ЗБІЛЬШЕННЯ ЕФФЕКТИВНОСТІ МУЛЬТИМОДАЛЬНИХ ПЕРЕВЕЗЕНЬ ЗА АЛЬТЕРНАТИВНОГО ВИКОРИСТАННЯ РІЗНИХ ВИДІВ ТРАНСПОРТУ

Актуальність. Актуальність проведеного дослідження обумовлюється тим, що в Україні зростають обсяги перевезення вантажів за використання мультимодальних технологій. Тому збільшення ефективності мультимодальних перевезень з застосуванням новітніх методів їх оптимізації є на часі. Особливою мірою це стосується тих видів транспорту, частка яких в загальному вантажообігу є відносно невеликою.

Мета та завдання. Основною метою дослідження є розвиток теоретико-прикладних положень та алгоритмів пошуку оптимального рішення за декількома цільовими функціями з різною шкалою вимірювання для збільшення ефективності мультимодальних перевезень, зокрема, за альтернативного використання різних видів транспорту. Для досягнення цієї мети поставлена наступна задача: дослідження впливу монополізації ринку перевезень окремими видами транспорту на надійність та ефективність перевезень; вирішення задачі оптимізації вантажних перевезень з загальнодержавної чи загальногалузевої точки зору; дослідження значення розвитку внутрішнього водного транспорту для збільшення ефективності та надійності мультимодальних перевезень; створення алгоритму пошуку оптимального рішення за декількома цільовими функціями.

Результати. Досліджено теоретико-прикладні положення пошуку оптимального рішення за декількома цільовими функціями з різною шкалою вимірювання для збільшення ефективності мультимодальних перевезень, у тому числі, за альтернативного використання різних видів транспорту. Проведеним дослідженням доведено, що вибір тільки однієї з традиційних цільових функцій транспортних компаній – собівартості чи часу перевезення не гарантує його ефективності без оцінки ризиків транспортування вантажів. Запропоновано алгоритм вибору оптимального рішення за декількома цільовими функціями. Для цього використано метод пошуку екстремуму кожного з них за власною нетривіальним підмножиною. Доведено, що ці множини, в загальному випадку, не є тотожними тому для знаходження рішення за декількома цільовими функціями, ускладненого їх різною розмірністю врахування ризиків транспортування вантажів. Запропоновані алгоритми оптимізації вантажних перевезень з загальнодержавної чи загальногалузевої точки зору, у тому числі, за альтернативного використання різних видів транспорту.

Висновки. Аналіз результатів проведеної дослідження дозволяє зробити наступні висновки: для використання ресурсу підвищення ефективності та надійності транспортування вантажів, особливо за мультимодальних технологій перевезення, треба вирішувати диспропорції вантажообороту за видами транспортування вантажів, відчільно, за мультимодальних технологій перевезення треба вирішувати диспропорції вантажообороту за видами транспортування вантажів з урахуванням ризиків транспортування вантажів. Існує численне різання рішення за декількома цільовими функціями. Впровадження цього алгоритму дозволить збільшити ефективність транспортування вантажів за альтернативного використання різних видів транспорту.
INCREASING THE EFFICIENCY OF MULTIMODAL TRANSPORTATION WITH ALTERNATIVE USE OF DIFFERENT TYPES OF TRANSPORT

Topicality. The urgency of the study is due to the fact that in Ukraine the volume of cargo transportation using multimodal technologies is growing. Therefore, increasing the efficiency of multimodal transportation using the latest methods of their optimization is timely. This is especially true for those modes of transport whose share in total freight turnover is relatively small.

Aim and tasks. The main purpose of the study is to develop theoretical and applied provisions and algorithms for finding the optimal solution for several target functions with different measurement scales to increase the efficiency of multimodal transportation, in particular, with the alternative use of different modes of transport. To achieve this goal, the following tasks arose: to study the impact of the monopolization of the transportation market by certain modes of transport on the reliability and efficiency of transportation; solving the problem of optimization of freight transportation from the national or general industry point of view; study of the importance of the development of inland water transport to increase the efficiency and reliability of multimodal transport; creating an algorithm for finding the optimal solution for several target functions.

Research results. Theoretical and applied positions of search of the optimum decision on several target functions with different scale of measurement for increase of efficiency of multimodal transportations, including, at alternative use of different types of transport are investigated. The study proved that the choice of only one of the traditional target functions of transport companies - the cost or time of transportation does not guarantee its effectiveness without assessing the risks of transportation of goods. An algorithm for selecting the optimal solution for several objective functions is proposed. To do this, we used the method of finding the extremum of each of them by its own nontrivial subset. It is proved that these sets, in the general case, are not identical, so to find a solution for several objective functions complicated by their different dimensions, the principle of compromise must be used. The study established a significant degree of monopolization of the transportation market by certain modes of transport and indicated that to solve the problem of optimization of freight transportation from the national or general industry point of view requires equalization of disparities in freight turnover by mode of transport.

Conclusion. Analysis of the results of the study allows us to draw the following conclusions: to use the resource to increase the efficiency and reliability of cargo transportation, especially for multimodal transportation technologies, it is necessary to equalize the disproportions of cargo turnover by types of cargo transportation to avoid monopolization of the transport market. To increase the efficiency of transportation, the latest algorithm for selecting the optimal solution for several target functions is proposed. The introduction of this algorithm to optimize multimodal transportation in scientific and practical problems will allow to take into account the risks and find a compromise solution in complex problems of finding solutions for the transportation of goods.
Key words: multimodal cargo transportation, information and communication technologies, types of transport, algorithm.

Problem statement and its connection with important scientific and practical tasks. Improving the efficiency of multimodal transportation (MMT) is not only a sign of increasing the efficiency of cargo turnover or, more broadly, the transport industry. This is a sign of the ability to renew, to acquire a modern technological level of the entire economy of Ukraine. A universal tool to increase the efficiency of traditional sectors of the economy is the introduction of information and communication technologies (ICT). They create a broad platform for communication between market participants and are accompanied by institutional changes. In the transport industry, ICT allows the introduction of new services, new logistics business models. ICT end-to-end document management has in fact served as a trigger for the formation of the MMT, which promotes Ukraine's integration into the international transport space. The efficiency of transportation at each stage of the MMT, regardless of the chosen target function: cost, time, reliability and safety of goods depends on the risks of transportation. Since multimodal transportation is performed using different modes of transport, the task is to increase the efficiency of MMT, in particular, with the alternative use of different modes of transport.

Analysis of recent publications on the problem. A significant body of scientific works of domestic and foreign scientists is devoted to the problems of increasing the efficiency of multimodal transport. Most researchers attribute the increase in transportation efficiency to a decrease in the degree of risk, other things being equal. Thus, Ciesla M. [1] used the method of risk map analysis. Identifying the most significant risks and finding those elements that are affected by these risks, from the point of view of Ciesla M. [1], minimizes the threat. But this method does not allow to take into account the threats identified during transportation and the impact of threats whose weight varies at significant intervals. Tsung-Yu Chou [2] MMT risks due to the break-even point of forwarding activities. It is interesting to use his methods of fuzzy decision-making in multicriteria problems. But using this approach to the specifics of the MMT for Taiwan, the author analyzed only the risks of partnership, operational and warehousing risks. The article by Hryhorak M. [3] is devoted to the analysis of the so-called ecosystem approach to increase the efficiency of the MMT for the introduction of an integrated multimodal service which is to strengthen the vertical and horizontal ties of transport participants and strengthen the information component at all stages. There are other approaches. Thus Ngavichaikit A. [4] used elements of competence (EOC) and functional analysis, Xiong G. [5] applied genetic algorithms, Fang X. [6] used a slightly eclectic synergistic approach of four components: innovation, management, business operations and information components. Xiaoping Fang X. [7] proposed an indicative approach and factor analysis. The relevance of the methods used is questionable. Harris I. [8] points out, in his view, the slowdown in the efficiency of information and communication technologies (ICT) and insists on the removal of barriers to MMT and the introduction of an integrated transport network. It comes to this in his analysis and Agamez-Arias A. [8]. Boschian V. [9] insists on metamodelling - the use of a reference model and sets of simulation models. Verduzco-Garza T. [10] analyzing different approaches prefers a hybrid model of nonlinear mixed programming based on the Lagrange method and evolutionary algorithms.

Allocation of previously unsolved parts of the general problem. Analysis of a wide range of scientific papers shows a thorough study of the problem of efficiency of multimodal transport. But the same analysis, on the one hand, indicates the lack of relevant mathematical models for finding the optimal solution for MMT for several target functions, on the other hand, the lack of analysis of the use of different modes of transport at different stages of MMT to reduce risk and thus increase transportation efficiency. The problem of optimization of freight traffic is considered in the general case as a problem of finding the optimum of the objective function. Under the target function is understood the purpose of the service of transportation of goods, either from the point of view of its provider or from the point of view of its consumer. This can be, for example, minimizing the cost (or cost) of transportation; transportation time; guaranteeing maximum safety, reliability of transportation and storage of cargo; minimization of threats and risks of transportation, etc. But the problem of optimizing freight traffic can be considered from a national or industry-wide point of view. Then the target function should be understood, for example, the equalization of disparities in cargo turnover by mode of transportation in Ukraine and the EU; entry of seaports of Ukraine in the TOP-100 ports of the world that specialize in container or multimodal cargo transportation; growth of volumes of transit of containers through the transport system of Ukraine to a certain value in due time; increasing the degree of containerization of cargo transportation to a certain value within a certain period; growth of the index of logistics efficiency of transportsations to a certain value in the world rating; strengthening Ukraine's position among the transit countries of the Black Sea-Azov region, etc. In this case, a
The share of modes of transport in national freight transport (%)

<table>
<thead>
<tr>
<th>Years</th>
<th>Railway</th>
<th>Marine</th>
<th>IWT</th>
<th>Automobile</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014</td>
<td>23.79579</td>
<td>0.172815</td>
<td>0.193729</td>
<td>69.69226</td>
</tr>
<tr>
<td>2015</td>
<td>23.73898</td>
<td>0.223258</td>
<td>0.214027</td>
<td>69.22416</td>
</tr>
<tr>
<td>2016</td>
<td>22.26365</td>
<td>0.196587</td>
<td>0.236086</td>
<td>70.37996</td>
</tr>
<tr>
<td>2017</td>
<td>21.46323</td>
<td>0.14242</td>
<td>0.230102</td>
<td>70.90178</td>
</tr>
<tr>
<td>2018</td>
<td>19.61935</td>
<td>0.115157</td>
<td>0.225079</td>
<td>73.37464</td>
</tr>
<tr>
<td>2019</td>
<td>19.82071</td>
<td>0.134294</td>
<td>0.252729</td>
<td>72.65105</td>
</tr>
<tr>
<td>2020</td>
<td>20.36241</td>
<td>0.123478</td>
<td>0.232234</td>
<td>70.16145</td>
</tr>
</tbody>
</table>

Source: Compiled by the authors based on [11] and other sources

This creates a situation when defending their narrow corporate interests modes of transport-monopolists limit the activities of other modes of transport. There are cases, for example, when Ukrzaliznytsia restricted the supply of rolling stock to seaports during the period of the largest export deliveries of grain. This not only caused direct damage to sea carriers but also undermined their reputation as reliable partners in the MMT at the international level. Restrictions on the development of water transport and, in particular, IWT, thus, may lead to the creation of certain additional risks of MMT. Today, the cost of transporting IWT is slightly higher than rail transport. But, as the study showed, the analysis of the interval of change in the degree of risk allows us to assert the prospects for the development of IWT not only from a national point of view, but also from the point of view of transport and logistics companies. That is why (see Table 1) for the period 2017-2019 the share of IWT in the national volume of traffic increased.

**Formulation of research objectives (problem statement).** This allows us to formulate the purpose of the study - the development of theoretical and applied provisions and algorithms for finding the optimal solution for several target functions with different measurement scales to increase the efficiency of multimodal transport, in particular, the alternative use of different modes of transport. The task of the research is to develop theoretical and methodological principles and practical recommendations for finding the best alternatives to routes and individual stages of MMT routes and to justify the use of other modes of transport to reduce transportation risks and increase their efficiency.

**An outline of the main results and their justification.** Analysis of the above objective functions proves that some of them do not contradict each other, moreover, in some cases they are derived from each other. Each of these target functions depends on a continuum of elements of transportation to which by decomposition it is possible to reduce process of transportation of freights. Of course, not all of these continua are identical for each of the objective functions. Similar problems were solved by Ballester E. [12], Carosi L. [13] and Salas-Molina F. [14]. Then the general continuum of elements of transportation should be considered as space which should include all subspaces of elements of transportation of each of target functions. In this case, subspaces may have common elements or not have a certain part of common elements:

\[ \theta \ni \theta_1, \theta_2, \theta_3, \ldots, \theta_n(1) \]

where \( \theta \) - the general continuum of elements of transportation; \( \theta_1, \theta_2, \theta_3, \ldots, \theta_n \) - subspaces of transportation elements of each set \( l, 2, 3 \ldots n \) target functions; \( n \) – total number of target functions.

That is, \( \theta \) is a superset, a \( \theta_1, \theta_2, \theta_3, \ldots, \theta_n \) - are subsets. Feature of the superset \( \theta \) and subsets \( \theta_1, \theta_2, \theta_3, \ldots, \theta_n \) is that they do not contain empty sets.

Then:

\[ \theta_1, \theta_2, \theta_3, \ldots, \theta_n \in \theta; \]

\[ \theta_1, \theta_2, \theta_3, \ldots, \theta_n \neq \emptyset; (2) \]
\[ \theta_1, \theta_2, \theta_3, \ldots, \theta_n \cup \theta \]

This means that each set of selection \( (1, 2, 3, \ldots, n) \) is a proper or non-trivial subset. In that case:

\[ \theta - \theta_1 - \theta_2 - \theta_3 \ldots - \theta_n = \emptyset (3) \]

The problem of choosing the optimal solution for several objective functions is that the extremum of each of them is chosen by its own non-trivial subset. And these sets, in the general case, are not identical. For example, you can minimize transportation time but this will not minimize the cost of transportation. The following approaches to solving this problem are possible. The first can be used according to the following algorithm:

1. Find the optimal values of each of the objective functions for its own non-trivial subset.
2. By expert evaluation or by implementing the approach of game theory - a game with a non-zero sum, we determine which of the compromise solutions will be the best.

But this approach can be implemented for simple problems with a small number of variables.

The second approach can be implemented using binary ratio optimization. That is, the decomposition of the problem and the subsequent iterative pairwise comparison of alternative solutions. It is performed according to the following algorithm. Denote by \( F^r, F^c, F^r_c \) values of objective functions, respectively, extreme in time \( t \), extreme at cost \( c \), and strictly extreme at cost \( c \). The general continuum of elements of transportation \( \theta \). Denote by \( F^r, F^c, F^r_c \) the values of the objective functions, respectively, as close as possible to the time extremum \( t \), as close as possible to the extreme in cost and strictly as close as possible to the extreme in terms of cost on the general continuum of elements of transportation \( \theta \). Let on the general continuum of elements of transportation \( \theta \) the ratio of preference is set \( t \). That is, it induces two selection functions on the matrix of elements \( X \subset B_1 \):}

\[ F^r(X) = \{ x \in X | \forall y \in X [x R y] \} (4) \]

\[ F^c(X) = \{ x \in X | \forall y \in X [x R y] \} (5) \]

In this case, the selection functions are formulated \( F^r(X) \) – dominance and \( F^c(X) \) – locking. These two functions define two principles of choice for finding a compromise solution using the pairwise comparison approach. Selection function \( F^r \) – dominance means that the value of the parameter \( x \) should not be selected as the base when such a parameter exists \( y \), which is more desirable than \( x \) \( (y R x) \) and should be chosen if alternatives \( y \) do not exist \( (y R x) \). For practical implementation of the algorithm of binary relations \( (R) \) we use approaches: problems on a matrix and problems on a graph. The problem of relations on the matrix is as follows. Let be a common continuum \( \theta \) includes \( n \) elements \( b \). We form a matrix \( n \times m \), which is defined as \( B(R) = (b_{ij}(R)) \) according to the following principle:

\[ b_{ij}(R) = \begin{cases} 1 \text{ у випадку } (x_i, y_j) \in R \\ 0 \text{ випадку } (x_i, y_j) \notin R \end{cases} (6) \]

The problem of relations on the graph is as follows. Let the elements \( b \) general continuum \( \theta \) represented by nodes of the graph \( A \), which we denote \( x_i \). We set the rule: graph \( A(R) \) of the relation \( R \) has an edge directed from \( x_i \) to \( x_{i+1} \) if performed \( (x_i R x_{i+1}) \). To formalize competitive advantage, we use the following approach:

\[ R = \{(x, y) | x, y \in \theta, [\text{наявна перевага}] \} (7) \]

For multimodal transportation of goods on the route \( L \) we use the approach of transitive closure:

\[ x R y \Leftrightarrow \forall \theta, L = \{ l_1 = x, l_2, l_3, \ldots, l_{n-1}, l_n = y \} [l_i R l_{i+1}] \forall i \in \{1, \ldots, n-1 \} \]
where $\hat{R}$ is the execution of the relation $R$ for all elements of the route $L$. To find the best alternatives, we use an approach based on the formation of so-called externally stable set $E$:

$$\forall y \in \Theta \mid E \ [\exists x \in E | xRy]$$ (9)

The condition for achieving the result is to obtain a solution by the Neumann-Montgenstern method, which is applied at similar limits in the work of Duchinskaya N.I. [15] and in [16,17,18]. When from a set of objective functions on a common continuum of transportation elements $\theta$ allocate extreme in time $\tau$ (marking them accordingly $F^\tau_t$), extreme in cost $c$ ($F^c_t$) and severely extreme in cost $c^*$ ($F^c_{**}$), then, according to equations (4) - (9), the set of the best alternatives can be found as:

$$F^\tau_t = \{x \in E | \forall y \in \Theta [y \neq x | xRy]\}$$ (10)

$$F^c_{**} = \{x \in E | \forall y \in \Theta, y \neq x | y \neq x \}$$ (11)

This means that finding a subset of elements that meets the definition of "route" or "subset of routes" must meet the following requirements: the set of best alternative transportation options should include only incomparable options (if $x$ is preferable to $y$, then $y$ is not selected) and vice versa - if $y$ is not the desired variant, then among $x$ there is a variant that is more desirable than $y$.

![Fig. 1. Transit transportation through the ports of Ukraine.](source)

*Source: Compiled by the authors based on [19] and other sources*

The best solution is to find a direct or tangible connection between the various target functions. Here is an example of such an approach. All other things being equal, some routes may be losing either in terms of cost of transportation or time. However, if there is a possible increase in the level of risk at certain stages of the routes during the time scheduled for transportation, they may be considered desirable. To do this, the scale of measurement of each of the types of risks must be compared with the cost, time or other units of measurement of the selected target functions. In addition, it is necessary to consider the need to use this target function. The probability of risk at a particular stage or route of transportation for the relevant objective function can be taken into account according to the following formula:

$$f = \frac{\int_{x_1}^{x_2} x \varphi(x)dx}{\int_{x_1}^{x_2} \varphi(x)dx}$$ (12)

An example of an increase in the risk of transportation on the route is the reduction to zero of transit traffic through the port of Mariupol since 2014 (see Fig. 1). The increasing risk of hostilities has forced carriers to choose other routes, albeit with an increase in cost and time of transportation. Thus, analyzing the dynamics of transit traffic in general through all ports of Ukraine and, for example, the dynamics of transit...
traffic through the port of Pivdennyi can indicate an increase in traffic through the port on a small lag in time after the reduction of traffic through the port of Mariupol. Thus, carriers find the optimal solution for the integrated indicator of the efficiency of MME for several target functions, slightly inferior to the values of the target functions of time and cost, but increasing reliability by reducing the degree of risk at the stage of transit cargo by sea. Let’s estimate from this point of view river routes. Thus, the time of transportation by inland water transport (IWT) is on average longer than rail. Yes, the cost of transportation, in particular, grain, is according to our calculations, about five percent higher than the use of rail transport. However, with the existing risks of disruption of contract deliveries in the case of railway use and, in the case of risk reduction, for the use of IWT, i.e., the introduction of the equation of component security of supply, river transport becomes a desirable option. Therefore, it is important to determine the values of the target functions that are extreme, rigidly extreme and closest to the extreme before the risk assessment. This reduces the amount of calculations, because then you need to weigh only those risks (or the multiplier effect of a particular set of risks) that will contribute to the intersection of the limit values of the objective functions. Thus, a necessary stimulus for the development of a national or industry-wide point of view of IWT is the situation with the main mode of transport on land in Ukraine - rail. But the current state of the railway, which is a monopolist for the transportation of goods across the country, on the one hand, does not allow to increase the efficiency of MMT without significant restructuring of rail transport, significant investments, etc., on the other - limits the efficiency of MMT with the use of IWT in decline and also needs significant resources to recover. While the railway is a monopolist, there are not many incentives for restructuring in the industry. That is why the introduction of IWT is an additional incentive in terms of reducing the risks of transportation, ensuring its reliability.

Conclusions and perspectives of further research. The presented results of the research are devoted to the increase of efficiency of multimodal transportation taking into account risks and optimization of transport routes. MMT by definition should be carried out using different modes of transport. Unfortunately, when choosing modes of transport, as proved in this study, the transport company faces the problem of a de facto monopolized transport market with two modes of transport - rail and road. The share of cargo transportation through the territory of Ukraine by inland water transport is insignificant. This can lead to increased transportation risks. Therefore, from a general industry point of view, more attention should be paid to upgrading IWT infrastructure. The paper proves that the choice of only one of the traditional target functions of transport companies - the cost or time of transportation does not guarantee its effectiveness without assessing the risks of transportation of goods. Therefore, an algorithm for selecting the optimal solution for several objective functions was proposed. To do this, a method for finding the extremum of each of them by its own nontrivial subset is proposed. It is proved that these sets, in the general case, are not identical. Especially since they can even be measured in different units. For example, you can minimize transportation time but this will not minimize the cost of transportation. Therefore, the best in terms of efficiency will be a compromise solution. It is indicated that the task of optimizing freight traffic should be considered not only in view of narrow corporate benefits, but also in view of national or industry interests. While the target function should be considered, for example, equalization of disparities in cargo turnover by mode of transport, comparing the situation in Ukraine and the EU; achieving such a stage in the development of maritime transport that the seaports of Ukraine are included in the TOP-100 ports of the world that specialize in container or multimodal cargo transportation; growth of volumes of transit of containers through the transport system of Ukraine to a certain value in due time; increasing the degree of containerization of cargo transportation to a certain value within a certain period; growth of the index of logistics efficiency of transportations to a certain value in the world rating; strengthening Ukraine’s position among the transit countries of the Black Sea-Azov region, etc. Such a task statement requires a long-term state program aimed at increasing the effectiveness of the MMT.

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