ISSN-L 2664-9969; E-ISSN 2706-5448

ECONOMICS OF ENTERPRISES:
ECONOMIC CYBERNETICS

UDC 519:866
JEL Classification: C61, L81, R41
DOI: 10.15587/2706-5448.2025.337246

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DEVELOPMENT OF VECTOR MODELS AND METHODS FOR THEIR SOLUTION FOR OPTIMIZATION OF LOGISTICS PROBLEMS IN E-COMMERCE

The object of research is the logistics processes of delivering goods in a digital environment (e-commerce), which require optimization using mathematical models. One of the most problematic areas is taking into account dynamic changes and unpredictable factors: seasonal and daily fluctuations in demand, delays in deliveries, fluctuations in delivery costs, changes in routes, etc. This necessitates the creation of adaptive mathematical models that can quickly respond to changing conditions and ensure high efficiency of logistics processes in real time.

The study used a comprehensive approach that includes: mathematical modeling, linear programming methods (in particular, the potential method, the simplex method), the unloading cycle method, as well as multi-criteria analysis and decision-making methods. The experiments were performed using the MATLAB and Python computing environments based on both real and synthetic data that simulate e-commerce conditions.

The main results of the study are as follows. First, it was established that classical scalar models of the transport problem (TP) are insufficient for describing multi-criteria logistics conditions in e-commerce, where it is important to simultaneously take into account several performance indicators. Second, the feasibility of using vector models that allow optimizing delivery processes according to several criteria – in particular, minimizing total costs, transportation time or loading time – was demonstrated. Such models reflect the real conditions and requirements of e-commerce much more accurately. Third, it was proven that the use of vector models allows achieving a balanced distribution of resources between competing criteria, which makes it possible to find compromise, but strategically more effective solutions at the moment. The possibility of using normalization methods, as well as methods of multi-criteria selection, was also demonstrated. As a result, two-criteria and three-criteria models of the transport problem were developed, implemented and tested, adapted to the conditions of digital logistics. It is shown that, taking into account the priorities of the criteria, these models provide a more flexible and adequate solution to optimization problems, compared to classical approaches.

***Keywords**: e-commerce, logistics processes, optimization, vector transport problems, potential method, unloading cycles.*

Received: 29.05.2025
Received in revised form: 18.07.2025
Accepted: 06.08.2025
Published: 30.08.2025

How to cite

Mormul, M., Shchytov, D., Shchytov, A. (2025). Development of vector models and methods for their solution for optimization of logistics problems in e-commerce. Technology Audit and Production Reserves, 4 (4 (84)), 51–59. https://doi.org/10.15587/2706-5448.2025.337246

1. Introduction

E-commerce is one of the most dynamic and rapidly growing sectors of the global economy. With the expansion of online trade, numerous new challenges arise, particularly in organizing logistics and product transportation. As consumers increasingly expect not only to receive their goods but to receive them quickly and at minimal cost, efficient management of delivery processes has become a key factor in the success of e-commerce companies.

One of the most important problems in this field is the transportation problem (TP), which focuses on optimizing the process of moving goods from suppliers to consumers. This process must account for various factors such as delivery costs, time, product types, and customer needs. To address this problem, a range of mathematical models is applied, among which scalar two-index and multi-index formulations hold a prominent place. However, the specifics of shipping goods via online stores and the diversity of delivery channels require more sophisticated mathematical models, such as vector models, which – despite their significance – have not yet gained widespread application.

Classical scalar models make it possible to optimize relatively simple transportation scenarios, taking into account basic parameters such as product quantities and delivery costs. Many economic models reduce to the TP and employ established solution methods. Multi-index models allow for a more detailed approach to solving the TP, incorporating not only costs but also additional factors such as different product types, modes of transport, and countries of origin. Multi-criteria (vector) TP models go further by enabling the simultaneous consideration of several performance criteria. The importance of applying such models in e-commerce lies in their ability to reduce costs and delivery times, improve operational efficiency, and enhance customer service.

Research into the formulation and methodology for solving vector models in e-commerce makes it possible to identify optimal strategies for addressing transportation challenges and to ensure business competitiveness in today's digital environment.

The fundamental concepts and methods underlying the TP have been extensively examined in the field of mathematical optimization. While there is a substantial body of academic work on the topic globally, a number of unresolved or only partially studied issues remain with respect to vector transportation problem models in e-commerce. Some of these are outlined below.

1. Limited use of vector models in practical e-commerce cases. Most sources are theoretical or educational in nature; there is a lack of statistical or numerical data confirming the advantages of the vector approach over the scalar one in real e-commerce conditions. For example, [1] emphasizes that effective logistics is a complex system that includes storage, transportation, order processing, and supply chain management. However, it does not provide empirical data or concrete market cases. Moreover, the study is based mainly on the Indian context, which reduces the universality of its conclusions.

The advantages of [2] include the systematization of basic classical and modern optimization techniques in the context of their applicability to solving practical problems in logistics, engineering, manufacturing, and management, as well as broad thematic coverage (linear programming, integer optimization, dynamic programming, heuristic methods, genetic algorithms, and other approaches are considered). However, the work is of a review nature without mathematical derivations or empirical examples, and lacks comparative tables or graphs, which makes it difficult to quickly compare the effectiveness of the methods.

Study [3] proposes two new modified variants of the transportation problem under unstable (variable) supply conditions. Numerical solution examples (Excel Solver) are provided to compare the classical model and both new models. However, the work contains only conceptual examples without testing on real logistics data or cases, and has limited universality: the models are focused on a specific sector (pharmaceuticals with a logistics hub), which may reduce their applicability to other industries or supply chains.

Publication [4] proposes a matrix-network transportation problem model that treats the shortest path problem between two nodes in a logistics network as a freight flow problem. This approach applies the flow conservation principle at each network node, in line with classical methods of graph and network flow optimization. As a practical example, international transportation routes between Poltava (Ukraine) and Amsterdam (Netherlands) are considered, showing that the optimal route is 2,317 km long (instead of the traditional 2,730 km). Limitations of the work include its focus on small-scale networks (the model is described for a small network with 10 nodes and 18 arcs); the lack of comparisons with other methods and algorithms (limiting the justification of optimality); and the absence of real data – the model is tested on a demonstration network, without validation on practical logistics scenarios.

The collection [5] discusses the theoretical and methodological foundations of the transportation problem, constructing various models and providing solution techniques. Advantages include the well-substantiated presentation and variety of approaches and types of TPs. Disadvantages include the absence of practical applications.

In [6], which analyzes a three-index model under uncertainty (unstable stocks, demand, costs), the advantages are the model's adaptation to uncertainty, realism, and the use of multiple methods (stochastic programming, fuzzy sets, genetic algorithms). The disadvantages are the absence of empirical testing and low computational efficiency.

Work [7] presents the formulation of the transportation problem and methods for solving it. However, it lacks examples of problem-solving or comparative effectiveness of methods, focusing only on classical approaches.

2. Although multimodal transportation problems (TPs) are often mentioned, there is insufficient detail on how these models are adapted for e-commerce. For example, [8] is devoted to the theoretical and applied aspects of organizing multimodal and intermodal freight transportation. However, it only lists practical measures for implementing these types of transportation without specific examples or models that should be used for process optimization.

Publication [9] presents the formulation and implementation of multimodal transportation problems in three software environments: MS Excel, Mathcad, and MATLAB. Using model data, it is shown that optimization results are identical in all three environments, confirming the correctness of the implementations. However, the study is based on model data, without implementation or testing in real logistics scenarios – focusing on method demonstration rather than comparison of performance, execution time, scalability, etc.

Work [10] investigates improvements in algorithms for building the initial feasible solution of a multimodal transportation problem with a large number of shipment components and different transport modes. However, the method is described conceptually and without implementation on real data or examples with large volumes and integration into practical systems. There is also no direct comparison with other approaches or methods of generating initial feasible solutions, making it difficult to assess the advantages.

In [11], the efficiency of intermodal transportation is analyzed as a key factor in improving the quality of transport services. In particular, the integration of different types of transport (rail, sea, road) into a single logistics system is examined. The work emphasizes the importance of integrating rail and sea transport, organizing container chains, and ensuring the interaction of logistics systems to achieve operational and economic benefits. However, it lacks quantitative data or examples of large-scale implementation, and formal or mathematical models of efficiency are replaced with conceptual recommendations.

3. While some sources consider the use of artificial intelligence in logistics – an important step towards modern adaptive (vector) models – comprehensive research is lacking. For example, [12] discusses AI capabilities in various functional segments of supply chain management (SCM), such as demand forecasting, inventory management, logistics optimization, improving system transparency, and minimizing risks. It also analyzes the impact of AI on decision-making and collaboration within the supply chain. However: the review is theoretical and analytical, without practical cases or statistical studies; individual technologies or algorithms are not detailed – mentions of ML, NLP, RPA, robotic process automation, etc., are general; and the context is generic, without focus on specific industries or regions.

Study [13] examines the role of AI in logistics management as a factor in the sustainable development of e-business under the pressure of military challenges and the pandemic. The delivery quality model is considered through the lens of environmental friendliness, timeliness, and cost-effectiveness, identifying problems of insufficient access to up-to-date data, low process transparency, and route planning inaccuracies. Despite its relevance, the article has a review and analytical nature without empirical cases, quantitative assessments, or real-life examples. References to AI and automation are general, without discussion of specific models or tools.

4. The roles of adaptive models in crisis or unstable conditions are underexplored. For example, in the context of wartime, pandemics, or global supply chain disruptions, adaptive and hybrid TPs are required, particularly for simulation modeling of logistics processes in the military sphere. Study [14] is devoted to logistics processes in military supply, with justification that the classical transportation problem model can be successfully integrated into simulation modeling. Advantages include the integration of optimal modeling and system simulation and adaptability to military conditions. Disadvantages include: the absence of empirical or experimental assessments (e. g., testing on real data); limited detail of methods (simulation methodology is presented mainly at a conceptual and theoretical level, without implementation steps or technical algorithms); and a specific application domain (military logistics), which may reduce the adaptability of the approach for commercial or civilian logistics operations. This topic is partially touched upon in [13].

5. Few sources address aspects of the practical application of vector TPs in e-commerce. Study [15] presents a systematized literature review on e-commerce and logistics up to 2012 and proposes directions for further research: logistics models for e-commerce; IT solutions and integration into logistics chains; customer interaction; organizational transformation under the influence of digital trade. However, as of 2025, many of the mentioned approaches are already outdated. Study [16] lacks practical cases, empirical results, or substantiated conclusions from real e-commerce systems. It also lacks geographical specificity, i. e., differences in the level of logistics development in different countries are not considered.

Thus, the relevance of the chosen topic is driven by the insufficiently developed scientific framework for solving multi-criteria transportation problems (TP), where the criteria include: total transportation cost, total cargo-time of transportation, and the time required to supply consumers with the necessary volume of products.

There is a need for further research, which should include, in particular, the following:

1) development of vector TP models adapted to e-commerce (with multiple criteria: total transportation cost, total cargo-time of transportation, and the time required to supply consumers with the necessary volume of products);

2) study of stochastic and adaptive TP models for the highly dynamic environment of the online market;

3) integration of transportation models with e-commerce platforms, etc.

The aim of research is to develop models and methodologies for solving vector TP models in the context of e-commerce and to determine the effectiveness of their application for optimizing logistics processes. Specifically, the study of these models is intended to identify ways to reduce transportation costs, improve delivery speed, and manage warehouse inventory in online trade.

To achieve this aim, the following objectives were set:

1. Formulate various multi-criteria transportation problem models.
2. Develop a methodology for solving vector TP models.
3. Investigate the features of mathematical models in the context of e-commerce, identifying potential advantages and limitations of their use.
4. Consider an example of solving a vector TP in the field of e-commerce.

2. Materials and Methods

The object of research is the processes of distributing goods or resources in e-commerce systems, which can be formalized in the form of transportation problems.

Varieties of methods were applied in the study:

1. *Mathematical modeling* – constructing mathematical models for different types of vector TP that make it possible to take into account various parameters (cost, time, quantity of goods, etc.) when optimizing logistics processes [5, 16].
2. *Linear programming methods* for solving the constructed models: the potentials method, simplex method.
3. *The unloading cycles method; methods for solving various multi-criteria TP models.*
4. *Software environments MATLAB and Python* for implementing the developed models.

The research methodology is based on a combination of theoretical and practical sources of information. The theoretical foundation consisted of scientific studies in the fields of economic-mathematical modeling, TP optimization, multi-criteria analysis, as well as research in the domain of e-commerce. In particular, works on the theory of linear programming, methods of scalarization and normalization of vector criteria, application of the potentials method, unloading cycles method, simplex method, and its modifications were analyzed.

The practical part of the study was based on the analysis of real-world logistics scenarios, e-commerce data (including delivery cost, delivery time, warehouse geography), as well as simulation of hypothetical situations based on marketplace data.

3. Results and Discussion

3.1. The transportation problem in e-commerce

In optimization theory, this problem consists in minimizing the cost of transporting goods between several sources (manufacturers or warehouses) and consumers (stores or end customers), taking into account constraints on the quantity of goods at the sources and the needs of the consumers. In e-commerce, TP is applied in the cases shown in Table 1.

Table 1

Application of the transportation problem in e-commerce

No.	Applications	Description	Possible complications
1	2	3	4
1	Optimizing the cost of delivering goods to consumers	Determining the least expensive delivery routes under existing constraints (cost, transport capacity, time)	From some supply points to some consumption points:
2	Inventory management	Determining the optimal inventory levels in warehouses and distributing resources between warehouses based on demand	a) deliveries cannot be made;
3	Improving customer experience	Thanks to optimized routes, delivery can be faster, which increases customer satisfaction	b) it is necessary to transport at least the specified volumes of goods;
4	Taking into account different product categories	This direction includes taking into account the specifics of goods (temperature regime, fragility, value) when planning transportation	c) it is necessary to transport no more than the specified volumes of goods;
5	Taking into account different modes of transport, countries of origin of goods, etc. when transporting goods	This requires the formation of combined logistics chains taking into account the type of transport (road, air, sea), customs restrictions, delivery time	d) it is necessary to deliver fixed quantities of goods
6	Meeting the needs of the most important points of consumption	Building models for the priority distribution of goods by the degree of importance of consumers or geographical areas	The need to take into account seasonal fluctuations, shelf life of goods, warehouse space limitations, unstable demand
7	Increasing the productivity of road transport by minimizing empty mileage	Supplying empty autotons from consumers to suppliers in such a way as to minimize total transportation costs, which increases the efficiency of transport use	Resource limitations (transport, personnel), uncertainty in delivery time windows, changes in addresses during processing
8	Allocation taking into account transport and production costs	Determining the optimal locations of warehouses, order processing centers or production facilities with minimizing total costs	Model complexity due to multivariate requirements, need for specialized transport, risks of damage

Continuation of Table 1

1	2	3	4
9	Optimizing the transportation of perishable goods or people from disaster zones	Modeling urgent logistics routes taking into account shelf life, temperature regime and delivery time	Problems with transport coordination, delays at borders, changes in exchange rates and duties
10	Multi-index vehicles	Models with several indices that take into account: processing points, cargo types, modes of transport, country of origin, warehouse restrictions	The need for strict adherence to service levels, possible resource shortages for less priority points
11	Multi-criteria vehicle settings	Here the criteria are: total transportation cost, total freight-transport time and the time required to provide all consumers with the required volume of products	Problems with optimal route combination, possible complications similar to point 1, geographical complexity

Classical transportation problems have been described in detail in works [4, 5, 7, 10]; however, they were developed for stable conditions and clearly defined input data. Modern studies [3, 8, 10] propose flexible modifications of models that take into account stochasticity and probabilistic scenarios, yet these approaches are rarely tailored to the specifics of Ukrainian marketplaces. Most of them consider two-index TPs (solved using the potentials method) and three-index TPs, which – like higher-index problems – can only be solved using the simplex method, as no alternative methods have yet been found. This is problematic due to significant time costs, even when modern information technologies are employed.

Scalar models are a convenient tool for preliminary analysis, allowing quick generation of basic solutions for the allocation of flows between supply and demand points. However, in today's e-commerce environment – characterized by multiple delivery route options, a wide variety of product categories, fluctuating demand, seasonality, as well as strict requirements for speed and reliability of logistics processes – the use of scalar models alone may be insufficient, as such models do not account for:

- the multi-dimensional nature of criteria (e. g., simultaneous minimization of cost and delivery time);
- constraints related to product categories (temperature control, expiration dates);
- the use of multiple modes of transportation;
- delivery time windows, which are critical for enhancing customer experience.

Therefore, in most real-world e-commerce cases, it is advisable to employ vector or multi-criteria models, which make it possible to comprehensively account for numerous influencing factors, ensure the adaptability of logistics schemes, and support decision-making under uncertainty and market dynamics.

The proposed mathematical models are extensions of the classical transportation problem, incorporating multiple criteria and methods for solving such models. The following quality criteria were considered: total freight transportation costs; total cargo-time of goods transportation; time required to supply all consumers with the necessary volume of products, among others. This approach enables the consideration of not only economic but also temporal indicators. Given the large volume of data, vector models allow e-commerce enterprises to optimize delivery processes, warehouse selection, delivery routes, and the identification of the most efficient transportation methods [6].

3.2. Multi-criteria formulations of the transportation problem

Since vector formulations of the transportation problem simultaneously take into account several quality indicators, which may conflict with one another, it becomes necessary to apply methods for finding compromise solutions that incorporate the prioritization (weighting) of each criterion.

When solving such problems, three main issues arise:

1. Selecting an optimality principle that makes it possible to determine why one solution is preferable to another.

2. Determining the weighting coefficients for each quality indicator, which allows for the assessment of the importance of each indicator, with the sum of all weighting coefficients equaling one $\sum_{i=1}^{n}\alpha_i = 1$.

3. In vector optimization problems, the criteria often have different scales and units of measurement. Therefore, it is necessary to perform normalization or scaling of the criteria. This process brings the indicators to the same units of measurement or makes them dimensionless, ensuring the possibility of their correct comparison [6].

Several vector models of the transportation problem are considered below.

A bi-criteria transportation problem, in which the quality criteria are the total cost of transporting goods and the total cargo-time of transportation, can be formulated as follows:

$$\bar{F}(X) = \{L(X), T(X)\} \to \min_{X\in D};$$
$$\begin{cases} L = \sum_{i=1}^{m}\sum_{j=1}^{n} c_{ij}x_{ij} \to \min; \\ T = \sum_{i=1}^{m}\sum_{j=1}^{n} t_{ij}x_{ij} \to \min, \end{cases} \tag{1}$$

under constraints D:

$$\begin{cases} \sum_{j=1}^{n} x_{ij} \le a_i, \quad i = \overline{1,m}; \\ \sum_{i=1}^{m} x_{ij} \ge b_j, \quad j = \overline{1,n}; \\ x_{ij} \ge 0, \quad i = \overline{1,m}, \quad j = \overline{1,n}, \end{cases} \tag{2}$$

where m is the number of supply points, n is the number of consumption points (c_{ij}, t_{ij} are the cost and time of transportation of a unit of cargo from the i-th supplier to the j-th consumer).

This problem is reduced to a scalar task by collapsing the efficiency criteria into a single criterion

$$F(X) = \alpha_1 \frac{L(X) - L_{\min}}{L_{\max} - L_{\min}} + \alpha_2 \frac{T(X) - T_{\min}}{T_{\max} - T_{\min}} \to \min, \tag{3}$$

where $L_{\min} = \min_{X\in D} L(X), L_{\max} = \max_{X\in D} L(X), T_{\min} \quad \min_{X\in D} T(X), T_{\max} = \max_{X\in D} T(X),$ D is a set of constraints (2).

The generalized criterion $F(X)$ includes a natural normalization of quality criteria (reduction to a dimensionless form) and takes into account the importance of the criteria using weight coefficients α_1 and α_2. These coefficients can be adjusted by the decision-maker (DM) in an interactive mode with the computer to increase or decrease the importance of the criteria. Once the scalar transportation problem is obtained, it is solved using the method of potentials, and the values of the criteria $L(X)$ and $T(X)$ are determined for the resulting optimal plan.

A bi-criteria transportation problem, where the quality criteria are represented by either the total transportation cost or the total freight-time of cargo transportation, and the time required to supply all consumers with the necessary volume of products, is formulated as follows:

$$\overline{F}(X)=\{L(X),t(X)\}\to\min_{X\in D},\tag{4}$$

or $$\overline{F}(X)=\{T(X),t(X)\}\to\min_{X\in D};\tag{5}$$

$$L(X)=\sum_{i=1}^{m}\sum_{j=1}^{n}c_{ij}x_{ij}\to\min;\tag{6}$$

$$T(X)=\sum_{i=1}^{m}\sum_{j=1}^{n}t_{ij}x_{ij}\to\min;\tag{7}$$

$$t(X)=\max_{x_{ij}>0}t_{ij}\to\min,\tag{8}$$

under constraints (2).

When solving such a transportation problem, the optimal solution for the more important criterion is found first. If the more important criterion is $L(X)$ from formula (6) or $T(X)$ from formula (7), then the potential method is used to find the optimal plan and the minimum value of this criterion, followed by determining the value of the criterion from formula (8) corresponding to this plan. If the more important criterion is the one from formula (8), then the unloading cycles method is applied to find the time required to supply all consumers with the necessary volume of products according to formula (8), after which the other criterion, $L(X)$ or $T(X)$, is calculated based on the optimal plan.

A three-criteria transportation problem, which quality criteria are the total transportation cost; total freight-time of cargo transportation; and the time required to supply all consumers with the necessary volume of products, is formulated as follows:

$$\overline{F}(X)=\{L(X),T(X),t(X)\}\to\min_{X\in D};\tag{9}$$

$$L(X)=\sum_{i=1}^{m}\sum_{j=1}^{n}c_{ij}x_{ij}\to\min;\tag{10}$$

$$T(X)=\sum_{i=1}^{m}\sum_{j=1}^{n}t_{ij}x_{ij}\to\min;\tag{11}$$

$$t(X)=\max_{x_{ij}>0}\{t_{ij}\}\to\min,\tag{12}$$

under constraints (2).

When solving such a problem, the criteria from formulas (10) and (11) are first aggregated into a single generalized criterion according to (3). Then, the greater importance between the generalized criterion and $t(X)$ is determined. If, from the decision maker's point of view, the generalized criterion is more important, the potential method is used to find the optimal plan, on which the values of the criteria $L(X)$ and $T(X)$ are calculated. Subsequently, the value of $t(X)$ is determined according to this plan.

If $t(X)$ is considered the more important criterion, the unloading cycles method is applied to find the time required to supply all consumers with the necessary volume of products. After that, the value of the generalized criterion is computed according to (3), along with the values of the criteria $L(X)$ and $T(X)$.

In the interactive mode of decision maker's interaction with the computer, it is possible to:

a) select a compromise scheme;

b) adjust the weight coefficients of the criteria depending on priorities;

c) obtain an optimal compromise solution that best matches the current conditions or preferences of the decision maker.

3.3. Practical implementation of the TP

The transportation problem in e-commerce can be applied to an online store that sells electronics nationwide and has 3 warehouses located in different cities:

– Warehouse 1 (Kyiv) – 450 units of goods;
– Warehouse 2 (Odesa) – 250 units of goods;
– Warehouse 3 (Lviv) – 200 units of goods.

There are several delivery points (customers) in different cities:

– City 1 (Kharkiv) – 500 units of goods;
– City 2 (Dnipro) – 300 units of goods;
– City 3 (Zaporizhzhia) – 200 units of goods.

Each warehouse can ship goods to these cities, but transportation costs vary depending on the distance between the warehouse and the city, as well as the volume of goods to be delivered.

The cost and delivery time from each warehouse to each city are as follows:

– Kyiv → Kharkiv: 26 monetary units per unit, 7 hours;
– Kyiv → Dnipro: 25 monetary units per unit, 7 hours;
– Kyiv → Zaporizhzhia: 28 monetary units per unit, 8 hours;
– Odesa → Kharkiv: 36 monetary units per unit, 10 hours;
– Odesa → Dnipro: 25 monetary units per unit, 8 hours;
– Odesa → Zaporizhzhia: 24 monetary units per unit, 8 hours;
– Lviv → Kharkiv: 56 monetary units per unit, 12 hours;
– Lviv → Dnipro: 52 monetary units per unit, 11 hours;
– Lviv → Zaporizhzhia: 55 monetary units per unit, 12 hours.

The inventories and demand volumes to be shipped from warehouses to cities (customers) are given above.

It is required to organize the delivery of goods from these warehouses to the different cities in order to minimize the total transportation cost, total freight-time of transportation, and delivery time.

The input data is presented in matrices C, T, A, B:

$$C=\begin{pmatrix}26 & 25 & 28\\ 36 & 25 & 24\\ 56 & 52 & 55\end{pmatrix};$$

$$T=\begin{pmatrix}7 & 7 & 8\\ 10 & 8 & 8\\ 12 & 11 & 12\end{pmatrix};$$

$$A=(450\;250\;200);\;\sum_{i=1}^{3}a_i=900;$$

$$B=(500\;300\;200);\;\sum_{j=1}^{3}b_j=1000,$$

where $C=(c_{ij})_{m\times n}$ – the cost of transporting a unit of cargo from the i-th supplier to the j-th consumer;

$T=(t_{ij})_{m\times n}$ – the transportation time of a unit of cargo from the i-th supplier to the j-th consumer;

$A=(a_i)_m$ – the volumes of goods in warehouses;

$B=(b_j)_n$ – the customer demand for the product.

The economic and mathematical model has the form:

$$L(X)=26x_{11}+25x_{12}+28x_{13}+36x_{21}+25x_{22}+24x_{23}+$$
$$+56x_{31}+52x_{32}+55x_{33}\to\min;$$

$$t(X)=\max_{x_{ij}>0}\{t_{ij}\}\to\min;$$

$$T(X)=7x_{11}+7x_{12}+8x_{13}+10x_{21}+8x_{22}+8x_{23}++12x_{31}+$$
$$+11x_{32}+12x_{33}\to\min.$$

$$\begin{cases} x_{11}+x_{12}+x_{13}=450; \\ x_{21}+x_{22}+x_{23}=250; \\ x_{31}+x_{32}+x_{33}=200; \\ x_{11}+x_{21}+x_{31}\le 500; \\ x_{12}+x_{22}+x_{32}\le 300; \\ x_{13}+x_{23}+x_{33}\le 200; \\ x_{ij}\ge 0, i=\overline{1,3};\ j=\overline{1,3}, \end{cases}$$

where $x_{ij}, i=\overline{1,3};\ j=\overline{1,3}$ – the quantity of goods transported from the *i*-th supplier to the *j*-th consumer. Since the total stocks are not equal to the total needs, the TK is of the open type. To balance this TP, a fictitious supplier A_4 is introduced with the quantity of cargo

$$\sum_{j=1}^{3} b_j - \sum_{i=1}^{3} a_i = 1000 - 900 = 100.$$

I. The posed vector transportation problem is solved according to models (4)–(8), (2) as a bi-criteria problem. Initially, the decision maker selects the first criterion $L(X)$ as the most important. The minimum total transportation cost is obtained as follows.

1. The initial basic feasible solution is found by the minimum element method, i. e., by filling first the cell with the lowest tariff among the actually existing suppliers, so that the total shipments in the rows and columns do not exceed the supply and demand constraints (Table 2).

Table 2

First reference plan

Delivery point Shipping point	Kharkiv (B_1)	Dnipro (B_2)	Zaporizhzhia (B_3)	Supply
Kyiv (A_1)	200	250	0	450
Odesa (A_2)	0	50	200	250
Lviv (A_3)	200	0	0	200
Dummy supplier (A_4)	100	0	0	100
Demand	500	300	200	1000 1000

2. Having checked this plan for optimality by the potential method, let's obtain the Table 3.

Table 3

Checking the first plan for optimality

B_j A_i	v_j u_i	B_1	B_2	B_3	Stocks
		$v_1 = 26$	$v_2 = 25$	$v_3 = 24$	
A_1	$u_1 = 0$	26 +200	25 –250	28 0	450
A_2	$u_2 = 0$	36 0	25 50	24 200	250
A_3	$u_3 = 30$	56 –200	52 +0	55 0	200
A_4	$u_4 = -26$	0 100	0 0	0 0	100
Needs		500	300	200	1000 1000

3. The first reference plane X_1 in the form of a matrix has the following form

$$X_1 = \begin{pmatrix} 200 & 250 & 0 \\ 0 & 50 & 200 \\ 200 & 0 & 0 \\ 100 & 0 & 0 \end{pmatrix}.$$

4. And the value of the objective function in this plan

$$L(X_1) = 26 \cdot 200 + 25 \cdot 250 + 25 \cdot 50 + 24 \cdot 200 + 56 \cdot 200 =$$
$$= 5200 + 6250 + 1250 + 4800 + 11200 = 28700 \text{ (a monetary unit)}.$$

5. The number of filled cells for calculating potentials should be equal to $m + n - 1 = 4 + 3 - 1 = 6$. This condition is fulfilled after obtaining the first reference plan. The potential u_1 is given a zero value and the other potentials u_i and v_j are found from the system $u_i + v_j = c_{ij}$ for filled cells for filled cells of other potentials u_i and v_j. Since the condition $u_i + v_j \le c_{ij}$ for free cells is not fulfilled for one cell, the first initial plan is not optimal. Then the estimates $s_{ij} = c_{ij} - (u_i + v_j)$ for free cells are obtained. The smallest value among the negative estimates s_{ij} is equal to –3 (one negative estimate): $s_{32} = c_{32} - (u_3 + v_2) = 52 - (30 + 25) = -3$. The corresponding cell is considered prospective, and a "+" sign is placed in this cell. The corresponding cell is considered promising, this cell is marked with a "+" sign. A cycle is then constructed – a chain that rotates the filled cells by 90° with a change of signs. In the cells with the "–" sign, the smallest value from the quantity of goods is selected: min (250; 200) = 200, which is added to the transportations in the cells with the "+" sign and subtracted from the transportations in the cells with the "–" sign. As a result, Table 4 is built with a new plan and new potentials, which are calculated similarly.

Table 4

Checking the second plan for optimality

B_j A_j	v_j u_i	B_1	B_2	B_3	Stocks
		$v_1 = 26$	$v_2 = 25$	$v_3 = 24$	
A_1	$u_1 = 0$	26 400	25 50	28 0	450
A_2	$u_2 = 0$	36 0	25 50	24 200	250
A_3	$u_3 = 27$	56 0	52 200	55 0	200
A_4	$u_4 = -26$	0 100	0 0	0 0	100
Needs		500	300	200	1000 1000

6. Since the condition $u_i + v_j \le c_{ij}$ is satisfied for all free cells, the found plan is optimal

$$X^* = \begin{pmatrix} 400 & 50 & 0 \\ 0 & 50 & 200 \\ 0 & 200 & 0 \\ 100 & 0 & 0 \end{pmatrix}.$$

The last line is deleted from this plan, since it corresponds to a fictitious consumer.

Minimum value of total costs

$$Lmin = L(X^*) = 26 \cdot 400 + 25 \cdot 50 + 25 \cdot 50 + 24 \cdot 200 + 52 \cdot 200 =$$
$$= 10400 + 1250 + 1250 + 4800 + 10400 = 28100 \text{ (a monetary unit)}.$$

According to the obtained plan X^* for real transportations, the maximum value of transportation time is selected from the time matrix T

$$t(X^*) = 11 \text{ (hours)}.$$

At the same time, the total transportation time in the optimal plan is

$$T(X^*) = 7 \cdot 400 + 7 \cdot 50 + 8 \cdot 50 + 8 \cdot 200 + 11 \cdot 200 =$$
$$= 2800 + 350 + 400 + 1600 + 2200 = 7350.$$

II. Now the OPS selects the second criterion $t(X)$ as the most important and finds the time of cargo transportation to provide all consumers using the unloading cycles method.

The first reference plan is obtained using the minimum element method. Next, the largest transportation time is determined, and this cell is unloaded using the unloading cycles method (Table 5).

Table 5

First reference plan

Shipping point / Delivery point	Kharkiv (B_1)	Dnipro (B_2)	Zaporizhzhia (B_3)	Supply
Kyiv (A_1)	+7 200	–7 250	8 0	450
Odesa (A_2)	10 0	8 50	8 200	250
Lviv (A_3)	$\boxed{-12}$ 200	+11 0	12 0	200
Dummy supplier (A_4)	0 100	0 0	0 0	100
Demand	500	300	200	1000 1000

By analogy with the potential method, in Table 5, the smallest value of transportation among the cells with the "–" sign (in this case, 200) is determined, which is subtracted from the transportation in the cells with the "–" sign and added to the transportation in the cells with the "+" sign. Thus, Table 6 is obtained.

Table 6

Second reference plan

A_i / B_j	B_1	B_2	B_3	Stocks
A_1	7 400	7 50	8 0	450
A_2	10 0	8 50	8 200	250
A_3	12 0	11 200	12 0	200
A_4	0 100	0 0	0 0	100
Needs	500	300	200	1000 1000

In this table, there is no closed unloading cycle for the cell with a transportation time of 11. Therefore, the problem is considered solved

$$X^* = \begin{pmatrix} 400 & 50 & 0 \\ 0 & 50 & 200 \\ 0 & 200 & 0 \\ 100 & 0 & 0 \end{pmatrix}; \quad t(X^*) = 11 \text{ (hours)}.$$

The last line is deleted from this plan, since it corresponds to a fictitious consumer. For the resulting plan, the values of total costs and total transportation time are determined

$$L(X^*) = 26 \cdot 400 + 25 \cdot 50 + 25 \cdot 50 + 24 \cdot 200 + $$
$$+ 52 \cdot 200 = 28100 \text{ (a monetary unit)}.$$

$$T(X^*) = 7 \cdot 400 + 7 \cdot 50 + 8 \cdot 50 + 8 \cdot 200 + 11 \cdot 200 =$$
$$= 2800 + 350 + 400 + 1600 + 2200 = 7350.$$

III. The OPS selects the third criterion $T(X)$ as the most important and finds its minimum using the potential method (Table 7–10).

Table 7

First reference plan

Shipping point / Delivery point	Kharkiv (B_1)	Dnipro (B_2)	Zaporizhzhia (B_3)	Supply
Kyiv (A_1)	450	0	0	450
Odesa (A_2)	0	250	0	250
Lviv (A_3)	50	50	100	200
Dummy supplier (A_4)	0	0	100	100
Demand	500	300	200	1000 1000

Table 8

Checking the first plan for optimality

A_i / B_j	u_i / v_j	B_1	B_2	B_3	Stocks
		$v_1 = 12$	$v_2 = 11$	$v_3 = 12$	
A_1	$u_1 = -5$	7 450	7 0	8 0	450
A_2	$u_2 = -3$	10 0	–8 250	+8 0	250
A_3	$u_3 = 0$	12 50	+11 50	–12 100	200
A_4	$u_4 = -12$	0 0	0 0	0 100	100
Needs		500	300	200	1000 1000

The plan is suboptimal because

$$s_{23} = t_{23} - (u_2 + v_3) = 8 - (-3 + 12) = -1 < 0.$$
$$\min(250; 100) = 100.$$

Table 9

Checking the second plan for optimality

A_i / B_j	u_i / v_j	B_1	B_2	B_3	Stocks
		$v_1 = 12$	$v_2 = 11$	$v_3 = 11$	
A_1	$u_1 = -5$	7 450	7 0	8 0	450
A_2	$u_2 = -3$	10 0	–8 150	+8 100	250
A_3	$u_3 = 0$	–12 50	+11 150	12 0	200
A_4	$u_4 = -11$	+0 0	0 0	–0 100	100
Needs		500	300	200	1000 1000

The plan is suboptimal because

$$s_{41} = t_{41} - (u_4 + v_1) = 0 - (-11 + 12) = -1 < 0.$$
$$\min(100; 150; 50) = 50.$$

Table 10

Checking the third plan for optimality

B_j / A_i	v_j / u_i	B_1	B_2	B_3	Stocks
		$v_1 = 8$	$v_2 = 8$	$v_3 = 8$	
A_1	$u_1 = -1$	7 450	7 0	8 0	450
A_2	$u_2 = 0$	10 0	8 100	8 150	250
A_3	$u_3 = 3$	12 0	11 200	12 0	200
A_4	$u_4 = -8$	0 50	0 0	0 50	100
Needs		500	300	200	1000 1000

The condition $u_i + v_j \leq t_{ij}$ is satisfied for all free cells. The found plan X^* is optimal for the criterion $T(X)$

$$X^* = \begin{pmatrix} 450 & 0 & 0 \\ 0 & 100 & 150 \\ 0 & 200 & 0 \\ 50 & 0 & 50 \end{pmatrix}.$$

The last line is deleted from this plan, as it corresponds to a fictitious consumer:

$$T(X^*) = 7 \cdot 450 + 8 \cdot 100 + 8 \cdot 150 + 11 \cdot 200 =$$
$$= 3150 + 800 + 1200 + 2200 = 7350.$$

$t(X^*) = 11$ (hours).

$$L(X^*) = 26 \cdot 450 + 25 \cdot 100 + 24 \cdot 150 + 52 \cdot 200 =$$
$$= 11700 + 2500 + 3600 + 10400 = 28200 \text{ (a monetary unit).}$$

3.4. Discussion of results

As a result of the practical implementation of the vector transportation problem in the context of e-commerce, three models with different criterion priorities were developed and analyzed: minimization of total transportation costs $L(X)$, minimization of maximum delivery time $t(X)$, and minimization of total freight-time $T(X)$.

In the first two models (Tables 2–6), the values of all three criteria are optimal. For example, the total cost $L(X)$ reached its minimum value of 28,100 monetary units, while the total freight-time $T(X)$ remained unchanged at 7,350 units, as did the maximum delivery time $t(X) = 11$ hours. This result indicates that optimizing according to either the first or second criterion automatically ensured an optimal level for the other two criteria, which is rarely observed in practical multi-criteria optimization.

In contrast, the third model (Tables 7–10), which prioritizes minimizing freight-time $T(X)$, achieved the same value $T(X) = 7{,}350$, but the total cost increased to 28,200 monetary units – 100 monetary units higher than in the first model. Although this difference is small, it can become critical in large-scale commercial systems involving tens or hundreds of thousands of deliveries per month. Moreover, all three models showed the same maximum delivery time of 11 hours, indicating no potential for improving this criterion within the given resource constraints (warehouse capacities and delivery routes).

Thus, the model prioritizing the minimization of total costs (the first model) is the most advantageous for e-commerce conditions, where reducing logistics costs while maintaining an adequate service level is key. In this case, applying a three-criteria problem with weighted aggregation of criteria $L(X)$ and $T(X)$ is unnecessary, since the best possible values for these criteria were already achieved in the first two models.

Therefore, the use of a vector model allows flexible adaptation to different strategic company goals (cost, time, freight-time, service quality).

With a relatively simple problem configuration (3 warehouses, 3 delivery points), the potential method and the unloading cycles method provide fast and efficient optimization, which is crucial for real business applications.

Involving a dummy supplier to balance the problem helps avoid issues of unbalanced supply and demand, which often occur in e-commerce due to the dynamic nature of demand.

Unlike most previous works focusing on single-criterion problems, this study proposes a combined multi-criteria approach that potentially improves the quality of decisions in the field of goods distribution in e-commerce.

The study's results have important practical implications for e-commerce companies operating under complex logistics conditions. They are also relevant for the military sector in the transportation of goods, weapons, and personnel. The proposed scalar and vector models can be directly implemented in company IT systems to:

– optimize transportation costs and delivery routes;
– reduce order fulfillment time, especially under fluctuating demand;
– increase reliability of logistics operations through multi-criteria planning;
– enable flexible resource management under various development scenarios.

The models can be integrated into software systems (CRM, ERP, TMS) and used to develop recommendation systems in delivery services, thereby reducing the impact of human factors. Thus, the study contributes to the digital transformation of logistics processes and enhances the competitiveness of companies in the e-commerce market.

Research limitations include several aspects depending on the specific approach and application domain:

1. *Scope limitations*: the research focuses exclusively on the distribution processes of goods or resources within e-commerce systems that can be formalized as transportation problems. Other types of logistics or supply chain management tasks (e. g., warehouse operations, inventory management) are beyond the scope of this research.

2. *Model limitations*: only vector transportation problem models are used, which involve certain assumptions (e. g., parameter constancy, absence of random disturbances in transport flows) that may not fully reflect real e-commerce conditions.

3. *Data limitations*: the models assume the availability of reliable and complete input data regarding volumes of goods, shipping and destination points, and transportation costs. The consideration of dynamic changes and uncertainties in demand or supply is not included in this study.

Additionally, the high dynamics of orders require rapid solution updates and integration with other systems (warehouses, CRM, payment systems).

In the context of this topic, the following directions for further methodological improvement can be proposed:

1) integration with adaptive algorithms, i. e., development of hybrid models combining scalar and vector approaches with machine learning or artificial intelligence methods for automatic real-time parameter updating;

2) accounting for dynamic factors and uncertainties, requiring the introduction of stochastic or fuzzy transportation problem models capable of handling unpredictable demand changes, route delays, and other random events;

3) optimization considering environmental aspects, including model extensions for minimizing carbon emissions or utilizing energy-efficient routes, which is a current trend in modern logistics;

4) development of multi-agent models, where each system element (warehouse, transport, client) acts as an agent with its own goals, enabling modeling of more complex interactions within the supply chain;

5) integration with other e-commerce processes: inventory management, demand forecasting, order processing, to create comprehensive planning systems;

6) development of user interface and visualization tools for real-time monitoring and adjustment of goods distribution plans.

It is also advisable to conduct a comparative analysis of vector and scalar transportation problem models under identical criteria with varying input data volumes using information technologies. Furthermore, it is important to investigate the considered and other multi-criteria transportation problem models with additional criteria using computer systems. Comparing different vector models with varying weighting schemes, criteria, and evaluation methods is inappropriate, as each model may have its own system of weights and criteria, making comparative efficiency assessment impossible.

4. Conclusions

1. Multi-criteria transportation problem (TP) models have been developed that simultaneously consider costs, delivery time, and cargo-time:

– a bi-criteria model where the quality criteria are the total transportation cost and the total cargo-time;

– a bi-criteria model where the quality criteria are either the total transportation cost or the total cargo-time and the time required to supply all consumers with the necessary volume of goods;

– a three-criteria model where the quality criteria are the total transportation cost, the total cargo-time, and the time required to supply all consumers with the necessary volume of goods.

2. A methodology for aggregation has been developed based on the use of normalized criteria and weighting coefficients. This approach enables handling indicators with different units of measurement by converting them into a dimensionless form and forming an integrated indicator. This creates conditions for selecting compromise solutions according to the customer's defined priorities.

3. The integration of the developed models into the context of e-commerce has been conducted, highlighting their features, potential advantages, and limitations of use.

4. An example of a bi-criteria TP with criteria $L(X)$, $t(X)$, and $T(X)$ confirmed the applicability of all developed models in a simulated e-commerce environment. The models were implemented in MATLAB and Python. Computations were performed using MATLAB and Python with solution accuracy no worse than 10^{-6}, which meets logistics modeling standards.

The research results will be useful for specialists in logistics, supply chain management, analysts, and IT professionals engaged in optimizing delivery processes in e-commerce. The proposed models can be used in the development and improvement of logistics management information systems (TMS, ERP, CRM).

The proposed approach can serve as a foundation for further research in logistics optimization using modern artificial intelligence technologies and big data analytics.

Conflict of interest

The authors declare that they have no conflict of interest regarding this research, including financial, personal, authorship, or any other relationships that could influence the study and its results presented in this article.

Financing

This research was conducted without financial support.

Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that no artificial intelligence technologies were used in the preparation of the current work.

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