This paper reports a comparative analysis of the known methods for reducing open transportation problems to a balanced form in order to further optimize freight traffic based on them. A series of significant shortcomings have been revealed that largely narrow the scope of their application. A new method has been proposed, termed the method of proportional redistribution of cargo transportation volumes among participants in the transportation process, devoid of the identified shortcomings.

The transportation problem is a special case of the general linear programming problem, to which one of the methods for solving it, namely the simplex one, can be applied. A procedure to construct a simplex table based on the data from the transport table has been described, as well as the algorithm of subsequent simplex transformations.

A transportation problem is often stated in the form of a map of the location of transport hubs of cargo dispatch and destination. A matrix-network model has been proposed, which makes it possible to reduce the network representation to a matrix form with the subsequent finding of the optimal plan for cargo transportation.

In order to identify the priority of methods for reducing open transportation problems to a balanced form, 100 transportation problems that are unbalanced in terms of the volume of cargo transportation were solved. That was done with the help of a designed decision support system for the management of freight transport. As a criterion, the best freight transportation plan was chosen.

As a result, the simplex method proved the best in 48 cases, the coefficient method – in 27, the dummy node method – in 16, and the difference method – in 9 cases. The use of a decision support system for the management of freight transport has increased its efficiency by an average of 25 %

Keywords: transport network, optimization, dummy node, difference, coefficient, simplex, decision-making

OPTIMIZING UNBALANCED FREIGHT DELIVERIES IN TRANSPORTATION NETWORKS

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1. Introduction

In most cases, there is a practical event when the volumes of supply and demand for the transported goods do not coincide and, as a result, an open or unbalanced transportation problem (TP), in terms of cargo transportation volumes, arises. In these cases, the search for an optimal freight plan for a particular TP requires an informed choice of the most appropriate methods for a given TP.

First of all, this applies to methods for reducing open transportation problems to a balanced form since finding the optimal plan for cargo transportation based on an unbalanced TP is theoretically impossible; it practically leads to inefficient freight transportation. At the same time, the results of the subsequent optimization of freight traffic after using different methods of reduction are different.

It should also be noted that all known and widely used freight transport optimization techniques are applied exclusively to the matrix model of their representation, that is when the original TP data are summarized in a transport table (TT). And this, in turn, involves reducing the network representation of TP to its matrix form because a TP in practice is often set in the form of a map of the location of transport nodes of cargo dispatch and destination, that is, in the form of a transport network (TN). The preliminary stage in this process is the construction of a matrix of correspondence between all participants in the transport process – cargo suppliers and consumers.

The above features of optimization of unbalanced freight traffic within TN imply the development of new methods and approaches to solving this problem, which are based on the use of modern tools of information technology. This indicates

the relevance of research aimed at finding the optimal plan for unbalanced freight traffic within TN.

2. Literature review and problem statement

A transportation problem is a special type of network optimization task in which goods are transported from a set of points of dispatch (PD) to a set of destination points (DP) in accordance with the volume of supply and demand of cargo at these points. As a result, the total cost of transporting the goods should be minimal.

In this case, the procedure for solving a TP consists of the following stages:
– Stage 1: mathematical statement of TP;
– Stage 2: search for the initial basic acceptable solution;
– Stage 3: optimization of the initial basic acceptable solution obtained in the second stage.

Paper [1] proposes a new approach to finding the initial basic permissible solution to TP. It is based on the joint accounting of the total costs of cargo transportation by rows and columns in TT. Penalties here can be either the cost of transportation of a unit of cargo, or the distance, or the time to overcome this distance between the cargo PD and DP. A comparative study using several TPs shows that the new approach provides the same or better initial possible solution than a number of existing ones.

The procedure for solving TP described above does not take into consideration one essential condition that is often encountered in practice, namely, the imbalance in the volume of cargo transportation. In this case, after the first stage, it is necessary to carry out an additional stage of reducing the TO, unbalanced in terms of volumes of cargo transportation, to a closed type.

Recently, in order to solve balanced TPs, weighted algorithms of alternative cost have been developed [2], the peculiarity of which is the introduction of supply and demand in the form of weighting coefficients to control the flow of goods. These algorithms are not applicable to unbalanced TPs when balanced with zero fictitious transportation costs, as is the case in existing classical approaches. A modified dynamically updated weighted algorithm based on opportunity cost [3] is proposed, built into the least cost method, which is suitable for both balanced and unbalanced TPs.

Study [4] describes two most well-known methods for reducing open TPs to a balanced form:
– Method 1: introduction of an additional (fictitious) point of dispatch (destination) of the cargo;
– Method 2: reduction of the volume of supply (demand) by the amount of non-compliance in one of PD (DP).

The use of the first of the methods often does not satisfy the application of individual consumers of goods, especially those located at a considerable distance from PD, while the second method has significant limitations on its use. In order to remove these shortcomings, a new method for reducing the open TP to a balanced form, namely the coefficient method of balancing TP, is proposed.

Paper [5] deals with the issues of finding optimal freight transportation plans using linear programming and spreadsheets; that consideration is purely economic in nature. Also, the cited paper does not reveal the essence of the mathematical apparatus for converting TP to the problem of linear programming and the subsequent finding of the optimal plan for freight traffic.

In management, the ultimate goal is to make the right decision by the person who makes this decision (a decision-maker, DM), at a time when the parameters of cargo transportation are uncertain due to globalization and other uncontrollable factors. In study [6], the linear programming problem is solved using a fuzzy linear membership function where the upper and lower values of the goals are the desired goals. However, in some cases, the results obtained do not satisfy the DM. This issue can be resolved by devising an appropriate methodology for using the simplex method, which can effectively find optimal freight transport plans for both open and closed TPs.

Modeling traffic distribution and highlighting optimal flows in multi-tier networks is of paramount importance for the development of efficient multimodal network infrastructures. The results, based on optimal transport theory, offer powerful and computationally efficient methods for solving this problem, but they mainly focus on modeling single-tier networks. As an application, work [7] considers TNs where each level is connected to a separate transport system and shows how the distribution of traffic changes when configuring this parameter by levels. The model paves the way for further analysis of optimal flows and navigation strategies in real multi-layer networks. However, the cited study only considers balanced freight transport.

Paper [8] devised a modification of the method of the ant algorithm to optimize the transportation route, taking into consideration the traffic flow within TN. The proposed modification of the ant algorithm for optimizing the route of cargo delivery when the speed of the traffic flow changes in specific sections within TN is tested on the example of a specific street network in the salesman's task. A quantitative and comparative analysis of the solution to the problem of optimizing the route of cargo delivery within TN using the method of the ant algorithm and the corresponding results of other existing classical methods was carried out. The reported results of the cited study show the prospects of using the proposed modification of the ant algorithm to solve routing problems, in particular, for TN characterized by high dimensionality and dynamism of functional parameters. That can be solved by devising a decision support system for managing freight traffic in transport networks, which is based on the use of modern information technology tools [9].

3. The aim and objectives of the study

The aim of this work is to devise a new approach to the optimization of unbalanced freight traffic in transport networks, which are based on the use of modern tools of information technology. This will make it possible to significantly increase the efficiency of freight traffic in transport networks.

To accomplish the aim, the following tasks have been set:
– to devise a new method of proportional redistribution of cargo transportation volumes among participants in the transportation process for unbalanced freight traffic;
– to improve the methodology for using the simplex method to find the optimal freight transport plan;
– to devise technology for the formation of a matrix-network model for optimizing unbalanced freight traffic in transport networks;
– to design a decision support system for the management of freight traffic in transport networks, which is based on the use of modern tools of information technology.

4. The study materials and methods

The object of this study is the process of unbalanced freight traffic in transport networks.

The main hypothesis of our study assumes that in order to increase the efficiency of unbalanced freight transportation, it is necessary to first reduce them to a balanced form by all known methods and choose the best one from the obtained optimal freight transport plans.

As a simplification, in this study, we adopted a linear form to represent the process of freight transport, and as a result, linear optimization is used to further obtain their optimal plans.

Theoretical studies were carried out using existing theoretical methods (the method of a fictitious node of cargo delivery/consumption, the difference method, the simplex method) and models – a matrix model for representing freight traffic. As a result of their comparative analysis, a new method of coefficients and a matrix-network model for the representation of cargo transportation were devised.

As a result of theoretical research, the software for the designed decision support system for the management of freight deliveries in transport networks was developed. The software was experimentally tested using real data on the activities of a number of motor transport enterprises in the Association of International Road Carriers of Ukraine.

The experimental data obtained coincided in many cases with the results of the activities of the motor transport enterprises participating in the experiment, and, in some cases, showed a better result. All this testifies to the adequacy of the proposed models and methods.

5. Results of studying the process of optimization of unbalanced freight traffic in transport networks

5. 1. The coefficient method of reducing unbalanced freight traffic to a balanced form

According to the definition of TP, from m points of departure (PDs) A_1, A_2, ..., A_m, in which stocks of homogeneous cargo are concentrated in quantities, respectively, a_1, a_2, ..., a_m units, it is necessary to transport this cargo to n destination points (DPs) B_1, B_2, ..., B_n in accordance with the orders for them for b_1, b_2, ..., b_n units. It is also assumed that the sum of all orders is equal to the sum of all inventories, namely:

$$\left| \sum_{i=1}^{m} a_i = \sum_{j=1}^{n} b_j \right|. \tag{1}$$

The matrix (table) of the cost of transporting a unit of cargo between each PD and each DP is set as follows:

$$\begin{vmatrix} c_{11} & c_{12} & \cdots & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ c_{m1} & c_{m2} & \cdots & c_{mn} \end{vmatrix}. \tag{2}$$

And the matrix (table) of the corresponding volumes of traffic is as follows:

$$\begin{vmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{vmatrix}, \tag{3}$$

where c_{ij} is the cost of transporting a unit of cargo from A_i to B_j, and x_{ij} is the amount of cargo transported from A_i to B_j.

It is necessary to transport the cargo in such a way that all orders are fulfilled and the total cost (Z) of all transportation would be minimal, that is:

$$Z = c_{11} \times x_{11} + c_{12} \times x_{12} + ... + c_{mn} \times x_{mn} => \min. \tag{4}$$

A TP that meets condition (1) is termed a closed or balanced TP.

There are two most well-known methods for reducing open TPs to a balanced form, namely the introduction of additional (fictitious) cargo PD (DP) – the method of a fictitious node; reduction of the volume of supply (demand) by the amount of non-compliance in one of PDs (DPs) – the difference method.

The first method has two variants, namely, the first variant where

$$\sum_{i=1}^{m} a_i > \sum_{j=1}^{n} b_j,$$

that is, supply exceeds demand. In this case, the need for a fictitious DP B_{n+1} is:

$$b_{n+1} = \sum_{i=1}^{m} a_i - \sum_{j=1}^{n} b_j.$$

The second option is used if

$$\sum_{j=1}^{n} b_j > \sum_{i=1}^{m} a_i,$$

that is, demand exceeds supply. In this case, the stocks of fictitious PD A_{m+1} are:

$$a_{m+1} = \sum_{j=1}^{n} b_j - \sum_{i=1}^{m} a_i.$$

In this case, either an additional column or an additional row appears in the cost matrix, respectively, all elements of which are assigned zero transportation costs.

The TP becomes balanced in the case of the introduction of an additional DP but, at the same time, the cargo is not partially or completely exported from individual PDs. The TP also becomes balanced by the introduction of additional PD, but some DPs are not partially or completely satisfied with the requests for cargo.

In the second method, in order to bring the TP to a balanced form, the difference modulus $\left| \sum_{i=1}^{m} a_i - \sum_{j=1}^{n} b_j \right|$ is subtracted from PD $\left(\text{at } \sum_{i=1}^{m} a_i > \sum_{j=1}^{n} b_j \right)$, with the highest supply value, or

from the DP $\left(\text{at } \sum_{j=1}^{n} b_j > \sum_{i=1}^{m} a_i \right)$, with the highest demand value. This method is not applicable when this greatest supply (demand) value is less than the subtracted difference modu-

lus $\left| \sum_{i=1}^{m} a_i - \sum_{j=1}^{n} b_j \right|$.

The application of the first of the methods, in the case of the first option, does not perform the delivery of goods from individual PDs, especially those located at a considerable distance from the DP. And in the second case, it does not satisfy the orders of individual cargo DPs, also located at a considerable distance from PD.

The use of the second method has certain limitations of its applicability. In order to remove these shortcomings, a new

method has been developed to reduce the open TP to a balanced form, namely the coefficient method of balancing the volume of cargo supply.

This method is based on a decrease in the supply (demand) of goods of all PDs or DPs, proportional to the volume of stocks (orders). In the case of excess supply of cargo over its demand $\sum_{i=1}^{m} a_i > \sum_{j=1}^{n} b_j$, the coefficient of reduction of supply volumes is calculated:

$$k_a = \frac{\sum_{i=1}^{m} a_i - \sum_{j=1}^{n} b_j}{\sum_{i=1}^{m} a_i}. \tag{5}$$

After that, the supply volumes of all PDs ($i=1,m$) are reduced to values $a_i^* = (1-k_a) \times a_i$ and the problem becomes balanced with the same volumes of orders b_j ($j=1,n$) and the same TP dimensionality.

If the demand for the cargo exceeds its supply $\sum_{j=1}^{n} b_j > \sum_{i=1}^{m} a_i$, the corresponding coefficient of decrease in demand volumes in all DPs ($j=1,n$) is calculated as follows:

$$k_b = \frac{\sum_{j=1}^{n} b_j - \sum_{i=1}^{m} a_i}{\sum_{j=1}^{n} b_j}. \tag{6}$$

These volumes of orders are then reduced to values $b_j^* = (1-k_b)*b_j$ and the TP becomes balanced with the same volumes of stocks a_i ($i=1,m$) and the same dimensionality.

The coefficient method of balancing the volume of cargo delivery differs from the method of the fictitious node by a more equitable distribution of cargo flows between the participants in the transport process and has no restrictions on its applicability, unlike the difference method.

As a comparative analysis of the methods, the TP is considered below in the form of three plants (PDs) producing articles distributed to four warehouses (DPs).

The costs of transporting a unit of production from each plant to each warehouse are also set (Table 1). It is necessary to minimize transportation costs under the condition that the products are required by 30 units more than they are produced. For comparison, we show the application of all the above methods of reducing TP to a closed form.

Table 1

Initial information on the transportation problem

Plant \ Warehouse	No. 1	No. 2	No. 3	No. 4	Delivery volume
No. 1	10	8	9	10	80
No. 2	4	2	3	4	10
No. 3	3	4	5	4	50
Delivery volume	20	50	40	60	140 / 170

Optimization of freight traffic in the above TP in the Excel environment is as follows:

a) in the case of a fictitious node – the introduction of the fourth fictitious plant (Table 2);

b) in the case of applying the difference method – reducing the volume of the largest order at the fourth warehouse (Table 3);

c) in the case of application of the difference method – a proportional decrease in the volume of orders of all warehouses (Table 4);

d) in the case of TP imbalance (Table 5).

Table 2

Introducing the fourth fictitious plant

Plant \ Warehouse	No. 1	No. 2	No. 3	No. 4	Delivery volume
No. 1	0	41	39	0	80
No. 2	0	9	1	0	10
No. 3	20	0	0	30	50
No. 4	0	0	0	30	30
Delivery volume	20	50	40	60	170 / 170
Transportation cost					880

Table 3

Reducing the volume of the order at the fourth warehouse

Plant \ Warehouse	No. 1	No. 2	No. 3	No. 4	Delivery volume
No. 1	0	22	40	18	80
No. 2	0	10	0	0	10
No. 3	20	18	0	12	50
Delivery volume	20	50	40	30	140 / 140
Transportation cost					917

Table 4

Proportional reduction in the volume of orders of all warehouses

Plant \ Warehouse	No. 1	No. 2	No. 3	No. 4	Delivery volume
No. 1	0	15.41	32.94	31.65	80
No. 2	0	10.00	0	0	10
No. 3	16.47	15.77	0	17.76	50
Delivery volume	16.47	41.18	32.94	49.41	140 / 140
Transportation cost					940

Table 5

Optimization of freight traffic in the unbalanced state of TP

Plant \ Warehouse	No. 1	No. 2	No. 3	No. 4	Delivery volume
No. 1	20	20	20	20	80
No. 2	0	3.33	3.33	3.33	10
No. 3	0	16.67	16.67	16.67	50
Delivery volume	20	50	40	60	140 / 170
Transportation cost					987

The best (minimum transport costs) result was shown by the method of the fictitious node – 880 conditional monetary units (cmu), the second result was demonstrated by the difference method – 917 cmu, the third – the coefficient method – 940 cmu. The largest transport costs of 987 cmu were incurred after optimizing freight traffic on an unbalanced TP.

It should also be noted that during experimental studies, the advantage of the coefficient method was revealed in 27 cases out of 100.

5. 2. Methodology for using the simplex method to find the optimal freight transport plan

The transportation problem is a special case of the general linear programming problem (GLPP), to which one of the effective methods for solving the OSLP, namely the simplex method (SM), can be applied. Let us describe the developed methodology for using the SM to find the optimal plan for freight transportation. First, a transportation table (TT), built on the basis of the TP from Table 1, is represented in the following form (Table 6).

$$\begin{cases} x_{11}+x_{12}+x_{13}+x_{14} & =80, \\ x_{21}+x_{22}+x_{23}+x_{24} & =10, \\ x_{31}+x_{32}+x_{33}+x_{34} & =50, \\ x_{11}+ \quad x_{21}+ \quad x_{31}+ & =20, \\ x_{12}+ \quad x_{22}+ \quad x_{32}+ & =50, \\ x_{13}+ \quad x_{23}+ \quad x_{33}+ & =40, \\ x_{14}+ \quad x_{24}+ \quad x_{34}+ & =60. \end{cases} \quad (7)$$

Next, the variables $x_{11} \rightarrow x_1$, $x_{12} \rightarrow x_2$, ..., $x_{34} \rightarrow x_{12}$ are replaced; additional basic variables x_{13}, x_{14}, x_{15}, x_{16}, x_{17}, x_{18} and x_{19} are added to each equation. And, in order for the resulting system of equations to be linearly independent and, as a consequence, produce a single solution, one equation, for example, the last one, is discarded:

$$\begin{cases} x_1+x_2+x_3+x_4+ & =80, \\ x_5+x_6+x_7+x_8+ & =10, \\ x_9+x_{10}+x_{11}+x_{12}+ & =50, \\ x_1+ \quad x_5+ \quad x_9+ & =20, \\ x_2+ \quad x_6+ \quad x_{10}+ & =50, \\ x_3+ \quad x_7+ \quad x_{11}+ & =40. \end{cases} \quad (8)$$

Next, the first simplex table (ST) is built, which adapts to the Excel table sheet (Fig. 1).

After performing six simplex transformations, the resulting ST is compiled (Fig. 2).

The optimal plan of cargo transportation obtained from the resulting ST is transferred to TT (Table 7).

The transport costs of the optimal freight transport plan obtained with the help of SM on an unbalanced TP are 880 cmu.

This is the best result of all the values of optimal plans that were obtained after reducing the unbalanced TP to a balanced form by the above methods.

From this, it can be concluded that an improved methodology for using the SM method to find the optimal freight transport plan can be effectively applied to unbalanced TPs as well.

The experimental testing of the procedure for using the simplex method to find the optimal freight transport plan has confirmed the effectiveness of its application in half of the cases (48 cases out of 100).

Table 6

Transportation table

Plant \ Warehouse	No. 1	No. 2	No. 3	No. 4	Delivery volume
No. 1	10	8	9	10	80
	x_{11}	x_{12}	x_{13}	x_{14}	
No. 2	4	2	3	4	10
	x_{21}	x_{22}	x_{23}	x_{24}	
No. 3	3	4	5	4	50
	x_{31}	x_{32}	x_{33}	x_{34}	
Delivery volume	20	50	40	60	140 / 170

Note: x_{ij} is the volume of cargo transported from the i-th of its supplier to the j-th of its consumer

The next step is when freight transportation is reduced to the form of a system of linear equations; in this case, the equations are written separately on the rows and columns of TT:

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
		СТ0		X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	X15	X16	X17	X18
1																					
2	СБi	ХБi	ВБi	10	8	9	10	4	2	3	4	3	4	5	4	11	11	11	11	11	11
3	11	13	80	1	1	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0
4	11	14	10	0	0	0	0	1	1	1	1	0	0	0	0	0	1	0	0	0	0
5	11	15	50	0	0	0	0	0	0	0	0	1	1	1	1	0	0	1	0	0	0
6	11	16	20	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	1	0	0
7	11	17	50	0	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	1	0
8	11	18	40	0	0	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	1
9	C0 =		2750	12	14	13	1	18	20	19	7	19	18	17	7	0	0	0	0	0	0

Fig. 1. Initial simplex table

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
67		СТ6		X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	X15	X16	X17	X18
68	СБi	ХБi	ВБi	10	8	9	10	4	2	3	4	3	4	5	4	11	11	11	11	11	11
69	4	12	30	0	0	0	1	0	0	0	1	0	0	0	1	1	1	-1	-1	-1
70	2	6	10	0	0	0	0	1	1	1	1	0	0	0	0	1	0	0	0	0
71	4	10	0	-1	0	0	-1	-1	0	0	-1	0	1	1	0	-1	-1	0	0	1	1
72	3	9	20	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	1	0	0
73	8	2	40	1	1	0	1	0	0	-1	0	0	0	-1	0	1	0	0	0	0	-1
74	9	3	40	0	0	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	1
75	C6 =		880	-3	0	0	-2	-3	0	0	-2	0	0	0	0	-3	-9	-7	-12	-11	-10

Fig. 2. Resulting simplex table

Table 7

The optimal plan of cargo transportation
in the transportation table

Plant \ Warehouse	No. 1	No. 2	No. 3	No. 4	Delivery volume
No. 1	10	8	9	10	80
		$x_2=40$	$x_3=40$		
No. 2	4	2	3	4	10
		$x_6=10$			
No. 3	3	4	5	4	50
	$x_9=20$			$x_{12}=30$	
Delivery volume	20	50	40	60	140 / 170

5. 3. Technology that builds a matrix-network model of optimization of unbalanced freight traffic in transport networks

Often, the TP is set in the form of a map of the location of transport hubs of cargo dispatch and destination. Below we consider the devised technology for building a matrix-network model (MNM) for optimizing unbalanced freight traffic within TN, which makes it possible to reduce the network representation to a matrix form with the subsequent finding of the optimal plan for cargo transportation.

MSM management of cargo transportation within TN includes five stages [10].

As a demonstration of these stages, a specific TN is discussed below (Fig. 3).

The TN contains 3 points of departure – A_1, A_2, and 4 destination points – B_1, B_2, B_3, B_4 of a homogeneous cargo. The distance between the points is indicated on the corresponding edges, the volumes of deliveries and orders of cargo are indicated in the corresponding graphic objects of transport hubs.
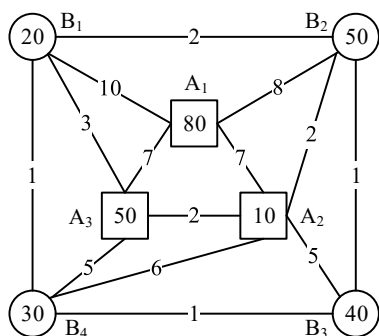
Fig. 3. The transport network of cargo transportation

The first stage in the formation of MNM is the compilation of an array of distances between the neighboring nodes of TN. To do this, it is enough to specify the distance from the PD to DP of each edge of the graph in one direction since the distance in the opposite direction is assumed to be the same (Table 8).

It should be noted that this stage involves manual compilation of the array.

At the second stage, a matrix of transport correspondence between all nodes of TN is automatically built (through the appropriate program) based on the distance array. The dis-

tance between non-neighboring (adjacent) nodes is set equal to infinity (Table 9).

Table 8

Array of distances between neighboring nodes
of the transportation network

No. of entry	PD	DP	Distance	No. of entry	PD	DP	Distance
1	A_1	B_1	10	8	A_2	A_3	2
2	A_1	B_2	8	9	A_3	B_1	3
3	A_1	A_2	7	10	A_3	B_4	5
4	A_1	A_3	7	11	B_1	B_2	2
5	A_2	B_2	2	12	B_1	B_4	1
6	A_2	B_3	5	13	B_2	B_3	1
7	A_2	B_4	6	14	B_3	B_4	1

Table 9

Matrix of transport correspondence between all nodes
of the transportation network

Transportation nodes	A_1	A_2	A_3	B_1	B_2	B_3	B_4
A_1	∞	7	7	10	8	∞	∞
A_2	7	∞	2	∞	2	5	6
A_3	7	2	∞	3	∞	∞	5
B_1	10	∞	3	∞	5	∞	3
B_2	8	2	∞	5	∞	1	∞
B_3	∞	5	∞	∞	1	∞	1
B_4	∞	6	5	3	∞	1	∞

The matrix with respect to its main diagonal is symmetrical, due to the non-orientation of transport correspondence.

It should be noted that the infinity value in the program is simulated obviously greater than each of the distances of TN – usually, this value can be equal to the sum of all existing distances in TN.

The method of shortest routes is the method of the third stage in the construction of MNM. This method (the modified Dijkstra's method), using the data of the correspondence matrix (Table 9), finds both the values of the shortest distances within TN from each PD to each DP (Table 10), and the routes corresponding to these distances, which may contain intermediate points on the ways of cargo movement (Fig. 4).

The fourth stage implies compiling a classical TT (Table 11), based on the data from Table 10, and finding the optimal plan for the transportation of goods, the cost of implementation of which is 880 cmu.

Table 10

TN shortest distance matrix

PD \ DP	B_1	B_2	B_3	B_4
A_1	10	8	9	10
A_2	4	2	3	4
A_3	3	4	5	4

$$A_1 \xrightarrow{4} B_1 = 10; \qquad A_2 \xrightarrow{2} B_2 \xrightarrow{2} B_1 = 4;$$
$$A_1 \xrightarrow{4} B_2 = 8; \qquad A_2 \xrightarrow{2} B_2 = 2;$$
$$A_1 \xrightarrow{8} B_2 \xrightarrow{1} B_3 = 9; \qquad A_2 \xrightarrow{2} B_2 \xrightarrow{1} B_3 = 3;$$
$$A_1 \xrightarrow{8} B_2 \xrightarrow{1} B_3 \xrightarrow{1} B_4 = 10; \qquad A_2 \xrightarrow{2} B_2 \xrightarrow{1} B_3 \xrightarrow{1} B_4 = 4;$$

$$A_3 \xrightarrow{3} B_1 = 3;$$
$$A_3 \xrightarrow{2} A_2 \xrightarrow{2} B_2 = 4;$$
$$A_3 \xrightarrow{2} A_2 \xrightarrow{2} B_2 \xrightarrow{1} B_3 = 5;$$
$$A_3 \xrightarrow{3} B_1 \xrightarrow{1} B_4 = 4;$$

Fig. 4. Shortest distance routes

Table 11

Optimal cargo transportation plan

PD \ DP	B_1	B_2	B_3	B_4	Stocks
A_1	10	8	9	10	80
	–	$X_2=50$	$X_3=30$	–	
A_2	4	2	3	4	10
	–	–	$X_7=10$	–	
A_3	3	4	5	4	50
	$X_9=20$	–	–	$X_{12}=30$	
Orders	20	50	40	30	–

The last fifth stage in the construction of MNM is the representation of the results of the found optimal plan for the transportation of goods within TN (Fig. 5).
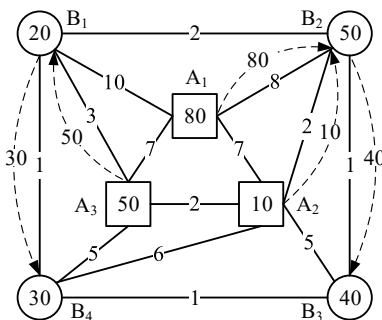
Fig. 5. The optimal plan of cargo delivery in the transportation network

Traffic flows in Fig. 5 will be distributed as follows: of the 80 conditional cargo units (ccu) that are dispatched from A_1, 50 ccu will remain at B_2; 30 ccu will go in transit to B_3; 10 ccu, which are sent from A_2, will transit through B_2 to B_3; of the 50 ccu that are sent from A_3, 20 ccu will remain at B_1, and 30 ccu will go in transit to B_4.

The devised technology for the construction of MNM regarding the optimization of unbalanced freight traffic within TN is a complete cycle of finding optimal freight transportation plans, starting from setting the input data of TP to obtaining the ultimate result. The second and third stages of the technology include unique algorithms for constructing a correspondence matrix and a transportation table.

The technology was experimentally tested both for transportation problems of small and medium dimensionalities (10 to 100 transport nodes) and for transportation problems of large dimensionality (101 to 600 transport nodes) in the transport system of Ukraine.

5. 4. Decision support system for the management of freight deliveries in transport networks

As an example, the step-by-step operation of the decision support system (DSS) for the management of unbalanced freight traffic in the transport network of Ukraine is considered below:

– step 1: selection of PD and DP and setting the volumes of supply and consumption of cargo (in Fig. 6, the total demand for cargo exceeds its total supply by 30 ccu);

– step 2: search for the shortest routes of cargo transportation (Fig. 7);

– step 3: selection of the optimal plan for cargo transportation (Fig. 8);

– step 4: construction of an optimal plan for cargo transportation (Fig. 9).

Fig. 6. Selection of points of departure/destination and setting the volume of cargo delivery

Fig. 7. The shortest routes of cargo transportation

Demand by consumers exceeds the proposal by suppliers by 30 cargo units.
It is required to match the demand and supply.

Reducing unbalanced TP to a balanced form using the SIMPLEX method and its further optimization by the method of different rents produced the best optimal cargo transportation plan.

```
FICTIOTIOUS node method = 52670
DIFFERENCE method       = 57700
COEFFICIENT method      = 55520
SIMPLEX method          = 52540
```

Fig. 8. Choosing the optimal cargo transportation plan

	Запоріжжя	Рівне	Суми	Чернівці
Вінниця		50		30
Київ			10	
Черкаси	20		30	

Fig. 9. The optimal cargo transportation plan

Using the cities of Vinnitsa, Kyiv, and Cherkasy as PDs, and the cities of Zaporizhzhia, Rivne, Sumy, and Chernivtsi as DPs, while changing the volume of delivery and consumption of cargo, we consider the following examples of the application of all the above methods for reducing open TNs to a balanced form, as well as the simplex method and the matrix-network model for optimizing unbalanced freight traffic in transport networks:

a) in the case of using the fictitious supplier/consumer method, we obtain (Fig. 10, *a, b*);

b) in the case of using the difference method, we obtain (Fig. 11, *a, b*);

c) in the case of using the coefficient method of coefficients, we obtain (Fig. 12, *a, b*).

Demand by consumers exceeds the proposal by suppliers by 10 cargo units.
It is required to match the demand and supply.

Reducing unbalanced TP to a balanced form using the method of FICTITIOUS node and its further optimization by the method of different rents produced the best optimal cargo transportation plan.

```
FICTITIOUS node method = 51930
DIFFERENCE method       = 54730
COEFFICIENT method      = 57520
SIMPLEX method          = 52460
```

a

	Запоріжжя	Рівне	Суми	Чернівці
Вінниця		30		50
Київ			10	
Черкаси	20	20	10	

b

Fig. 10. Results of the decision support system operation using the fictitious supplier/consumer method: *a* — selection of the optimal plan for cargo transportation; *b* — the optimal plan of cargo transportation

Proposal by suppliers exceeds the demand by consumers by 10 cargo units.
It is required to match the supply and demand.

Reducing unbalanced TP to a balanced form using the DIFFERENCE method and its further optimization by the method of different rents produced the best optimal cargo transportation plan.

```
FICTITIOUS node method = 51330
DIFFERENCE method       = 50720
COEFFICIENT method      = 56780
SIMPLEX method          = 53110
```

a

	Запоріжжя	Рівне	Суми	Чернівці
Вінниця		40		30
Київ			10	
Черкаси	10		40	

b

Fig. 11. Results of the decision support system operation using the difference method: *a* — selection of the optimal cargo transportation plan; *b* — the optimal plan of cargo transportation

Demand by consumers exceeds the proposal by suppliers by 20 cargo units.
It is required to match the demand and supply.

Reducing unbalanced TP to a balanced form using the COEFFICIENT method and its further optimization by the method of different rents produced the best optimal cargo transportation plan.

```
FICTITIOUS node method = 55220
DIFFERENCE method       = 54180
COEFFICIENT method      = 52657
SIMPLEX method          = 54490
```

a

	Запоріжжя	Рівне	Суми	Чернівці
Вінниця		30.59		49.41
Київ			10.00	
Черкаси	16.47	10.59	22.94	

b

Fig. 12. Results of the decision support system operation using the method of coefficients: *a* — selection of the optimal plan for cargo transportation; *b* — the optimal plan of cargo transportation

Fig. 13 shows a block diagram of the algorithm for the operation of the decision support system.
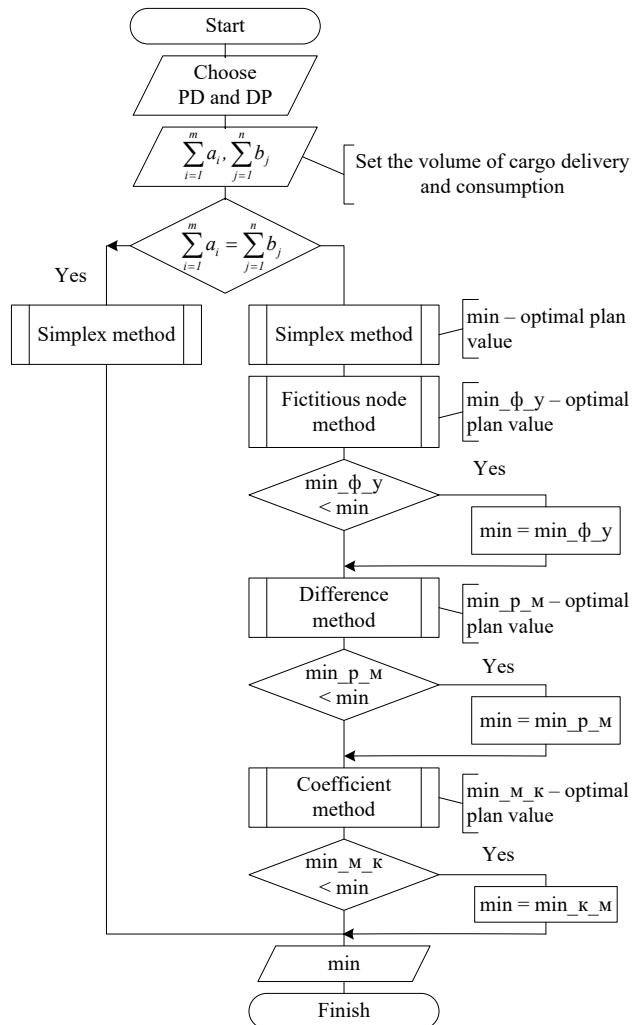

Fig. 13. Flowchart of the algorithm for selecting the optimal cargo transportation plan

In order to prioritize the methods discussed above to reduce unbalanced freight transportation to a balanced form, 100 real TPs were solved with the help of DSS to find optimal freight transport plans.

As a result, as a method for reducing these open TPs to a balanced form, the simplex method in 48 cases, the coefficient method in 27, the fictitious supplier/consumer method in 16 cases, and the difference method in 9 cases were used.

6. Discussion of results of the process of optimization of unbalanced freight deliveries in transportation networks

The description of the process of optimization of unbalanced freight traffic within TN and the results of experimental studies based on its analysis, obtained with the help of the developed decision support system, allow us to draw the following conclusions on the tasks set in the current study.

1. The coefficient method of reducing unbalanced freight transportation to a balanced state is more equitable, which is manifested in the redistribution of traffic volumes. This feature is manifested in a proportional decrease in the volume of demand (supply) of cargo among the participants in the transportation process.

If the supply of goods exceeds its demand $\sum_{i=1}^{m} a_i > \sum_{j=1}^{n} b_j$, the coefficient of reduction of supply volumes (5) is calculated. After that, the supply volumes of all PD ($i=1,m$) are reduced to values $a_i^* = (1 - k_a) \times a_i$ and the problem becomes balanced with the same volumes of orders b_j ($j=1,n$) and the same TP dimensionality.

If the demand for the cargo exceeds its supply $\sum_{j=1}^{n} b_j > \sum_{i=1}^{m} a_i$, the corresponding coefficient of reduction of demand volumes (6) in all DPs ($j=1,n$) is calculated. These volumes of claims are then reduced to values $b_j^* = (1 - k_b) * b_j$ and the TP becomes balanced with the same volumes of stocks a_i ($i=1,m$) and the same dimensionality.

The coefficient method of balancing the volume of cargo delivery differs from the method of the fictitious node by a more equitable distribution of cargo flows among the participants in the transportation process and has no restrictions on its applicability, unlike the difference method.

The current study is to be advanced towards improving the coefficient method. Below, on the example of exceeding the supply of cargo over its demand $\sum_{i=1}^{m} a_i > \sum_{j=1}^{n} b_j$, the main idea of this improvement is considered, namely:

– in each line of the matrix of the cost of transportation of a unit of cargo between each PD and each DP (2), their sum C_i ($i=1,m$) is found;

– all the C_i amounts found are summed up – $C = \sum_{i=1}^{m} C_i$;

– the supply volumes of all PDs ($i=1,m$) are reduced to values:

$$a_i^* = a_i - \left(\sum_{i=1}^{m} a_i - \sum_{j=1}^{n} b_j \right) \times C_i \Big/ C$$

and the problem becomes balanced with the same volumes of orders b_j ($j=1,n$) and the same TP dimensionality.

The proposed modified coefficient method has all the advantages relative to the existing ones, as well as the coefficient method, and has another additional one. It is in the fact that in the process of balancing the volume of cargo transportation, the optimization of freight traffic also proceeds in parallel. This is explained by the fact that, unlike the coefficient method, in which the criterion for reducing the volume of supply is their values, in the modified coefficient method, this criterion is the cost of transportation of a unit of cargo between the participants in the transportation process. That is, the more expensive the cost of cargo delivery to the transport hub, the more it needs to reduce the volume of supply/consumption. Conversely, the cheaper the cost of delivering cargo to a transport hub, the less it needs to reduce the volume of supply/consumption.

2. As the results of experimental studies have shown, methods for reducing open TPs to a balanced form are a mandatory preparatory (preliminary) stage before the subsequent application of cargo optimization procedures. This is because freight plans derived from unbalanced TPs have been found to be the most inefficient.

An exception to this is SM, which has shown its viability and high efficiency in finding optimal freight transport plans, both balanced and unbalanced TPs. The methodology for using SM to find the optimal freight transport plan for unbalanced TP includes the following steps:

– construction of TT for cargo transportation (Table 6);
– construction of a system of linear equations ((7), (8));
– construction of the initial ST (Fig. 2);
– carrying out simplex transformations (Fig. 3);
– interpretation of the resulting ST – construction of an optimal plan of freight transportation in TT (Table 7).

As a result of the analysis of experimental data, it was revealed that in the event of an excess of the supply of cargo over its demand, the standard SM algorithm works with an error. This is due to the fact that after the optimization of freight traffic, the difference modulus $\left| \sum_{i=1}^{m} a_i - \sum_{j=1}^{n} b_j \right|$ is also distributed in the optimal plan to one of the DPs, thereby increasing the value of transport costs due to fictitious cargo transportation.

Therefore, the fifth step of the methodology for using SM was finalized (improved) to find the optimal freight transport plan for unbalanced TPs, which takes into consideration this feature and makes appropriate adjustments to the optimal freight transport plan in TT (Table 7).

The current study is to be advanced towards improving the third step of the procedure under consideration, which is to alternately discard one of the equations in the system of linear equations (7) and further choose the most efficient one from the obtained optimal freight transportation plans.

3. Technology for the construction of MNM for the optimization of unbalanced freight traffic within TN has been devised, which includes the following stages:

– a compilation of an array of distances between neighboring nodes of TN (Table 8);
– construction of a matrix of transport correspondence between all nodes of TN (Table 9);
– finding the shortest distances within TN from each PD to each DP (Table 10);
– finding the optimal plan for cargo transportation (Table 11);
– representation of the results of the found optimal plan for the transportation of goods within TN (Fig. 6).

The technology is a full cycle of finding optimal freight transport plans, starting from the task of setting the input data of TP to obtaining the result; all of them are automated, with the exception of the first stage. It should be noted that the second and third stages of the technology include unique algorithms for constructing a correspondence matrix and TT.

The current study is to be advanced by developing additional algorithmic and software support for the first and second stages of the technology, which is aimed at giving it the property of openness. The latter involves the automatic expansion of the matrix of transport correspondence between all nodes within TN (Table 9) when a new transport node is added to TN.

4. DSS on freight transport management in transportation networks consistently performs the following steps:

– step 1: selection of PD and DP and setting the volumes of supply and consumption of cargo (Fig. 7);

– step 2: search for the shortest routes of cargo transportation (Fig. 8);

– step 3: selection of the optimal cargo transportation plan (Fig. 9);

– step 4: construction of an optimal plan for cargo transportation (Fig. 10).

The use of DSS would make it possible in practice to always choose the most profitable, from an economic point of view, management decisions. The analysis of the results of using all methods on a set of practical examples allows us to conclude that none of them has an absolute advantage over the others. This fact is explained by the fact that each of the methods in rare cases of its application showed a better result compared to the results of the others. The software for the designed decision support system for the management of freight deliveries within TN has been developed, which operates in accordance with the scheme shown in Fig. 14.
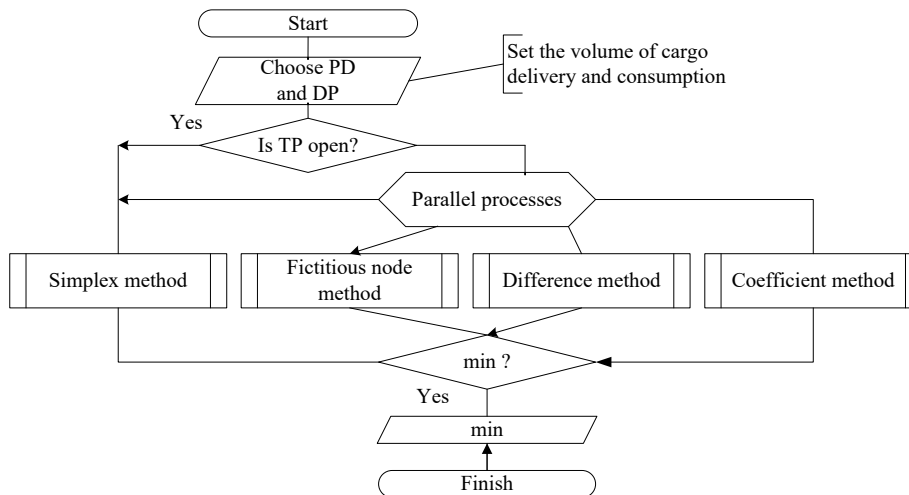

Fig. 14. Operational scheme of the decision support system for the management of freight deliveries in transportation networks

In Fig. 14, the min parameter denotes the lowest value of all values of optimal freight plans obtained after the reduction of unbalanced cargo transportation by the fictitious node method, the difference method, and the method of coefficients, to the balanced type.

The current study is to be advanced by building a larger database on PD and DP in the transport system of Ukraine involving transport hubs of Western Europe.

7. Conclusions

1. The devised coefficient method of redistribution of volumes of unbalanced freight traffic allocates them among all participants of the transport process in proportion to the volumes of deliveries/orders at the points of departure/destination of the goods. The coefficient method differs from the fictitious node method by a more equitable distribution of cargo flows between the participants in the transport process and has no restrictions on its applicability, unlike the difference method. It should also be noted that experimental studies revealed its advantage in 27 cases out of 100.

2. The results of our experimental studies of methods for reducing open TPs to a balanced form have shown that they are a mandatory preparatory (preliminary) stage before the subsequent application of cargo optimization procedures. This is because freight plans derived from unbalanced TPs have been found to be the most inefficient. The improved methodology for using the simplex method to find the optimal freight transport plan could be used for both unbalanced and balanced transportation problems. The experimental testing of this method confirmed the effectiveness of its use in half of the cases, namely in 48 cases out of 100.

3. The devised technology for the construction of a matrix-network model for optimizing unbalanced freight traffic in transport networks is a complete cycle of finding optimal freight transportation plans, starting from setting the input data of TP to obtaining the result; all of them are automated, with the exception of the first stage. It should be noted that the second and third stages of the technology include unique algorithms for constructing a correspondence matrix and TT. The technology was experimentally tested both for transportation problems of small and medium dimensionality (10 to 100 transport nodes) and for transportation problems of large dimensionality (101 to 600 transport nodes) within the transport system of Ukraine.

4. The designed decision support system for the management of freight traffic in transport networks, which is based on the use of modern tools of information technology, makes it possible to obtain a high economic, organizational, and technical effect. This was proved by finding the optimal plans for freight transportation using the real data from motor transport enterprises in the Association of International Road Carriers of Ukraine.

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