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MODEL OF DISTRIBUTED CARGO DELIVERY UNDER THE CONDITIONS OF A STATE OF WAR

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The article is devoted to the problem of cargo delivery in conditions of unreliable transport connections. The problem considered in the work belongs to the field of transport logistics. In particular, this problem often arises when planning the rear support of troops in the context of military operations. The peculiarity of cargo delivery under such conditions is that some transport routes may become impossible, and therefore it is necessary to distribute cargo flows in such a way as to minimize losses during delivery. Similar tasks arise in the civil sphere, when the reliability of transport communications is not guaranteed and can change quite quickly. Mathematical formulations of problems of this type are quite complex, the mathematical model is multi-criteria with a large number of limitations. But even after simplification and transition to one integrated criterion, the tasks remain difficult. The article considers the simplest mathematical model for this type of problem with the criterion of minimizing the risk of losses during cargo delivery with minimal information. As a rule, when solving transport problems by linear programming methods are limited to finding a basic acceptable plan with the minimum possible number of transportation routes. However, when implementing such plans, the reliability of cargo delivery is sharply reduced, and the risks of losses during transportation increase. In the presence of possible losses during cargo transportation, it is much more reasonable to diversify delivery routes. In addition, even in peacetime, diversification allows more efficient use of existing ways of delivering goods. For example, the load on the road surface is reduced, the intensity of traffic on individual routes is reduced, and the risks of traffic accidents are reduced. All of the above shows the relevance of the study of mathematical models of transport problems, in which in addition to the known criteria (transportation costs) there are also criteria related to the minimization of possible losses. One of these mathematical models is the subject of research in this work.

МОДЕЛЬ РОЗПОДІЛЕННОЇ ДОСТАВКИ ВАНТАЖІВ В УМОВАХ ВОЄННОГО СТАНУ

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мінімаксний критерій

Стаття присвячена проблемі доставки вантажів за умови ненадійності транспортних сполучень. Проблема, що розглядається у роботі, належить до галузі транспортної логістики. Зокрема, ця проблема часто виникає при плануванні тилового забезпечення військ в умовах воєнних дій. Особливістю доставки вантажів за таких умов є те, що деякі транспортні маршрути можуть стати неможливими і тому необхідно розподіляти вантажопотоки таким чином, щоб мінімізувати втрати під час доставки. Аналогічні завдання виникають і у цивільній сфері, коли надійність транспортних комунікацій не є гарантованою та може досить швидко змінюватись. Математичні формулювання задач даного типу виявляються досить складними, математична модель є багатокритеріальною з великою кількістю обмежень. Але навіть після спрощення

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та переходу до одного інтегрованого критерію задачі залишаються важкими. У статті розглядається найпростіша математична модель для такого типу задач із критерієм мінімізації ризику втрат при доставці вантажу за наявності мінімальної інформації. Як правило, при розв'язанні транспортних задач методами лінійного програмування обмежуються пошуком базового припустимого плану з мінімально можливим числом маршрутів перевезення. Однак при реалізації таких планів різко знижується надійність доставки вантажів, збільшуються ризики втрат при перевезеннях. За наявності можливих втрат при транспортуванні вантажу набагато розумніше диверсифікувати маршрути доставки. Крім того, навіть за умов мирного часу, диверсифікація дозволяє більш ефективно використовувати існуючі шляхи доставки вантажів. Наприклад, знижується навантаження на покриття доріг, зменшується інтенсивність руху окремими маршрутами, зменшуються ризики дорожньо-транспортних пригод. Усе сказане вище показує актуальність дослідження математичних моделей транспортних задач, у яких поруч із відомими критеріями (витрати на перевезення) присутні й критерії, пов'язані з мінімізацією можливих втрат. Одна з таких математичних моделей є предметом дослідження цієї роботи.

Statement of the problem

The problem considered in the work belongs to the field of transport logistics. This problem arises if there are risks of loss of goods or parts of goods during transportation along a certain route. In particular, this problem often arises when planning the rear support of troops in the conditions of military operations. The peculiarity of cargo delivery under such conditions is that some transport routes may become impossible and therefore it is necessary to distribute cargo flows in such a way as to minimize losses during delivery.

Consider the problem in the following formulation: there are n points where the same type of product is stored and m points of consumption of this product. From any point of storage the goods can be delivered to any point of consumption along the appropriate route. At the same time, any of the nm routes connecting the points of storage and consumption may turn out to be unreliable. The task is to find such a plan for the delivery of goods, according to which possible losses will be minimal.

Analysis of latest research and publications

The problem considered in the article refers to a wide class of transport problems studied and analyzed in transport logistics.

The theory of logistics began to develop actively in the 20th century [1–4], the concept of «logistics» entered economic terminology only from the mid-1950s. The view of transport logistics in its modern form was formed in the USA, but it is being improved and actively developed in the works of domestic and foreign scientists [1; 5–8].

In particular, work [8] summarizes various approaches to the definition of the concept of «transport logistics», it is substantiated that transport is the source of the main costs in the logistics system. The article also reveals the essence of the general function, purpose and tasks of transport logistics, which includes, in particular, the determination of a rational delivery route.

According to [6], transport logistics is an integral part of the logistics system, which ensures the technical, technological and economic consistency of all its subsystems, plays a decisive role in optimizing the management of material flows.

The allocation of transport into an independent field of logistics was facilitated by the following factors [5; 7; 8]:

1) impossibility of managing material flows without transportation;

2) the ability of transport to implement the basic idea of logistics – to create a system that is reliable, stable and optimally functioning: «supply – production – distribution – consumption»;

3) the need to solve a number of transport problems regarding the choice of distribution channels for raw materials, semi-finished products and finished products within the logistics system;

4) the presence of a large number of transport and forwarding enterprises, which play a significant role in the organization of optimal delivery of goods, both in domestic transportation and in international communication;

5) a high share of transport costs in the total amount of logistics costs. Their value can reach 50% or more of the total logistics costs for the promotion of goods from the primary source of raw materials to the final consumer of finished products [9; 10];

6) significant specific weight of the transport component in the foreign trade price of goods (especially for countries with long transportation distances).

Transport logistics, as an integral part of the overall logistics system, helps to solve the three main tasks of this system [7], which are related to:

1) formation of market service areas;

2) development of a transport process organization system (transportation plan, activity distribution plan, cargo flow formation plan, vehicle movement schedule, etc.);

3) management of stocks and their maintenance by vehicles, information systems.

In work [8] nine groups of global problems of transport logistics of Ukraine (financial, technical-technological, informational, economic, international, customs, environmental, labor) are highlighted and the main ways of overcoming them are considered. Among them, one of the important problems identified is the revision of the system for evaluating the efficiency of transport logistics activity [7]. This is caused, in particular, by rapid changes in the conditions of social development, the emergence of new types of risks that accompany them. For example, the definition of logistics risk is given in [11] and logistics risks are also classified depending on the stages of logistics activity. It is important that for each of the stages of logistics activity, the types of logistics risks, their sources, as well as methods of unconditional and conditional optimization, which allow them to be avoided or significantly reduced, are given. In particular, at the supply stage, it is recommended to use linear and dynamic programming methods, as well as unconditional optimization methods to minimize and prevent transportation risks and risks of inventory formation.

It is necessary to emphasize the fact that today it is already impossible to imagine solving the problems of managing traffic flows without the use of mathematical methods, models and information systems. Mathematical methods of modern transport logistics began to develop from the beginning of the 20th century. In addition to models and methods that have already become classical, models based on new ideas and paradigms have acquired active development and improvement [12–16].

The analysis of the works of scientists makes it possible to assert that new approaches are needed for problems arising in the field of transport logistics [17–21].

In [17] was investigated the influence of the introduction of Industry 4.0 technologies in companies with the aim of optimizing their production processes and organizational structures. The result of this research was a maturity model for logistics 4.0, which is able to determine the level of maturity of companies in the implementation of Industry 4.0 technologies in their logistics processes, as well as a roadmap for strengthening the digitalization of logistics processes, according to the principles of the fourth industrial revolution.

The work [18] is devoted to the issue of estimating the cost function from losses after natural disasters, the work [19] is devoted to the problems of logistics management in emergency situations.

Modern mathematical tools (fuzzy mathematics, genetic algorithms, etc.) are applied in articles [20–22] to develop decision-making models supporting the analysis and selection of sustainable supplier development programs (SSDP) and logistics management of perishable products with a limited and random shelf life.

The need to use new approaches is due to the fact that the mathematical formulations of problems of this type are quite complex, the mathematical model contains a large number of restrictions and several criteria for the quality of the solution. Moreover, even after simplification and transition to one integrated criterion, the tasks remain difficult. The work [23] is devoted to the problems of solving the classical transport problem. In particular, this article analyzes the impact of external factors on the planning and implementation of transport processes.

A feature of the cargo delivery process under martial law is the lack of information about the state of transport routes, and especially their reliability. Therefore, the research of mathematical models of transport problems is relevant, in which, in addition to the known criteria (transportation costs), there are also criteria related to the minimization of possible losses.

Goals formulation

In the conditions of martial law, new risks appear in the process of transportation of products, which are caused by military actions (aircraft, artillery strikes, attacks, etc.) and lead to certain (possibly complete) losses of the cargo. To minimize these losses, taking into account the enemy's ability to choose only some of the possible routes to cause losses, it is necessary to distribute (parallelize) the process of cargo transportation as much as possible. At the same time, considering that the actions of the enemy are unknown, it is advisable to develop such a transportation plan, which ensures minimal losses in the worst case, in order to assess possible losses. This leads to the need to build appropriate mathematical models and methods for finding optimal solutions to logistical problems within these models.

The purpose of this article is to develop a mathematical model of distributed cargo delivery under martial law conditions, taking into account the uncertainty of information about the reliability of transport routes.

Presentation of the main research material

The basis for the development of a new mathematical model will be the classical formulation of the transport problem with n $(i=1,2,...,n)$ production points and m $(j=1,2,...,m)$ points of cargo (goods) consumption. It is known that cargo is stored in bulk at storage points a_i , $i=1,2,...,n$ and the volume of consumption in the corresponding points of consumption is b_j , $j=1,2,...,m$.

For each of the acceptable transportation (delivery) routes (i,j) a value is determined p_{ij} – share of possible losses on this route. It is assumed that $0\le p_{ij}\le 1$ or everyone $(\forall)(i,j)$ Extreme values p_{ij} from the specified interval mean: $p_{ij}=0$ – transportation route (i,j) is absolutely reliable (loss of cargo is impossible), $p_{ij}=1$ – transportation route (i,j) is completely unreliable (in the event of a blow or attack, the entire load is completely lost).

The task is to develop such a plan for the transportation of all cargo from storage points to points of consumption, which provides minimal possible cargo losses.

All possible routes (i,j) deliveries will be considered acceptable. But we will consider only such a case when $0<p_{ij}<1$ or $\forall(i,j)$ Thus, the situation for which an appropriate mathematical model will be built is characterized by the following conditions:

1. About the probability of the appearance of threats losses (for example, as a result of a blow) nothing is known.
2. It is necessary to calculate the appearance of threats of various losses.
3. The solution is implemented only once, so there is no statistical information.
4. Losses are expected on only one of the routes.

In the accepted assumptions, it is reasonable to use the minimax criterion as a criterion for evaluating the efficiency of traffic flow distribution. This criterion is often called the guaranteed result criterion (the «pessimism» criterion) or the «bottleneck» criterion. This is due to the fact that it makes it possible to find the best of the worst possible admissible solutions.

Consider a closed (balanced) transport problem, that is, a problem for which the condition holds $\sum_{i=1}^{n} a_i = \sum_{j=1}^{m} b_i$.

The admissible solution of the problem is determined by the matrix $\left(x_{ij}\right)_{i=1,2,\ldots,n}^{j=1,2,\ldots,m}$, where each element of the matrix x_{ij} is equal to the volume of transportation of goods from point i to point j. Taking into account the balance condition, we obtain the following standard constraints of the transport problem:

$$\sum_{j=1}^{m} x_{ij} = a_i \ , \quad i = 1,2,\ldots,n,$$
$$\sum_{i=1}^{n} x_{ij} = b_j \ , \ j = 1,2,\ldots,m, \qquad (1)$$
$$x_{ij} \ge 0 \quad , \quad \forall (i,j).$$

The criterion of the problem with taking into account of the above assumptions is the minimax criterion:

$$\max_{\substack{i=1,2,\ldots,n \\ j=1,2,\ldots,m}} p_{ij} x_{ij} \to \min . \qquad (2)$$

Taking into account the limitation and closedness of the domain of admissible solutions, which is determined by relations (1), it can be stated that the problem always has an optimal solution. We denote the value of the criterion at the optimal solution by V. It is obvious that V is a strictly positive value.

It follows from (2) that for the optimal solution of the problem $\forall (i,j), \quad i = 1,2,..,n, \quad j = 1,2,\ldots,m$ there is inequality:

$$p_{ij} x_{ij} \le V . \qquad (3)$$

Let's introduce new variables by putting:

$$z = \frac{1}{V}, \qquad y_{ij} = z p_{ij} x_{ij} \qquad (4)$$

Then mathematical model of the problem of distribution of traffic flows (or models distributed cargo delivery) takes the form of a linear programming problem (LPP) with (nm+1) variables:

$$z \to \max \qquad (5)$$

subject to restrictions:

$$z a_i - \sum_{j=1}^{m} \frac{y_{ij}}{p_{ij}} = 0, \quad i = 1,2,\ldots,n,$$
$$z b_j - \sum_{i=1}^{n} \frac{y_{ij}}{p_{ij}} = 0, \quad j = 1,2,\ldots,m, \qquad (6)$$
$$0 \le y_{ij} \le 1 \ , \qquad \forall (i,j).$$

This problem, in turn, can be solved by the usual methods of finding optimal solutions of the LPP (simplex method, interior point method, ellipsoid method and others [12; 13]). Note that the problem can be solved under the condition that not all routes are admissible. In this case, in (6) it is necessary to limit yourself to only admissible routes and move from equations to inequalities.

Inequalities follow from relations (6):

$$z a_i \le \sum_{j=1}^{m} \frac{1}{p_{ij}} \ , \qquad i = 1,2,\ldots,n,$$
$$z b_j \le \sum_{i=1}^{n} \frac{1}{p_{ij}} \ , \qquad j = 1,2,\ldots,m.$$

In accordance we have an upper estimate for the value of the objective function:

$$z \le \min \left\{ \min_{\substack{i=1,2,\ldots,n \\ a_i > 0}} \sum_{j=1}^{m} \frac{1}{a_i p_{ij}}, \ \min_{\substack{j=1,2,\ldots,m \\ b_j > 0}} \sum_{i=1}^{n} \frac{1}{b_j p_{ij}} \right\}.$$

Let's consider the simplest (partial) case, when the volumes of storage at all points are the same and the volumes of product needs are also the same at all points of consumption:

$$a_1 = a_2 = \ldots = a_n = a, \quad b_1 = b_2 = \ldots = b_m = b .$$

It follows $an = bm$ from the condition of balance of the problem, and from relations (6) we have:

$$z = \frac{1}{na} \sum_{i=1}^{n} \sum_{j=1}^{m} \frac{y_{ij}}{p_{ij}} = \frac{1}{mb} \sum_{i=1}^{n} \sum_{j=1}^{m} \frac{y_{ij}}{p_{ij}} \le \frac{1}{na} \sum_{i=1}^{n} \sum_{j=1}^{m} \frac{1}{p_{ij}} .$$

Thus, the maximum of the objective function z is reached at:

$$y_{ij} = 1, \quad i = 1,2,\ldots,n, \quad j = 1,2,\ldots,m$$

and this maximum is equal to the magnitude $z^* = \frac{1}{na} \sum_{i=1}^{n} \sum_{j=1}^{m} \frac{1}{p_{ij}}$.

Let's enter the notation:

$$Q = \sum_{i=1}^{n} \sum_{j=1}^{m} \frac{1}{p_{ij}} .$$

From (4) follows that the optimal product delivery plan in this simplest case is determined by formulas:

$$x_{ij} = \frac{a}{p_{ij} Q} \qquad i = 1,2,\ldots,n, \quad j = 1,2,\ldots,m.$$

Let's consider the case now when among the routes there are absolutely reliable routes, i. e. such routes (i,j), for which $p_{ij} = 0$. In this case, the task is divided into two stages. The first of them solves the transport problem of the following type:

$$\sum_{p_{ij}=0} x_{ij} \to \max$$
$$\sum_{j=1, p_{ij}=0}^{m} x_{ij} \le a_i, \quad i = 1,2,\ldots,n,$$
$$\sum_{i=1, p_{ij}=0}^{n} x_{ij} \le b_j, \quad j = 1,2,\ldots,m,$$
$$x_{ij} \ge 0 \qquad \forall (i,j).$$

If it was possible to deliver all the goods to their destinations, the problem is solved. Otherwise, we add to the obtained solution the solution of a new transport problem of the form (5)-(6), in which there are only unreliable routes ($p_{ij} > 0$) and we are limited to the remaining goods in storage points and delivery points.

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Conclusions

The article is devoted to the problem of cargo delivery under the condition of unreliability of transport connections, which belongs to the field of transport logistics.

Such a problem arises in the conditions of martial law, as well as in the civilian sphere, when the reliability of transport communications is not guaranteed and can change quite quickly.

As a rule, when solving transport problems by linear programming methods are limited to finding a basic acceptable plan with the minimum possible number of transportation routes. However, when implementing such plans, the reliability of cargo delivery is sharply reduced, and the risks of losses during transportation increase. In the presence of possible losses during cargo transportation, it is much more reasonable to diversify delivery routes. In addition, even in peacetime, diversification allows more efficient use of existing ways of delivering goods. For example, the load on the road surface is reduced, the intensity of traffic on individual routes is reduced, and the risks of traffic accidents are reduced. All of the above shows the relevance of researching mathematical models of transport problems, in which, in addition to the known criteria (total transportation costs), there are also criteria related to the minimization of possible losses.

In the work, a mathematical model of cargo delivery under conditions of risk of losing a part of the goods on one of the routes was built. A method of finding the optimal solution of the considered version of the transport problem by reducing it to a linear programming problem is proposed. The simplest case of the problem is considered, for which it is possible to obtain an optimal solution in an explicit analytical form.

The mathematical model can be generalized to more complex cases of distributed delivery of goods under conditions of uncertainty and risk.

The results of the work can be used in the development and improvement of automated management systems in the field of transport logistics.

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