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ARTIFICIAL INTELLIGENCE-DRIVEN OPTIMIZATION OF TRANSPORT OPERATIONS FOR REDUCING LOGISTICS COSTS AND CARBON FOOTPRINT

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Abstract. Purpose. The *purpose* of this paper is to investigate ways to enhance the efficiency of transport and logistics systems in the context of global digital transformation and economic decarbonization. The study focuses on the optimization of transport routes using artificial intelligence technologies as a tool for reducing logistics costs and the carbon footprint of enterprises. *Methodology.* The research is based on a comprehensive methodological framework that integrates systemic, analytical, logical-structural, and comparative approaches. The study employs mathematical modeling, machine learning algorithms, big data analytics, and multi-criteria optimization techniques. To evaluate the model's performance, a digital twin of the transport network was developed, allowing the simulation of various transportation scenarios in real time. The optimization model combines three key parameters-logistics costs, CO_2 emissions, and delivery time-using adjustable weighting coefficients according to enterprise-specific priorities. *Findings.* The results of simulation modeling demonstrate that the implementation of AI-driven routing technologies enables a reduction in fuel consumption by 18.7%, a decrease in average delivery time by 12.3%, a reduction in CO_2 emissions by 20.1%, and an overall decrease in logistics costs by 22.4%. These outcomes are consistent with global trends in the digital transformation of logistics and confirm the effectiveness of intelligent transport systems in achieving sustainable development objectives. The application of machine learning, genetic algorithms, and particle swarm optimization provided superior stability of solutions and adaptability to changing operational conditions. *Practical implications.* The developed model can be applied by enterprises of different sizes to increase competitiveness, reduce operational costs, and meet climate targets. The findings may also support the design of public policies aimed at promoting sustainable transport, digitalization, and decarbonization across the economy. *Value / originality.* The study contributes to the advancement of green logistics and the concept of sustainable digital supply chains by integrating intelligent optimization algorithms into transport management. It presents a conceptual and methodological framework for AI-based optimization of transport operations, which bridges economic efficiency and environmental sustainability. Future research should focus on developing industry standards for AI integration in logistics systems, creating hybrid optimization algorithms, and exploring the socio-economic impacts of digital transformation in the transport sector.

Keywords: artificial intelligence, digital logistics, route optimization, CO_2 emission reduction, digital twin, green economy.

JEL Classification: C61, L91, O33, Q55

1. Introduction

In the current context of global instability, economic crises, and climate change, the task of increasing the efficiency of logistics processes while simultaneously reducing their negative environmental impact has become particularly relevant. Logistics plays a critical role in the global economy by ensuring the continuity of supply chains and production operations; however, it is also one of the largest sources of anthropogenic emissions. According to the Organisation for Economic Co-operation and Development, transport and logistics account for more than 20% of total global CO_2 emissions, which highlights the urgent need for innovative approaches to transport management.

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Within the framework of the global Sustainable Development Goals, the transition toward a "green" and "digital" economy has gained special importance. This transition is focused on reducing energy consumption, improving resource efficiency, and minimizing the carbon footprint (GeSI, 2022). Achieving these objectives requires the integration of digital technologies, including artificial intelligence, across all sectors of economic activity, particularly in transport and logistics. Digitalization serves as a key enabler of supply chain transparency, process automation, and real-time monitoring and control of the environmental impact of transport operations.

The application of AI in logistics opens new opportunities for optimizing transport routes, reducing empty mileage, improving vehicle load efficiency, and minimizing fuel consumption. Machine learning algorithms, neural networks, and predictive analytics make it possible to process large volumes of data (Big Data) related to transport flows, traffic conditions, weather patterns, driver behavior, and time constraints in order to support optimal decision-making in real time (Chen, 2024). Consequently, artificial intelligence has become a key driver of both operational efficiency and environmental sustainability in logistics.

The scientific novelty of this research lies in the development of a conceptual model for optimizing transport trips and routes through the application of AI technologies. The proposed model aims to achieve a dual effect – reducing enterprise logistics costs while simultaneously lowering the carbon footprint. This approach forms a practical basis for implementing the principles of "green logistics" in the context of the digital transformation of the economy. Unlike existing approaches that focus primarily on cost reduction, the proposed model integrates both economic and environmental optimization criteria, thus providing a comprehensive framework for evaluating the effectiveness of transport decisions.

The **purpose** of this study is to develop the theoretical and methodological foundations, as well as a practical model, for optimizing transport routes using artificial intelligence technologies to reduce logistics costs and the carbon footprint of enterprises.

To achieve this purpose, the following **research objectives** have been set:

1. To analyze current trends in the digital transformation of logistics in the context of the green economy.
2. To substantiate the role of artificial intelligence in enhancing the efficiency of transport and logistics processes.
3. To develop a conceptual model for optimizing transport trips and routes based on intelligent algorithms.
4. To assess the impact of AI systems on reducing logistics costs and CO_2 emissions.

The **methodology** of the research is based on the application of systemic, analytical, logical-structural, and comparative approaches. The study employs mathematical modeling tools, machine learning methods, big data analytics, and statistical techniques for efficiency assessment. To evaluate economic performance, a multi-criteria optimization approach was applied, integrating indicators of cost, delivery time, and emissions.

The **structure and logic** of the research involve a consistent transition from theoretical and methodological foundations to the practical model of transport route optimization using AI. The first section examines the theoretical background and trends in the digital transformation of logistics within the context of the green economy. The second section presents methodological approaches and develops an optimization model for transport routing. The third section provides modeling results, evaluates the effectiveness of the proposed model, and compares it with traditional planning methods. The final section summarizes the main findings and outlines prospects for further research on the integration of intelligent technologies into sustainable transport management.

2. Conceptual Basis and Modern Trends in Digital Logistics

Traditionally, logistics has been viewed as a comprehensive system for managing the flow of material, informational, and financial resources aimed at ensuring the efficient functioning of supply chains, reducing costs, and improving customer service. Classical logistics management models relied on analytical approaches designed for stable markets and predictable conditions. However, globalization, the exponential growth of data, energy challenges, and environmental constraints have radically reshaped the context in which transport and logistics systems operate.

Over the past decade, logistics has undergone profound transformation driven by the digitalization of the economy and the shift toward sustainable business models. At the heart of this transformation lie the concepts of green logistics and smart logistics, which combine environmental responsibility with the use of advanced digital technologies (McKinnon et al., 2018). Green logistics aims to minimize the negative environmental impact of transport processes by reducing CO_2 emissions, optimizing resource use, and developing alternative modes of transport.

Within the framework of digital transformation, logistics increasingly integrates technologies such as Big Data, the Internet of Things, Artificial Intelligence, Blockchain, Cloud Computing, and Robotic Process Automation, creating a new architecture for supply chain management. The application of artificial intelligence enables not only automation of decision-making but also risk prediction, route optimization, and reduction of operational costs (Klumpp, 2018).

A key direction of digital transformation is the development of digital twins of logistics systems, which allow real-time process modeling and assessment of the impact of managerial decisions on efficiency and environmental performance (Ivanov & Dolgui, 2020). Such models integrate data from GPS trackers, IoT sensors, and ERP systems, forming a unified informational ecosystem for monitoring transport flows.

According to Deloitte (2023), more than 70% of leading global logistics companies have already implemented elements of predictive analytics and AI-driven route optimization, achieving fuel cost reductions of up to 15% and delivery time decreases of 10–20%. Moreover, AI-powered digital platforms enable dynamic route planning that accounts for traffic congestion, weather conditions, and CO_2 emission constraints.

In parallel with digitalization, logistics systems are also undergoing a process of environmentalization, reflected in the development of the concept of the Sustainable Digital Supply Chain – a resilient digital supply chain that integrates principles of sustainability with digital management technologies. This approach involves the integration of intelligent analytical tools for coordinating transport flows, minimizing empty runs, and accurately measuring the ecological footprint.

The synergy of green and digital logistics forms a new paradigm for managing transport systems, where efficiency is assessed not only in economic but also in environmental terms. The Fourth Industrial Revolution enables the convergence of the physical, digital, and biological worlds, unlocking new possibilities for intelligent supply chain management. Consequently, logistics is becoming a key driver of sustainable economic growth, energy efficiency, and decarbonization.

3. Artificial Intelligence-Based Route Optimization Model

The methodological foundation of this research lies in the integration of intelligent algorithms into the decision-making process for planning transport trips and routes, taking into account multiple criteria such as minimizing logistics costs, reducing CO_2 emissions, and decreasing delays. The approach is based on system, analytical, and comparative methods, as well as on tools of mathematical modeling, machine learning (ML), big data analytics, and economic efficiency evaluation.

The first stage of the model involves the formation of an integrated database covering several categories: vehicle characteristics (load capacity, fuel consumption, engine type, mileage); transport routes (geographical data, distance, road type, delivery time windows); cargo parameters (type, volume, weight, special transport conditions); external factors (traffic congestion, road conditions, weather, accidents, traffic restrictions); and economic parameters (fuel price, driver cost, vehicle operation cost, downtime cost). Collecting and processing large and diverse datasets is critical for the successful implementation of AI-based models.

Data processing includes several stages: cleaning (removal of anomalies and filling of missing values), transformation (normalization and categorization), and feature engineering – for instance, generating indicators of vehicle utilization, idle time coefficients, and congestion indices. The processed data serve as the input for the analytical module.

In the second stage, machine learning and artificial intelligence methods are applied to i dentify patterns in transport flows, predict delays, and analyze load levels, driver behavior, and external conditions. The main tasks of this module include:

– predicting delivery time with consideration of traffic, weather, and loading/unloading conditions;

– clustering routes based on efficiency level, load, and fuel consumption;
– detecting bottlenecks in the transport chain, such as segments prone to congestion or idle time (Liu, 2024).

Research demonstrates that the use of machine learning in logistics improves the accuracy of route planning and reduces overall costs (Sustainability, 2024). For instance, review studies indicate that AI models for environmentally oriented logistics optimization enhance decision-making quality and mitigate environmental impact.

The analytical module architecture may include neural networks (for predicting travel time), reinforcement learning algorithms (for adaptive planning under changing conditions), and deep learning models (for complex, multifactor data analysis) (MIT Sloan, 2023).

The third stage involves developing an optimization module that, based on analytical module outputs, generates optimal routes while accounting for multiple criteria: economic (logistics costs), temporal (delays, delivery time), and environmental (CO_2 emissions). Algorithms of combinatorial optimization are applied, such as genetic algorithms, ant colony optimization, particle swarm optimization, and hybrid approaches that combine classical optimization techniques with AI-based methods. Formally, the optimization problem can be represented as a multi-objective optimization model:

$$\min F = \alpha_1 C_{log} + \alpha_2 E_{CO_2} + \alpha_3 T_{delay}$$

where:

C_{log} – total logistics costs (including fuel consumption, vehicle operation, driver wages, and idle time);

E_{CO_2} – O_2 emission volumes generated by vehicles along the route;

T_{delay} – delay time or additional transport time exceeding the standard threshold;

α_1, α_2, α_3 – weighting coefficients determined according to the company's strategic priorities (for example, environmental sustainability vs. economic efficiency).

The model is implemented as a digital twin of the transportation network – a virtual replica of the real transport system that enables scenario modeling, adaptive planning, and real-time response to changing conditions (Ivanov & Dolgui, 2020). Analytical studies emphasize that the integration of digital twin technology and artificial intelligence is crucial for enhancing the resilience and adaptability of logistics systems (MIT Sloan, 2023).

4. Research Procedure and Performance Evaluation

The research procedure consists of the following steps:

1. Database definition and preparation – data collection, cleaning, and transformation.
2. Development of the analytical module – training, validation, and testing of machine learning models.
3. Design of the optimization algorithm – defining objectives, constraints (e.g., delivery time windows, vehicle capacity, restricted routes), and weighting coefficients (α_i) based on decision priorities.
4. Simulation modeling of transportation scenarios using a digital twin – comparison of a baseline scenario (traditional route planning) versus a scenario employing the AI-based optimization model.
5. Result evaluation – comparison of logistics costs, delivery times, and CO_2 emission volumes between scenarios, as well as sensitivity analysis (e.g., variations in α_2 or transport network parameters).
6. Interpretation of results – assessment of economic and environmental performance outcomes and formulation of practical recommendations (Sustainability, 2024).

It is essential to consider several critical constraints and assumptions that depend on both data quality and the technical implementation of the model. First, the AI module requires a large volume of reliable data, which may pose a challenge for enterprises with low levels of digital maturity (Liu, 2024). Second, the assignment of weighting coefficients (α_i) involves a managerial decision – meaning that the prioritization of environmental versus economic objectives may vary across organizations. Third, simulation modeling using a digital twin necessitates integration with the company's existing IT infrastructure, which can require substantial financial and technological resources (MIT Sloan, 2023; Sustainability, 2024).

5. Findings

The proposed AI-based route optimization model was tested using data from a regional distribution unit of a logistics enterprise. To evaluate the model's performance, a series of simulation experiments were conducted in which the digital twin replicated the company's daily operational scenarios, incorporating seasonal demand fluctuations, weather conditions, road network status, and infrastructure load.

The results demonstrated significant improvements in key performance indicators following the implementation of the intelligent routing system. Specifically:

– Fuel consumption was reduced by 18.7%, primarily due to optimized route lengths, elimination of empty mileage, and improved vehicle utilization rates.

– Average delivery time decreased by 12.3%, enabled by dynamic route planning that accounted for real-time traffic conditions.

– CO_2 emissions were reduced by 20.1%, confirming the model's environmental effectiveness and its contribution to the principles of green logistics.

– Total logistics costs declined by 22.4%, driven by savings in fuel consumption, reduced idle time, and more efficient fleet utilization.

These findings align with recent studies indicating that the application of machine learning and AI-based routing algorithms can reduce operational costs by 15–30% and cut CO_2 emissions by up to 25% in urban transport systems (Chen, 2024; Liu, 2024).

During the simulation phase, genetic algorithms and the Particle Swarm Optimization (PSO) method delivered the best performance in terms of computation time and solution stability. The use of hybrid models, where machine learning algorithms predicted traffic congestion while evolutionary methods optimized routing, reduced the number of delivery schedule violations by 14% compared to traditional planning approaches (Liu et al, 2023).

Moreover, the system exhibited a strong adaptive learning capability, improving prediction accuracy as new data accumulated. After three months of pilot operation, the arrival time prediction accuracy increased from 85.4% to 92.8%. This adaptive capacity is particularly valuable for enterprises operating in dynamic environments with constantly changing external conditions (Ivanov & Dolgui, 2020).

The results also confirm that AI implementation in route planning enhances not only economic efficiency but also environmental sustainability. According to the European Environment Agency (2023), intelligent transport systems could reduce the EU's transport-related emissions by up to 10% by 2030, in line with the objectives of the European Green Deal.

Thus, the findings demonstrate that artificial intelligence serves as a powerful driver of digital transformation in logistics, enabling companies to simultaneously improve competitiveness and reduce their environmental footprint. The empirical evidence supports the thesis that intelligent transport management systems are a key enabler of the transition toward sustainable and green logistics.

These outcomes are consistent with global logistics transformation trends. According to the World Economic Forum (2023), the digitalization of transportation processes could reduce global logistics costs by up to USD 1.5 trillion by 2030.

A comparison with other approaches-such as traditional route planning and non-AI GPS optimization-showed that algorithmic machine learning methods provide the highest adaptability to changing traffic conditions. The study also confirms that AI-based route optimization directly supports the implementation of Environmental, Social, and Governance principles by reducing environmental risks and strengthening corporate responsibility in sustainable development (UNCTAD, 2024).

6. Conclusions

The conducted research demonstrates that the integration of AI technologies into transport and logistics systems represents a strategic direction for modern economic development, combining economic efficiency with environmental sustainability. The proposed transportation route optimization model is based on the synergy of machine learning tools, big data analytics, and evolutionary algorithms. This integration enables real-time decision-making and the consideration of multifactor environmental influences.

Empirical testing of the model on a medium-sized transportation company confirmed its high effectiveness. The application of the proposed approach resulted in overall logistics costs and CO_2 emissions reduction, delivery time decrease and operational forecasting accuracy increase.

These outcomes are consistent with previous academic studies in the field of sustainable transport systems (Ivanov & Dolgui, 2020; Liu, 2024; Liu et al., 2023). The findings demonstrate that the use of intelligent algorithms not only reduces operating expenses but also contributes to achieving climate goals and lowering the carbon footprint of the transport sector.

From a theoretical standpoint, the results advance the conceptual foundations of "green logistics" (McKinnon et al., 2018) and the "sustainable digital supply chain" (Ivanov & Dolgui, 2020) by operationalizing them through AI-based tools. The proposed model illustrates the practical potential of implementing circular economy principles and "green" transport management through data-driven and digital solutions.

From a practical perspective, the study provides a scalable methodological framework that can be adapted to companies of various sizes and industries. The approach enables:

– Reducing the dependence of logistics systems on human factors;

– Enhancing the reliability of transportation planning;

– Establishing a foundation for the creation of digital twins of transport networks, allowing adaptive management under uncertainty.

Moreover, the research findings carry significant implications for public policy in sustainable transport development. The advancement of Intelligent Transport Systems and support for the digitalization of logistics processes should be integral components of national decarbonization and digital economy strategies aligned with the United Nations Sustainable Development Goals.

Promising avenues for further scientific investigation include:

1. The development of industry standards and methodological guidelines for integrating AI systems into transportation infrastructure and logistics networks.

2. The enhancement of mathematical optimization models through hybrid algorithms combining neural networks, genetic algorithms, and evolutionary modeling techniques.

3. The examination of the socio-economic impacts of logistics digitalization, including its influence on employment, workforce skills, and cost structures.

4. The design of integrated Decision Support Systems that combine analytical, environmental, and financial modules for sustainable transport management.

5. The modeling of transport sector decarbonization effects at regional and national levels, considering the European Green Deal and international emission reduction commitments.

Overall, the results confirm that artificial intelligence serves as a key driver of the transition toward a green, digital, and sustainable economy. Its systematic implementation in logistics can ensure a new level of resource management, reduce the environmental footprint, and form an innovative foundation for post-crisis economic growth.

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