 \cdot x^{-0,11}$	8
		l^3=2	$R = 850 \cdot x^{-0,027}$	5

Tab. 3

The characteristics of transportation time and its possible deviation for alternative carriers by different types of transport

Communication	Type of transportation	Transportation companies	$T_{ij}^{kl^k}$, days	$\Delta T_{ij}^{kl^k}$, days
A_{12}, A_{21}	k=1	l^1=1	5	0,5
		l^1=2	5	0,5
	k=2	l^2=1	8	1
	k=1	l^1=1	5	0,5

A_{13}, A_{31}		l^1=2	5	1
A_{17}, A_{71}	k=3	l^3=1	20	0,5
		l^3=2	22	1
A_{27}, A_{72}	k=3	l^3=1	18	1
		l^3=2	17	1
A_{24}, A_{42}	k=3	l^3=1	18	2
		l^3=2	16	1
		l^3=3	16	0,5
A_{37}, A_{73}	k=3	l^3=1	17	1
		l^3=2	20	1
A_{36}, A_{63}	k=3	l^3=1	10	1
		l^3=2	11	2
A_{47}, A_{74}	k=3	l^3=1	18	1
		l^3=2	17	1
A_{45}, A_{54}	k=3	l^3=1	18	2
		l^3=2	16	1
A_{65}, A_{56}	k=3	l^3=1	17	1
		l^3=2	20	1,5
A_{67}, A_{76}	k=3	l^3=1	10	1
		l^3=2	11	1
A_{75}, A_{57}	k=3	l^3=1	10	1
		l^3=2	11	0,5

The initial data on the volume of batches of transportation orders and time constraints are as follows:

$Q^1 = 3, Q^2 = 2, Q^3 = 3, Q^4 = 4$ (TEU),

$T*_1 = 34, T*_2 = 34, T*_3 = 34, T_4 = 34$ (days),

$\Delta T_1* = 2, \Delta T_2* = 2, \Delta T_3* = 3, \Delta T_4* = 3$ (days).

A graphical representation of certain cost dependencies on the volume of transportation (number of containers) is shown in Fig. 2. It should be noted that, in practice, the dependencies do not have such a "perfect" form; however, this does not affect the reliability of the results, as the primary objective is to identify a correlation between cost and the number of containers.

It should be noted that, based on the initial data on the transport network and alternative carriers, the model provides 200 control parameters (variables) that reflect alternatives for transportation on separate communications in both directions. For the given initial data, the first stage of the study obtained the following optimal schemes and composition of carriers (Fig. 3-5).

The time of multimodal transportation was respectively: $T_1 = 31, T_2 = 34{,}5, T_3 = 29{,}5, T_4 = 31$ (days).

Further, the conditions for time limits have been changed, taking into account $T*_1 = 32, T*_2 = 32, T*_3 = 32, T_4 = 32$ (days).

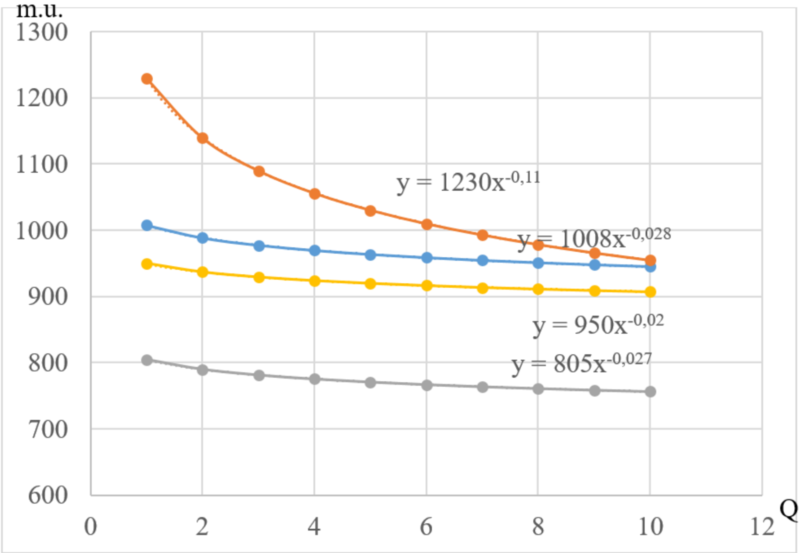

Fig. 2. Graphical interpretation of certain dependencies of transportation costs on the volume of the container batch

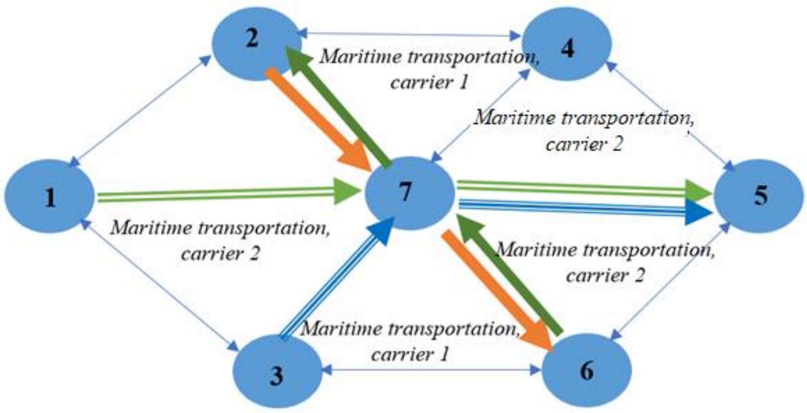

Fig. 3. Optimal schemes and composition of carriers for the baseline scenario

Reducing the allowable time for multimodal transportation led to changes in carriers on certain sections of the schemes (Figures 4-6), and, as a result, to an increase in the value of the objective function from 7066 to 8446 m.u. (monetary units, i.e., total costs). But this ensured that the transportation time conditions were met. For the given time conditions, the schemes, and composition of carriers provide: (days).

In this case, the time for the third order increases, but for the second order, the transportation time decreases from 34.5 days to 32 days. Thus, the multimodal operator can offer the shipper of the second order to accept the transportation time of 34.5 days, but at a lower cost, given that the total costs for the first option are significantly lower.

Thus, the average cost of multimodal transportation of one container with cargo under the first option is 7066/12=588.83 m.u., under the second option 8446/12=703.85 m.u. (12 TEU – the total number of containers with cargo in 4 orders), so the operator has the economic opportunity to offer a reduction in the cost of multimodal transportation for the customer if he agrees with the proposed transportation time.

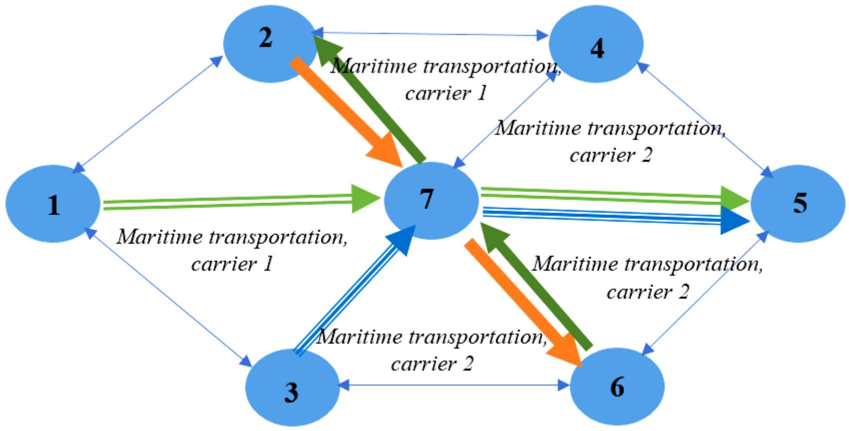

Fig. 4. Optimal schemes and composition of carriers to reduce the acceptable time of multimodal transportation

Further, in the course of the experimental study, a situation was assumed when one of the nodes – in this case, the "hub" – node 7 – was not operational; the current state of multimodal transportation demonstrates the practical possibility of such situations. This causes a change in the optimal schemes, as shown in Fig. 5, where Fig. 6 depicts the implementation of this optimization.

Further, for the given conditions, we considered different options for the volume of container batches for each order – one unit more and one unit less than for the initial option, i.e., the total number of 8, 12 and 16 TEU. Increasing the batch size logically led to a decrease in the average cost of transportation of one container in monetary units (m.u.), (Fig. 6).

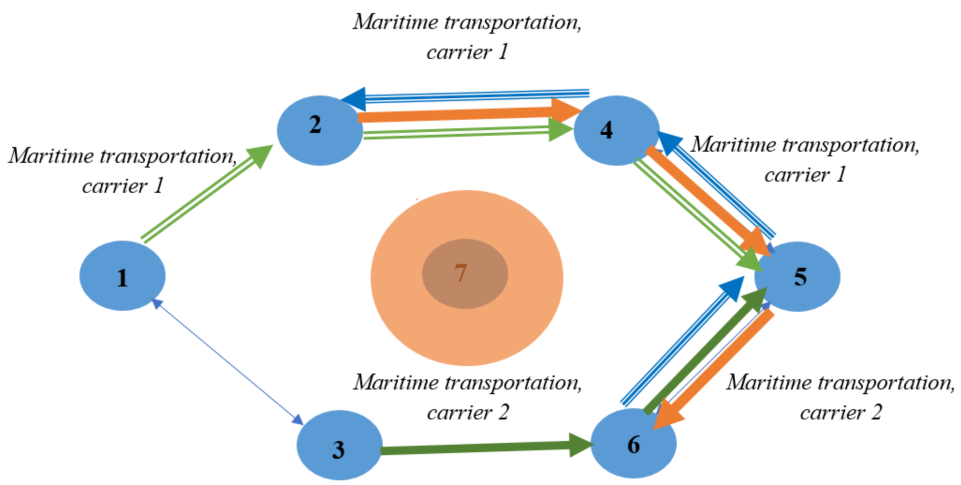

Fig. 5. Optimal schemes and composition of carriers when node 7 is excluded

Thus, experimental calculations have demonstrated how the proposed model is used as a tool for implementing the agile approach within the trade-off domain. Changes in the initial data are reflected in the change in the optimal values of the control parameters and the value of the objective function, which substantiates the reliability of the proposed models.

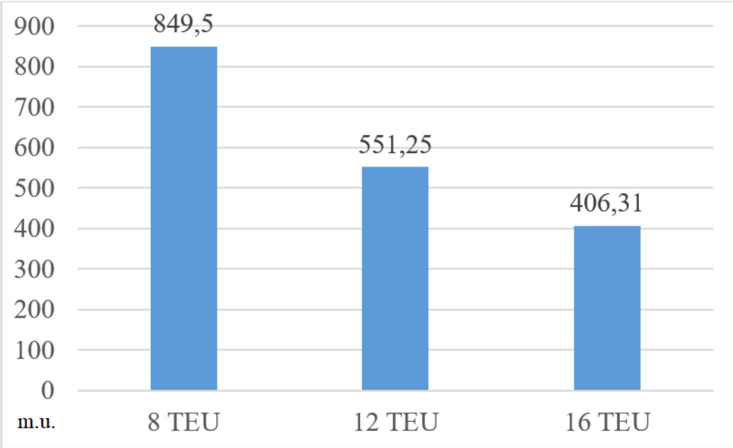

Fig. 6. Changes in the average cost of multimodal transportation per TEU for different total order volumes, m.u.

The special attention should be paid to the formation of a synergistic effect, based on the economies of scale that are formed when increasing the number of containers passing through the same communications using certain carriers, including in the opposite direction. Experimental studies have demonstrated the formation of this effect and its corresponding reflection in the optimization results.

Earlier, the mathematical expression for the synergistic effect was given in a general, more conceptual form. Taking into account the results obtained in this section, the expression for the synergistic effect can be presented as follows:

$$E_s = \sum_{m=1}^{M}\left(\sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{3}\sum_{l^k\in\Omega'^k_{ij}} R_{ij}^{kl^k}(x_{ij}^{mkl^k}\cdot Q^m) + \Delta R_{ij}^{kl^k}(x_{ij}^{mkl^k}\cdot Q^m)\right) - \sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{3}\sum_{l^k\in\Omega'^k_{ij}} R_{ij}^{kl^k}(\sum_{m=1}^{M} x_{ij}^{mkl^k}\cdot Q^m) + \Delta R_{ij}^{kl^k}(\sum_{m=1}^{M} x_{ij}^{mkl^k}\cdot Q^m) \quad (9)$$

where

$$\sum_{m=1}^{M}\left(\sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{3}\sum_{l^k\in\Omega'^k_{ij}} R_{ij}^{kl^k}(x_{ij}^{mkl^k}\cdot Q^m) + \Delta R_{ij}^{kl^k}(x_{ij}^{mkl^k}\cdot Q^m)\right) \quad (10)$$

– are the total costs for a multimodal transportation system without taking into account the possibilities of their integration, i.e.

$$\sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{3}\sum_{l^k\in\Omega'^k_{ij}} R_{ij}^{kl^k}(x_{ij}^{mkl^k}\cdot Q^m) + \Delta R_{ij}^{kl^k}(x_{ij}^{mkl^k}\cdot Q^m), m=\overline{1,M} \quad (11)$$

characterizes the costs of each individual multimodal transportation when considered locally.

It should be noted that the synergistic effect proposed in [7] was considered as an optimization criterion, and its maximization ensured the maximum profit of the freight forwarding company. In our opinion, the use of such a criterion is interesting from the point of view of the theoretical solution of the problem under consideration, but complicates the task in practical implementation. Since it is necessary to find and evaluate the optimal schemes and composition of carriers for each multimodal transportation (local level)). Despite the fact that modern information technology allows this to be done quickly, there is a question of whether it is feasible in practice. However, if such a need arises, the results presented in this section allow us to do so.

Thus, a model has been developed to determine the schemes (routes) and the composition of carriers for the multimodal transportation system of a multimodal operator. Varying the chains of the corresponding system – intermediate points, modes of transport and carriers – causes variation in the main characteristics of each multimodal transportation, as well as the total costs of the operator in the implementation of these transportations. The model takes into account the possibility of reloading vehicles, the use of a tariff system based on the dependence of the cost of transportation and the performance of individual transportation operations on the volume of the consignment (number of containers with cargo). This results in a synergistic effect that improves the efficiency of multimodal transportation for both the multimodal operator and cargo owners, providing them with a wider range of options in the area of compromise.

4. CONCLUSION

The model proposed in this article belongs to the class of nonlinear models (the objective function takes into account the nonlinear dependence of costs on the number of containers) and is based on the existing model of integral optimization of containerized cargo deliveries, but the development of this result is to take into account the specifics of multimodal transportation from the point of view of the operator. The model considers the operator's risks for each alternative option in the system, as well as its reliability. The synergistic effect that is formed when considering the multimodal transportation system in an integrated manner is formalized, based on the economies of scale that are formed when increasing the number of containers that pass through the same communications using certain carriers, including in the opposite direction. Relevant experimental studies have been carried out to substantiate the reliability of the optimization results based on the proposed model.

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