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# TRANSPORTATION PROBLEM MODEL WITH PRIORITIES FOR CARGO SUPPLIERS

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*The article proposes a mathematical model of the transport problem taking into account the priorities of cargo suppliers, which is focused on increasing the efficiency of transport flow management in conditions of heterogeneity of transportation participants and different levels of their importance. In modern transport and logistics systems, situations are increasingly arising when cost minimization is not the only and sufficient criterion for transportation efficiency. In practice of operating transport systems, there is a need for priority service for individual suppliers, which is due to the strategic importance of cargo, limited delivery time, social significance or terms of contractual obligations. Such cases include the transportation of humanitarian aid, energy resources, perishable products, medical products, as well as ensuring the continuity of critical production chains. The model is based on a lexicographic approach, which provides priority consideration of supplier priorities with subsequent minimization of transportation costs without the use of weight coefficients. Such a formulation of the problem increases the objectivity of decision-making, eliminates subjectivity in choosing model parameters and allows for the formalization of hierarchical requirements in transport planning. An algorithm for constructing a reference plan that takes into account the hierarchy of suppliers and combines it with local minimization of transportation costs has been developed. The potential method for finding the optimal plan has been improved by introducing restrictions on permissible recalculation cycles, which allows preserving the priority structure of the problem at the stage of iterative optimization. The proposed model can be applied in the practice of freight transportation with a hierarchical structure of participants.*

***Key words:*** *transport problem; potential method; freight transportation; optimal delivery plan; supplier priorities; lexicographic optimization; transport logistics.*

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**Introduction.** Effective management of transport processes is one of the key components of the functioning of modern logistics systems. The tasks of distributing cargo flows between suppliers and consumers arise in various sectors of the economy - from industry and the agricultural sector to energy, trade and humanitarian logistics. In most cases, such tasks are formalized in the form of a classical transport problem, which allows determining the optimal transportation plan based on the criterion of minimizing total transport costs, provided that consumer demand is met and suppliers' resources are fully used.

However, the practical conditions of operation of transport systems often go beyond the classical assumptions. In real logistics processes, suppliers can have different levels of importance, due to strategic, economic or social factors. In particular, this may apply to the transportation of humanitarian cargo, medical products, fuel and energy resources, products with a limited shelf life or servicing critical production facilities. In such cases, not only cost minimization is of paramount importance, but also ensuring priority service for individual suppliers.

Ignoring this aspect in the classical transport model can lead to situations where the economically optimal transport plan does not meet the real needs of the system, as it does not guarantee the priority delivery of goods from the most important suppliers. This necessitates the expansion of traditional approaches to solving transport problems by taking into account additional criteria, in particular priority.

One effective approach to taking into account the hierarchy of importance is the use of discrete priority indicators that allow formalizing the order of service of suppliers. This approach allows combining economic feasibility with practical requirements for the functioning of transport systems, ensuring a balance between minimizing costs and fulfilling priority tasks.

In this context, it is relevant to develop mathematical models of transport problems that take into account the priorities of suppliers, as well as appropriate algorithms for solving them. Of particular importance is the construction of such methods that allow integrating priority into the process of forming both the reference and optimal transportation plans without significantly complicating the computational procedures.

Thus, the study of transport problems taking into account priorities is a relevant scientific and applied direction, which is of great importance for increasing the efficiency of management of transport and logistics systems in the conditions of increasing complexity and dynamism of modern economic processes.

**Analysis of recent achievements and publications.** Modern linear programming transport problems are evolving towards a more complex model structure, transition to multi-criteria formulations, and consideration of additional conditions of priority, uncertainty, and dynamics of logistics systems.

A generalized mathematical and information model of the transport problem, focused on increasing the efficiency of freight transportation, is presented in [1], which lays down basic approaches to the formalization of transport flows in complex economic systems. However, the work does not consider the problem of taking into account discrete priorities of suppliers and their hierarchical influence on the formation of the transportation plan.

Further development of the classical transport problem taking into account the structural features of suppliers and their grouping is considered in [2], which creates the prerequisites for introducing additional characteristics of suppliers, in particular their priority when forming transportation plans. However, this model does not provide for lexicographic optimization and a mechanism for preserving priorities when searching for the optimal plan.

In [3], optimization of freight delivery processes at the enterprise level is considered, which allows taking into account organizational constraints and forming more adaptive transport solutions. However, the problem of formally introducing a hierarchy of suppliers into a classical transport problem is not raised in this study.

An extension of the transport model for the case of using different types of vehicles is presented in [4], where the heterogeneity of transport resources is taken into account, which indirectly affects the priority of using individual transportation directions. At the same time, the paper does not investigate the issue of priority service of suppliers as a separate optimization criterion.

Multi-criteria transportation models with fuzzy parameters were investigated in [5], where decision priorities can be specified through weights and fuzzy estimates of the importance of suppliers or consumers. However, the use of weights does not provide a rigid hierarchy of priorities, which is implemented in the lexicographic approach of the proposed work.

In [6], a model of a sustainable supply chain is proposed, in which the priority of orders and goods is taken into account through a multi-level decision-making system, which allows managing the order of satisfaction of needs. However, the paper does not consider the modification of the classical transportation problem and methods for its solution taking into account the priorities of suppliers.

Environmental and stochastic aspects of transport planning are considered in [7], where priorities can be formed as additional criteria along with cost and delay minimization. However, the issue of constructing a mathematical mechanism for preserving the priority structure during transport plan optimization is not investigated.

Dynamic transport systems with real-time adaptive routing are presented in [8], which allows changing transportation priorities during the execution of the transport plan. However, the main focus of the work is on routing, and not on the problems of distributing cargo flows between suppliers and consumers.

Integrated transport systems for combined transportation are considered in [9], where different types of flows can have different levels of priority in a single transport network. At the same time, the issue of formalizing the priorities of suppliers within the classical transport problem remains beyond the authors' attention.

Modern artificial intelligence methods for optimizing logistics processes are summarized in [10], in particular for problems where order priorities are determined dynamically based on environmental data. However, the work does not propose a mathematical model of the transportation problem with a clear lexicographic structure of criteria.

Environmentally oriented freight routing models are investigated in [11], where priorities can be related to minimizing the carbon footprint of individual shipments. However, the problem of prioritizing suppliers depending on their importance is not considered in the work.

Multi-criteria models for perishable goods delivery in [12] consider priority according to time constraints and the level of criticality of delivery. However, these approaches focus mainly on routing and time parameters, rather than on the hierarchy of suppliers in the transportation problem.

Applied optimization algorithms in specialized logistics systems are considered in [13], where the priority can be determined by the specifics of the industry, in particular pharmaceuticals. However, the work lacks a formalization of the transportation problem with discrete supplier priorities and corresponding constraints on the optimization process.

Hybrid intelligent traffic routing systems in [14] allow combining different optimization criteria, including the priority of individual routes. However, the issue of modifying the classical potential method to preserve the hierarchy of supplier priorities is not considered.

A systematization of vehicle routing problems is presented in [15], where it is shown that modern models increasingly include elements of priority transportation planning. However, the problem of constructing a transportation problem with lexicographic optimization and supplier priorities remains insufficiently studied.

Thus, the analysis of modern research shows that although multi-criteria, fuzziness and dynamism are widely used in transport problems, the issue of formal introduction and algorithmic consideration of supplier priorities in the classical transport problem remains insufficiently developed. This necessitates the development of a mathematical model of the transport problem with lexicographic consideration of supplier priorities and modified methods for constructing reference and optimal transportation plans.

**Goal and problem statement.** In modern transport and logistics systems, situations are increasingly arising when cost minimization is not the only and sufficient criterion for transportation efficiency. In the practice of operating transport systems, there is a need for priority service for individual suppliers, which is due to the strategic importance of the cargo, time constraints, social significance or terms of contractual obligations. Such cases include, in particular, the transportation of humanitarian aid, energy resources, perishable products, medical products, as well as the maintenance of critical production chains.

The classical transportation problem, which consists in finding a transportation plan with minimal costs, provided that the demand of all consumers is satisfied and the suppliers' inventories are completely removed, does not take into account such aspects. In it, all suppliers are considered equivalent, which can lead to economically optimal, but from a practical point of view unacceptable solutions, when less important suppliers are served before more priority ones.

In this regard, a scientific and applied problem arises of developing such a model of the transport problem that would allow taking into account the hierarchy of importance of suppliers and ensure priority execution of transportation for objects with a higher priority level, without violating the general balance constraints of the system.

The aim of the work is to develop a mathematical model of the transport problem with the priorities of cargo suppliers, in which each supplier is assigned a discrete priority indicator, as well as to form an effective algorithmic approach to its solution. In particular, it is planned to build a model with a lexicographic formulation of the objective function, where the dominant criterion is the maximization of the volume of transportation from suppliers with higher priority levels, and the secondary criterion is the minimization of total transport costs.

An additional task of the research is to develop modified methods for constructing reference and optimal transportation plans that would ensure that priorities are taken into account at all stages of solving the problem. This involves adapting classical approaches, in particular the least cost method and the potential method, by introducing rules that limit permissible redistributions of cargo flows according to the hierarchy of priorities.

Thus, the problem statement consists in determining a transportation plan that satisfies all balance constraints, ensures maximum consideration of supplier priority in the lexicographic sense, and at the same time minimizes total transportation costs.

This paper proposes a conceptual mathematical model of the transportation problem, focused on formalizing the mechanism for taking into account supplier priorities and building an appropriate algorithmic approach to the solution.

**Presentation of the main research material.** Let there be given *m* cargo suppliers $A_1$, $A_2$, ..., $A_i$, ..., $A_m$, which have cargo concentrated in quantities $a_1$, $a_2$, ..., $a_m$ units, respectively. This cargo needs to be transported to *n* cargo consumers $B_1$, $B_2$, ..., $B_j$,..., $B_n$, who need it in quantities $b_1$, $b_2$, ..., $b_n$ units, respectively.

Unlike the classical transportation problem, each supplier $A_i$ a discrete priority indicator is matched a discrete priority indicator is matched $p_i \in P$, where $P$is the set of possible priority values:

$$P = \{p_1; p_2; \dots; p_m\}. \tag{1}$$

The higher the value $p_i$, the higher the priority of the corresponding supplier, reflecting the need for priority shipment from him. The priority values may coincide for any number of suppliers.

It should be noted that in the case where all $p_i$are the same, the proposed model reduces to a classical transportation problem.

It is also assumed that suppliers' priorities may coincide.

In the form of the cost of transporting a unit of cargo from any supplier to any consumer, given in the form of a matrix:

$$\begin{pmatrix} C_{11} & C_{12} & \dots & C_{1n} \\ C_{21} & C_{22} & \dots & C_{2n} \\ \dots & \dots & \dots & \dots \\ C_{m1} & C_{m2} & \dots & C_{mn} \end{pmatrix} \tag{2}$$

or abbreviated:

$$C_{ij},$$

where *i* is the number of the cargo supplier, $i = \overline{1, m}$;

*j* – cargo consumer number, $j = \overline{1, n}$.

It is necessary to draw up a transportation plan that:

1) ensures priority shipment of cargo from suppliers with the highest priority;
2) satisfies the needs of all consumers;
3) has the lowest total cost.

Let us denote the transportation plan by:

$$X = \{x_{11}; x_{12}; \dots; x_{1n}; x_{21}; x_{22}; \dots; x_{2n}; \dots; x_{m1}; x_{m2}; \dots; x_{mn}\}, \tag{3}$$

where $x_{ij}$ – the amount of cargo transported from supplier $A_i$ to consumer $B_j$.

Let's build an objective function taking into account the priority of cargo suppliers.

Since the problem contains two criteria, it is advisable to use a lexicographic formulation.

The first (main) criterion is priority maximization.

For further formalization, let us introduce a set of different priority values that are actually implemented for given suppliers, and order them in descending order:

$$P^* = \{p^{(1)}, p^{(2)}, \ldots, p^{(k)}\}, \tag{4}$$

where $p^{(1)} > p^{(2)} > \cdots > p^{(k)}$.

Here $P^* \subseteq P$ – is the set of unique priority levels without repetitions and is the $p^{(r)}$– $r$-th level in descending order.

For each priority level, $p^{(r)}$ we enter the value:

$$S_r = \sum_{i:p_i=p^{(r)}} \sum_{j=1}^{n} x_{ij}, \tag{5}$$

which determines the total volume of cargo $S_r$ exported from suppliers with the corresponding priority level $p^{(r)}$.

Taking into account the introduced notations, the optimality criterion is formulated as a problem of lexicographic maximization of the following vector:

$$(S_1, S_2, \ldots, S_k) \to \max_{lex}. \tag{6}$$

This approach means that optimization is performed sequentially by priority level: first, the volume of transportation for suppliers with the highest priority level is maximized, then, among the solutions obtained, the volume of transportation for the next level is maximized, and so on. Thus, the possibility of improving the performance of lower priority suppliers by reducing the volume of transportation for higher priority suppliers is excluded.

The second criterion is cost minimization.

Among the set of transportation plans that are optimal in the lexicographic sense, the plan with the minimum total transportation cost is selected:

$$\begin{aligned} F = C_{11} \cdot x_{11} + C_{12} \cdot x_{12} + \cdots + C_{1n} \cdot x_{1n} + C_{21} \cdot x_{21} + C_{22} \cdot x_{22} + \cdots + C_{2n} \cdot x_{2n} + \cdots \\ + \\ + C_{m1} \cdot x_{m1} + C_{m2} \cdot x_{m2} + \cdots + C_{mn} \cdot x_{mn} = \\ = \sum_{i=1}^{m} \sum_{j=1}^{n} C_{ij} \cdot x_{ij} \to min \end{aligned} \tag{7}$$

under the conditions of fulfilling the balance constraints of the transport problem:

$$\begin{cases} \sum_{j=1}^{n} x_{ij} = a_i, \ i = \overline{1,m}, \\ \sum_{i=1}^{m} x_{ij} = b_j, \ j = \overline{1,n}, \\ x_{ij} \geq 0. \end{cases} \tag{8}$$

Thus, the objective function of the specified transport problem, taking into account the priorities of suppliers and the economic criterion of cost minimization, can be formulated in a single generalized statement. Since the problem simultaneously considers two different criteria - maximizing priority- weighted transportation volumes and minimizing the total cost of transportation - it is advisable to use a lexicographic approach to optimization.

To coordinate the optimization directions, the second criterion, which corresponds to the minimization of total transportation costs, is reduced to a maximization problem by changing the sign of, i.e., the quantity is considered $-F$.

Such a transformation allows us to consider both criteria in a single vector form without changing the substantive interpretation of the problem.

As a result, the generalized optimization criterion can be written as lexicographic maximization of the vector:

$$(S_1; S_2; \dots; S_k; -F) \to \max_{lex}. \qquad (9)$$

In this entry, the first components of the vector $S_r$, $r = \overline{1,k}$, determine the levels of transportation performance for suppliers in descending order of their priorities, ensuring a strict hierarchy of service. This means that the optimization process first achieves the maximum possible transportation performance for suppliers with the highest priority level, and only then does the following levels take into account.

The last component of the vector, equal to $-F$, reflects the economic criterion and ensures the selection of the least costly transportation plan among all solutions that are optimal in terms of the priority component. Thus, the proposed form of notation provides a clear separation of criteria according to their importance and implements the principle of sequential (lexicographical) optimization without mutual compensation between priority and cost.

The solution of the proposed transport problem taking into account the priorities of suppliers is carried out in two interconnected stages using modified classical approaches to constructing the reference and optimal plans. At the first stage, a reference plan is formed, which takes into account both the structure of transport costs and the priority of suppliers, after which the resulting plan is subject to further improvement using the modified potential method taking into account the priority constraints.

Let's consider the algorithm for constructing a reference plan.

The construction of a reference plan for a transportation problem with supplier priorities is carried out by gradually examining the rows of the transportation table in accordance with the decreasing level of supplier priority.

Let us consider a set of suppliers $A = \{A_i\}_{i=1}^{m}$ with priorities $p_i$, a set of consumers $B = \{B_j\}_{j=1}^{n}$, and a set of valid cells of the transport table.

Let's introduce the set of active suppliers:

$$I = \{1,2, \dots, m\}. \qquad (10)$$

The algorithm is executed until the set is completely empty $I$.

First, the maximum priority level among active providers is determined:

$$p^* = \max_{i \in I} p_i, \qquad (11)$$

and a set of suppliers of this level is formed:

$$I^* = \{i \in I \colon p_i = p^*\}. \qquad (12)$$

Next, any element is selected $i^* \in I^*$and the corresponding row is examined $i^*$.

This line defines the set of minimum values:

$$\Omega_{i^*} = \{j \in \{1, \dots, n\} \colon c_{i^* j} = \min_k c_{i^* k}\}. \qquad (13)$$

An index is selected $j^*$ from the set $\Omega_{i^*}$ for which the minimum cost rule is satisfied (in case of ambiguity, the choice is arbitrary).

The value of transportation is formed:

$$x_{i^*j^*} = \min(a_{i^*}, b_{j^*}). \quad (14)$$

After that, the residual values are updated:

$$\begin{cases} a'_{i^*} = a_{i^*} - x_{i^*j^*} \\ b'_{j^*} = b_{j^*} - x_{i^*j^*}. \end{cases} \quad (15)$$

If $a'_{i^*} = 0$, then $i^*$ is excluded from the set of active suppliers:

$$I' = I \setminus \{i^*\}. \quad (16)$$

If $b'_{j^*} = 0$, the corresponding consumer is considered satisfied and no longer participates in further iterations.

After that, the procedure is repeated, starting with determining the new maximum priority among the updated set $I$, until complete completion $I = \emptyset$.

The resulting matrix $X = \{x_{ij}\}$ is a reference plan for the transportation problem, built taking into account the hierarchy of supplier priorities and local minimization of transportation costs within each row.

Now let's consider a method for finding the optimal plan for a transportation problem taking into account supplier priorities. For this, the potential method is used, modified to take into account the priority hierarchy.

Based on the found reference plan, a planning table is built, which is supplemented by the potentials of suppliers $u_i$and consumers $v_j$.

The number of occupied cells is first checked. If it is less than $m + n - 1$, the plan is degenerated by introducing zero transports into free cells with the lowest cost values until the required number of basic cells is reached.

Next, one of the potentials (usually for the supplier with the largest number of basic cells) is taken equal to zero. The values of the other potentials are determined from the conditions:

$$u_i + v_j = c_{ij} \quad (17)$$

for all basic cells.

After that, the optimality condition for free cells is checked:

$$u_i + v_j \leq c_{ij}. \quad (18)$$

If this condition is met for all free cells, the resulting plan is optimal.

In the opposite case, for each cell in which the optimality condition is violated, the value is determined:

$$\Delta_{ij} = u_i + v_j - c_{ij}. \quad (19)$$

Among such cells, the cell $(i^*, j^*)$ with the maximum value is selected $\Delta_{ij}$, which is considered as a candidate for inclusion in the basis.

For the selected cell, a closed cycle is constructed, the vertices of which are alternately marked with the signs "+" and "–", starting from cell $(i^*, j^*)$.

Next, among the cells of the cycle marked with a "–" sign, the minimum transportation value is determined:

$$\theta = \min x_{ij}. \quad (20)$$

Unlike the classic potential method, this stage introduces an additional check related to supplier priorities.

Let the cell for which the minimum is reached $\theta$ belong to the row $i^-$, and the initial cell $(i^*, j^*)$ to the row $i^+$. The transition to a new plan is allowed only if one of the conditions is met:

$$\left[\begin{array}{l} i^- = i^+ \\ \\ p_{i^-} \le p_{i^+}. \end{array}\right. \tag{21}$$

That is, transportation exclusion is allowed only for the supplier whose priority is not higher than that of the supplier for whom transportation is increased.

If the specified condition is met, a new plan is formed by adding the value $\theta$ to the cells of the cycle marked with a "+" sign and subtracting it from the cells marked with a "−" sign.

If the condition is not met (i.e., the cycle assumes a reduction in transportation for the supplier with a higher priority), the constructed cycle is rejected, and the cell $(i^*, j^*)$ is not considered a candidate for inclusion in the basis.

It should be noted that the proposed restriction on permissible cycles is heuristic in nature, as it is aimed primarily at the practical preservation of the hierarchy of supplier priorities in the optimization process.

In this case, the transition is made to the next cell with violation of the optimality condition (by decreasing value $\Delta_{ij}$), for which the cycle is again constructed, and the specified condition is checked.

If none of the cells for which the optimality condition is violated satisfies the specified constraint, the current plan is considered optimal in the sense of a priority problem.

**Conclusions.** Thus, the paper presents a conceptual mathematical model of the transport problem taking into account the priorities of cargo suppliers, built on the basis of a lexicographic approach to optimization (1)−(9). A method of combining two criteria is proposed, which ensures the dominance of supplier priority over the minimization of transportation costs without the use of weight coefficients, which increases the objectivity of decision-making.

A modified algorithm for constructing a reference plan has been developed (10)−(16), which provides for a phased filling of the transport table in accordance with the decreasing level of supplier priorities, taking into account the minimization of costs within each row. This allows taking into account the hierarchy of suppliers when forming a transportation plan at the initial stage.

The potential method for finding the optimal plan has also been improved (17)−(21). The proposed modification consists in introducing restrictions on the permissible recalculation cycles, which makes it impossible to reduce transportation from suppliers with a higher priority. This ensures consistency of criteria and preservation of lexicographic optimality in the process of solving the problem.

In general, the proposed approach extends the classical transport problem and allows formalizing problems in which, along with cost minimization, it is necessary to take into account the hierarchy of suppliers. The results obtained can be used in the practice of freight transportation when building models for managing transport flows in logistics systems of varying complexity.

**Prospects for further research.** A promising direction is to expand the proposed model by taking into account the priorities of not only suppliers but also consumers. This will allow for more flexible transportation plans that take into account the criticality of meeting the demand of individual destinations, for example, depending on the urgency or importance of orders.

Of particular interest is the study of dynamic priorities that change during the transportation process. In particular, it is possible to take into account time factors, delays, changes in demand or external conditions that affect the order of service. This opens up opportunities for building adaptive models of transport tasks that can respond to changes in the environment in real time.

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**Афонін М. О., Славич В. П., Бабійчук К. О.** МОДЕЛЬ ТРАНСПОРТНОЇ ЗАДАЧІ З ПРІОРИТЕТАМИ ДЛЯ ПОСТАЧАЛЬНИКІВ ВАНТАЖУ

*У статті запропоновано математичну модель транспортної задачі з урахуванням пріоритетів постачальників вантажу, яка орієнтована на підвищення ефективності управління транспортними потоками в умовах неоднорідності учасників перевезень та різного рівня їхньої значущості. У сучасних транспортно-логістичних системах дедалі частіше виникають ситуації, коли мінімізація витрат не є єдиним і достатнім критерієм ефективності перевезень. У практиці функціонування транспортних систем існує необхідність першочергового обслуговування окремих постачальників, що зумовлено стратегічною важливістю вантажів, обмеженістю часу доставки, соціальною значущістю або умовами контрактних зобов'язань. До таких випадків належать перевезення гуманітарної допомоги, енергоресурсів, швидкопсувних продуктів, медичних препаратів, а також забезпечення безперервності критичних виробничих ланцюгів. Модель базується на лексикографічному підході, який забезпечує першочергове врахування пріоритетів постачальників із подальшою мінімізацією транспортних витрат без використання вагових коефіцієнтів. Така постановка задачі підвищує об'єктивність прийняття рішень, усуває суб'єктивність при виборі параметрів моделі та дозволяє формалізувати ієрархічні вимоги в транспортному плануванні. Розроблено алгоритм побудови опорного плану, що враховує ієрархію постачальників і поєднує її з локальною мінімізацією вартості перевезень. Удосконалено метод потенціалів для знаходження оптимального плану шляхом введення обмежень на допустимі цикли перерахунку, що дозволяє зберігати пріоритетну структуру задачі на етапі ітераційної оптимізації. Запропонована модель може бути застосована в практиці вантажних перевезень з ієрархічною структурою учасників.*

***Ключові слова:*** *транспортна задача, метод потенціалів, вантажні перевезення, оптимальний план доставки, пріоритети постачальників, лексикографічна оптимізація, транспортна логістика.*



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