

УДК 656.025.4:504.054:519.87

Н. PRYMACHENKO^{1*}, S. PETRYK^{2*}

^{1*} Candidate of Sciences (Technical), Associate Professor, Associate Professor at the Department of Transport Systems and Logistics, Ukrainian State University of Railway Transport, Kharkiv, Ukraine, ORCID ID: 0000-0001-7326-8997

^{2*} Postgraduate Student at the Department of Transport Systems and Logistics, Ukrainian State University of Railway Transport, Kharkiv, Ukraine, ORCID ID: 0009-0001-5573-9828

OPTIMIZATION OF MULTIMODAL TRANSPORTATION TAKING INTO ACCOUNT CO₂ EMISSIONS

Purpose. The purpose of the study is to improve the theoretical and methodological foundations of multimodal transportation optimization by developing a mathematical approach to selecting the optimal route based on economic, time, and environmental criteria. Particular attention is paid to transportation costs, delivery time, and CO₂ emissions, which enables a comprehensive assessment of the efficiency of alternative logistics solutions and improves the justification of route selection. **Methodology.** The methodological basis of the study includes a systems approach, mathematical modeling, multicriteria optimization, and comparative analysis of alternative routes. An objective function is proposed that integrates three main efficiency criteria of multimodal transportation: total transportation costs, delivery time, and CO₂ emissions. To ensure their appropriate comparison, the model provides for the normalization of indicators and the use of weighting coefficients, enabling a comprehensive assessment of different delivery options. The practical application of the model is demonstrated using the example of cargo transportation on the Shanghai–Hamburg route, involving maritime, rail, and road transport in different combinations. **Results.** The main criteria for assessing the efficiency of multimodal logistics solutions are systematized, and the feasibility of their comprehensive consideration when selecting a route is substantiated. It is established that focusing exclusively on transportation costs or delivery time does not provide a comprehensive assessment of transportation efficiency. The proposed approach enables the identification of a balanced route considering economic, time, and environmental characteristics and allows alternative transportation schemes to be compared using an integrated criterion. **Originality.** The approach to multimodal transportation optimization has been improved by integrating economic, time, and environmental criteria into a unified logistics decision-making model, thereby expanding the possibilities for comprehensive evaluation of transportation alternatives. **Practical implications.** The proposed model can be applied by transportation and logistics companies to compare alternative routes, justify combinations of transport modes, and improve the efficiency of transportation planning. The approach can be integrated into digital transportation analytics and decision-support systems and adapted to different transportation routes, changes in tariffs, and logistics conditions.

Keywords: multimodal transportation, logistics, transport optimization, digital technologies, environmental sustainability, CO₂ emissions.

Introduction

The modern global economy is characterized by the intensive development of international trade, which is accompanied by increasing complexity in logistics processes. Under these conditions, multimodal transportation has become one of the key mechanisms for enhancing the efficiency of transport systems, as it allows for the combination of different modes of transport to achieve economic benefits and reduce delivery times [1]. Despite its advantages, the organization of multimodal transportation faces several challenges: high coordination costs among supply chain participants, limited capacity of certain transport modes, unstable tariffs, and the need for schedule synchronization. This creates a demand for mathematical optimization methods that enable the identification

of the most efficient routes while accounting for economic and time-related parameters.

In addition to purely economic factors, environmental aspects—particularly greenhouse gas emissions, with CO₂ being the most significant—are gaining importance. Although the environmental component is not yet decisive for all market players, in modern logistics strategies it is increasingly considered a factor of long-term sustainability and competitiveness. Therefore, the study of multimodal transportation optimization addresses the integration of economic efficiency, time reliability, and adaptation to environmental challenges, opening new opportunities for digitalization and the development of transport infrastructure.

Purpose and objectives of the study

The main purpose of this study is to develop approaches to optimize multimodal freight transportation, taking into account CO₂ emissions, by using mathematical models and analytical methods for decision-making in logistics systems. The application of mathematical optimization tools will allow achieving a balance between economic efficiency and environmental sustainability, which is a key factor in modern transport logistics. To achieve this goal, the following research objectives have been defined:

- Analyze current models for organizing multimodal transportation with a focus on assessing the environmental footprint of various modes of transport.
- Identify key components of multimodal logistics and integrate environmental indicators (specifically, the volume of CO₂ emissions) into the transportation efficiency assessment system.
- Construct a mathematical model for optimizing multimodal transport routes, taking into account cost, time, and environmental criteria.
- Establish relationships between the parameters of multimodal transport (type of transport, route, speed, load, etc.) and their impact on overall carbon emissions.

Provide practical recommendations for reducing the carbon footprint in logistics chains by improving routing schemes, digitizing processes, and changing the structure of transport.

Research results

In modern logistics, multimodal transportation is increasingly used to ensure flexibility, reliability, and cost reduction in global supply chains. It involves the use of two or more modes of transport within a single logistics route, allowing for adaptation of delivery to geographical, economic, and environmental conditions. The most common models of multimodal transportation include:

Sea-Air Transport – combines the relative cheapness of sea transport with the speed of air

transport. This is an optimal option for delivering valuable and urgent cargo over long distances, especially from Asia to Europe via Middle Eastern hubs.

Road-Air Transport – used to deliver cargo to regions without direct air connections. Road transport provides delivery to/from airports, while air transport provides fast international transportation.

Rail-Road Transport – one of the most effective models in the context of reducing CO₂ emissions. The railway section provides transportation over long distances with a low carbon footprint, while the road section allows covering the last mile.

Combined Transport: Rail – Road – Inland Waterway – Sea Transport – a complex but extremely efficient logistics structure for transporting large volumes of cargo on international routes. This model allows using the advantages of each mode of transport, including minimizing CO₂ emissions on water sections.

Land Bridge Transport – includes crossing continents through large sections of railway or road infrastructure between seaports. The most famous example is China – Europe via the New Silk Road.

Over the past decade, the issue of emissions of pollutants and greenhouse gases into the atmosphere has become particularly relevant in connection with global warming and the increase in anthropogenic load. An important turning point was the period of 2019–2020, when, due to global quarantine restrictions caused by the COVID-19 pandemic, emissions sharply decreased in almost all sectors of the economy. However, since 2021, a reverse trend has been observed: due to the recovery of industrial activity, the increase in transportation volumes and the return to pre-crisis levels of production, the level of emissions has begun to grow rapidly again. This raises concerns about the sustainability of environmental policies and the need for systematic control over pollution sources.

Figure 1 presents a visual analysis of pollutant emissions for the period 2019–2023 in Ukraine.

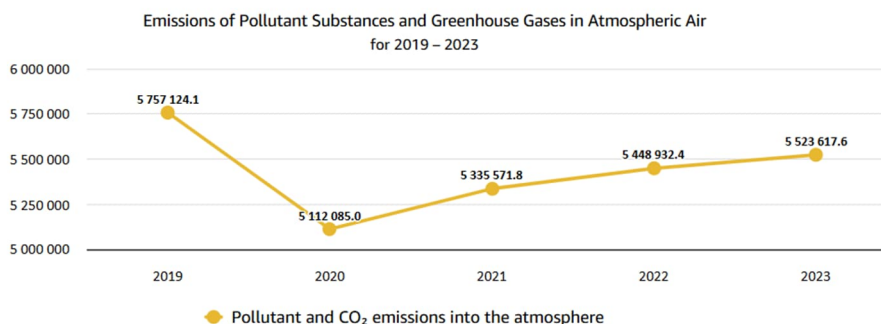


Figure 1. Emissions of pollutants and greenhouse gases into the atmospheric air in Ukraine.

To assess the effectiveness of a route, taking into account environmental aspects, the study uses an integrated model for optimizing multimodal transportation, which includes three key criteria: total transportation cost (C), delivery time (T), and volume of CO₂ emissions (E).

The objective function takes the form:

$$\min Z = \alpha C + \beta T + \gamma E \quad (1)$$

where Z – is the integral indicator of route efficiency, which we are trying to minimize;

α , β , γ – are weighting coefficients that determine the priority of each criterion:

α – weight of the economic component (cost);

β – weight of the time component (duration);

γ – weight of the environmental component (CO₂ emissions);

condition: $\alpha + \beta + \gamma = 1$

Each criterion is calculated as the sum of indicators for all sections of the route: Total transportation cost C:

$$C = \sum_{i=1}^n c_i x_i \quad (2)$$

where c_i – cost of transporting cargo on the segment i ;

$x_i \in \{0,1\}$ – binary variable indicating whether segment i is included in the selected route:

$x_i = 1$, if the segment is used;

$x_i = 0$, if the segment isn't used.

Total delivery time T:

$$T = \sum_{i=1}^n t_i x_i \quad (3)$$

where:

t_i – transportation duration on the segment i ;

$x_i \in \{0,1\}$ – binary variable indicating whether segment i is included in the selected route:

$x_i = 1$, if the segment is used;

$x_i = 0$, if the segment isn't used.

Total carbon dioxide emissions E:

$$E = \sum_{i=1}^n e_i x_i \quad (4)$$

where e_i – CO₂ emissions on the segment i ;

$x_i \in \{0,1\}$ – binary variable indicating whether section i is included in the selected route:

$x_i = 1$, if the segment is used;

$x_i = 0$, if the segment isn't used.

This function allows for flexible balancing between cost, delivery speed, and environmental friendliness, depending on the specific logistical goal. If minimizing delivery cost is important, the α indicator is increased; if the key indicator is speed, β is increased; if the company adheres to eco-standards, γ is increased. This model can be easily adapted to the needs of both a commercial logistics provider and a government regulator, for example, in the field of EU green corridors.

To illustrate the practical application of the proposed model, let's consider a hypothetical example of selecting the optimal cargo delivery route from the port of Shanghai (China) to a logistics hub in Hamburg (Germany). Three alternative routes are considered:

- Sea + road,

- Rail (transit through Eurasia),

- Multimodal chain "sea – rail – road" via the port of Rotterdam.

For each route, three key indicators are calculated:

- C (transportation cost);

- T (time in days);

- E (CO₂ emissions in kg).

Taking into account the weighting coefficients $\alpha=0.4$, $\beta=0.3$, $\gamma=0.3$, the objective function takes the form:

$$\min Z = 0,4C + 0,3T + 0,3E \quad (5)$$

The data for calculation are presented in Table 1.

Table 1

The data for calculation

Route	Cost (C), EUR	Time (T), days	Emissions (E), kg CO ₂	Route efficiency indicator (Z)
Sea + road	3200	32	950	1894,6
Rail (transit through Eurasia)	4300	18	600	1905,4
Multimodal chain "sea – rail – road" via the port of Rotterdam.	3700	26	700	1697,8

Analysis of the results shows that the third route (sea – rail – road) has the lowest value of the objective function $Z = 1697.8$, meaning it is the most optimal from the point of view of comprehensively considering cost, delivery time, and environmental impact. This indicates the feasibility of implementing a multi-criteria

approach in decision-making systems for managing multimodal transportation, with the possibility of adapting the model to the company's strategic priorities (for example, in favor of reducing CO₂ or accelerating delivery).

Scientific novelty

The scientific novelty of the study lies in improving the approach to multimodal transportation optimization by integrating economic, time, and environmental criteria into a unified logistics decision-making model, thereby expanding the possibilities for a comprehensive assessment of transportation alternatives. Unlike approaches primarily focused on minimizing transportation costs or reducing delivery time, the proposed approach considers CO₂ emissions simultaneously as a full-fledged optimization criterion. This enables a more informed selection among alternative routes and combinations of transport modes, taking into account their overall efficiency. In addition, the procedure for comparing criteria with different units of measurement has been improved through their normalization and the application of weighting coefficients, which enables the formation of an integrated assessment of alternative logistics solutions.

Conclusion

This study examined key aspects of optimizing multimodal transportation, taking into account economic, time, and environmental factors. The proposed multi-criteria model allows for a comprehensive consideration of costs, delivery times, and CO₂ emissions, which is extremely relevant in the context of modern European and global policies on decarbonizing logistics processes. The main models of multimodal transportation were analyzed, each of which has its advantages and limitations in terms of speed, cost, and environmental impact. The developed mathematical model allows for flexible adaptation of weighting coefficients depending on the company's strategic priorities. A practical calculation based on three alternative routes confirmed the effectiveness of using this approach. The lowest value of the objective function was obtained for a multimodal route with an optimal balance of costs, terms, and emissions, demonstrating its advantage over other options. Additionally, the dynamics of pollutant emissions into the atmosphere were considered, which indicates a critical need to control greenhouse gases in transport logistics. The decrease in emissions in 2020 due to quarantine restrictions, as well as their sharp increase in subsequent years, indicates the importance of integrating environmental criteria into decision-making processes. Thus, the improvement of multimodal transportation should be based not only on economic indicators, but also on environmental responsibility. The proposed approach has practical significance for logistics companies seeking to reduce environmental impact

without losing competitiveness, and also serves as a foundation for further scientific research in the field of sustainable transport systems.

REFERENCES

1. Bezverkha, R. P. Challenges and Prospects for the Development of Transport Systems. Thesis. 2021. Available at: https://er.nau.edu.ua/handle/NAU/50488?utm_source=chatgpt.com.
2. Zadoia, V. O., & Kuptsov, Yu. V. Multimodal Transportation as a Strategic Project for the Transformation of the Ukrainian Transport Market. Derzhavne upravlinnya: udoskonalennya ta rozvytok. 2023. No. 8. Available at: https://doi.org/10.32702/2307-2156.2023.8.13?utm_source=chatgpt.com.
3. Irtyshcheva, I., & Kornienko, K. Modern Development of the Transport System of Ukraine. Thesis. 2015. Available at: http://eir.nuos.edu.ua/xmlui/handle/123456789/5145?utm_source=chatgpt.com.
4. Kyrylova, O. V., Kyrylova, V. Yu., & Romakh, V. L. Theoretical Foundations of Transport Systems Functioning. Odesa National Maritime University. 2026. Available at: https://doi.org/10.47049/onmu-2026-mv1?utm_source=chatgpt.com.
5. Kuznietsova, K., Chenusha, O., & Petrenko, D. Multimodal Transportation as a Tool for Efficient International Logistics. Economic Synergy. 2022. No. 1–2. P. 81–91. Available at: https://doi.org/10.53920/es-2022-1;2-6?utm_source=chatgpt.com.
6. Kuznietsova, K., Chenusha, O., & Petrenko, D. Multimodal Transportation as a Tool for Efficient International Logistics. Economic Synergy. 2022. No. 1–2. P. 81–91. Available at: https://doi.org/10.53920/es-2022-1;2-6?utm_source=chatgpt.com.
7. Krashenin, A. et al. Formation of a Procedure to Assess Transport Technologies on the Principles of Qualimetry. Reliability and Durability of Railway Transport Engineering Structures and Buildings, Kharkiv, Ukraine. 2023. Available at: https://doi.org/10.1063/5.0120162?utm_source=chatgpt.com.
8. Herrmann, A., & Jungwirth, J. Multimodal Transportation. Inventing Mobility for All: Mastering Mobility-as-a-Service with Self-Driving Vehicles. 2022. P. 149–156. Available at: https://doi.org/10.1108/978-1-80043-176-820221015?utm_source=chatgpt.com.
9. Fang, X. et al. Synergy Degree Evaluation of Container Multimodal Transport System. Sustainability. 2020. Vol. 12, No. 4. P. 1487. Available at: https://doi.org/10.3390/su12041487?utm_source=chatgpt.com.
10. Fang, X. et al. Using Mixed Methods to Design Service Quality Evaluation Indicator System of Railway Container Multimodal Transport. Science Progress. 2019. Vol. 103, No. 1. P. 003685041989049. Available at: https://doi.org/10.1177/0036850419890491?utm_source=chatgpt.com.

Надійшла в редколегію 09.02.2026

Прийнята до друку 11.08.2026

ОПТИМІЗАЦІЯ МУЛЬТИМОДАЛЬНИХ ПЕРЕВЕЗЕНЬ З УРАХУВАННЯМ ВИКИДІВ CO₂

Мета. Метою дослідження є удосконалення теоретико-методичних засад оптимізації мультимодальних перевезень шляхом розроблення математичного підходу до вибору оптимального маршруту з урахуванням економічних, часових та екологічних критеріїв. Особливу увагу приділено транспортним витратам, тривалості доставки та обсягу викидів CO₂, що дає змогу комплексно оцінювати ефективність альтернативних логістичних рішень та підвищувати обґрунтованість вибору маршруту. **Методика.** Методологічну основу дослідження становлять системний підхід, математичне моделювання, багатокритеріальна оптимізація та порівняльний аналіз альтернативних маршрутів. Запропоновано цільову функцію, що інтегрує три основні критерії ефективності мультимодального перевезення: загальні транспортні витрати, час доставки та обсяг викидів CO₂. Для їх коректного порівняння передбачено нормалізацію показників і використання вагових коефіцієнтів, що забезпечує можливість комплексної оцінки різних варіантів доставки. Практичне застосування моделі продемонстровано на прикладі перевезення вантажу за напрямком Шанхай–Гамбург із використанням морського, залізничного та автомобільного транспорту в різних комбінаціях. **Результати.** Систематизовано основні критерії оцінювання ефективності мультимодальних логістичних рішень та обґрунтовано доцільність їх комплексного врахування під час вибору маршруту. Встановлено, що орієнтація виключно на вартість або час доставки не забезпечує всебічної оцінки ефективності перевезення. Запропонований підхід дає змогу визначати збалансований маршрут з урахуванням економічних, часових та екологічних характеристик і порівнювати альтернативні транспортні схеми за інтегральним критерієм. **Наукова новизна.** Удосконалено підхід до оптимізації мультимодальних перевезень шляхом інтеграції економічного, часового та екологічного критеріїв у єдину модель прийняття логістичних рішень, що розширює можливості комплексного оцінювання транспортних альтернатив. **Практична значимість.** Запропонована модель може застосовуватися транспортними та логістичними компаніями для порівняння альтернативних маршрутів, обґрунтування комбінацій видів транспорту та підвищення ефективності планування перевезень. Підхід може бути інтегрований у цифрові системи транспортної аналітики та підтримки прийняття рішень, а також адаптований до різних транспортних напрямків, змін тарифів та логістичних умов.

Ключові слова: мультимодальні перевезення, логістика, транспортна оптимізація, цифрові технології, екологічна стійкість, викиди CO₂.