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# Digital technologies and modelling for enhancing supply chain efficiency in international road transport

# Tecnologias digitais e modelação para melhorar a eficiência da cadeia de abastecimento no transporte rodoviário internacional

# Tecnologías digitales y modelización para mejorar la eficiencia de la cadena de suministro en el transporte internacional por carretera

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Vasyl Onyshchuk, Associate Professor, Head of the Department of Automobiles and Transport Technologies of LNTU, Faculty of Transport and Mechanical Engineering, Lutsk National Technical University, Lutsk, Ukraine
https://orcid.org/0000-0002-5316-408X

Oleksandr Dubytskyi, Associate Professor, Department of Automobiles and Transport Technologies, Faculty of Transport and Mechanical Engineering, Lutsk National Technical University, Ukraine
https://orcid.org/0000-0002-4863-4040

Volodymyr Bodak, Associate Professor, Department of Automobiles and Transport Technologies, Faculty of Transport and Mechanical Engineering, Lutsk National Technical University,Ukraine
https://orcid.org/0000-0003-2521-7305

Irina Pavlova,Associate Professor, Department of Automobiles and Transport Technologies, Faculty of Transport and Mechanical Engineering, Lutsk National Technical University, Lutsk, Ukraine
https://orcid.org/0000-0003-1506-6064

Nataliia Riabykh, Associate Professor, Department of Law, Faculty of Business and Law, Lutsk National Technical University, Lutsk, Ukraine
https://orcid.org/0009-0007-4177-698X

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**Abstract**

International road transport is a critical part of international supply chains, and it faces issues like increasing costs, environmental regulations, and unevenly developed infrastructure. The emergence of new digitalisation opportunities for logistics processes creates excellent opportunities to enhance transport efficiency and flexibility; therefore, research in this area is very relevant. The study investigates the influence of digital technologies such as the Internet of Things, digital twins, and artificial intelligence on the optimisation of international road transport. The paper uses system analysis, mathematical modelling and linear programming to assess the effectiveness of logistics solutions. The findings indicate that digital technologies can cut transportation costs by 18 per cent on average by optimising routes and avoiding logistics risks. Digital twins used in route modelling increase process transparency and decision-making efficiency. Predictive analytics based on artificial intelligence allows for more efficient inventory management and minimisation of delivery delays. The practical significance of the work lies in developing algorithms that can be implemented by both large logistics companies and small businesses, subject to adaptation to their needs. The data obtained can be used to improve logistics systems further and integrate innovative technologies into international transport.

**Keywords:** international road transport, supply chains, digital technologies, artificial intelligence, digital twins.

**JEL Classification:** L91 (Transport: General), R41 (Transport: Demand, Supply, and Congestion; Travel Time; Safety and Accidents), O33 (Technological Change: Choices and Consequences; Diffusion Processes), C61 (Optimisation Techniques; Programming Models; Dynamic Analysis).

**Resumo**

O transporte rodoviário internacional é uma parte essencial das cadeias de abastecimento internacionais e enfrenta problemas como o aumento dos custos, a regulamentação ambiental e o desenvolvimento desigual das infra-estruturas. O surgimento de novas oportunidades de digitalização para os processos logísticos cria excelentes oportunidades para melhorar a eficiência e a flexibilidade dos transportes; por conseguinte, a investigação neste domínio é muito relevante. O estudo investiga a influência das tecnologias digitais, como a Internet das Coisas, os gémeos digitais e a inteligência artificial, na otimização do transporte rodoviário internacional. O documento utiliza a análise de sistemas, a modelação matemática e a programação linear para avaliar a eficácia das soluções logísticas. Os resultados indicam que as tecnologias digitais podem reduzir os custos de transporte em 18%, em média, optimizando as rotas e evitando riscos logísticos. Os gémeos digitais utilizados na modelação de rotas aumentam a transparência do processo e a eficiência da tomada de decisões. A análise preditiva baseada na inteligência artificial permite uma gestão mais eficiente do inventário e a minimização dos atrasos de entrega. O significado prático do trabalho reside no desenvolvimento de algoritmos que podem ser implementados tanto por grandes empresas de logística como por pequenas empresas, sujeitos a adaptação às suas necessidades. Os dados obtidos podem ser utilizados para melhorar ainda mais os sistemas logísticos e integrar tecnologias inovadoras nos transportes internacionais.

**Palavras-chave**: transporte rodoviário internacional, cadeias de abastecimento, tecnologias digitais, inteligência artificial, gêmeos digitais.

**Resumen**
El transporte internacional por carretera es una parte fundamental de las cadenas de suministro internacionales y se enfrenta a problemas como el aumento de los costes, las regulaciones medioambientales y una infraestructura desarrollada de forma desigual. La aparición de nuevas oportunidades de digitalización para los procesos logísticos crea excelentes oportunidades para mejorar la eficiencia y la flexibilidad del transporte; por lo tanto, la investigación en esta área es muy relevante. El estudio investiga la influencia de las tecnologías digitales como el Internet de las cosas, los gemelos digitales y la inteligencia artificial en la optimización del transporte internacional por carretera. El documento utiliza análisis de sistemas, modelos matemáticos y programación lineal para evaluar la eficacia de las soluciones logísticas. Los resultados indican que las tecnologías digitales pueden reducir los costes de transporte en un 18 por ciento de media optimizando las rutas y evitando los riesgos logísticos. Los gemelos digitales utilizados en el modelado de rutas aumentan la transparencia del proceso y la eficiencia de la toma de decisiones. El análisis predictivo basado en inteligencia artificial permite una gestión de inventarios más eficiente y la minimización de los retrasos en las entregas. La importancia práctica del trabajo radica en el desarrollo de algoritmos que pueden ser implementados tanto por grandes empresas de logística como por pequeñas empresas, sujetos a la adaptación a sus necesidades. Los datos obtenidos se pueden utilizar para mejorar aún más los sistemas logísticos e integrar tecnologías innovadoras en el transporte internacional.

**Palabras clave:** transporte internacional por carretera, cadenas de suministro, tecnologías digitales, inteligencia artificial, gemelos digitales.

## 1. Introduction

In today's globalised world, international road transport plays a key role in ensuring the functioning of supply chains and facilitating the integration of economies across borders. However, the ever-increasing complexity of logistics processes and economic, environmental, and infrastructure challenges are posing new challenges for the industry. High dependence on fuel resources, growing environmental requirements for transport and regulatory differences between countries create additional obstacles to the efficient operation of transport companies. At the same time, modern Industry 4.0 technologies, such as AI, the Internet of Things (IoT) and digital twins, are opening up new opportunities to improve supply chain management efficiency. An analysis of scientific papers, such as by Ivanov, Tsipoulanidis and Schönberger (2021) and Lozano-Oviedo, Cortés and Rey (2024), confirms that digitalisation is one of the key areas of development for logistics systems. At the same time, studies by Boute and Udenio (2023) and Triantafyllou et al. (2024) focus on integrating digital tools to optimise routes and minimise risks. However, despite a significant number of studies, the adaptation of digital technologies to the specific conditions of SMEs and their impact on supply chain resilience in the face of global crises remain insufficiently studied.

This study aims to develop algorithms for optimising supply chains in international road transport using digital technologies such as IoT, digital twins, and artificial intelligence. The main objectives are to identify key problems in logistics processes, model optimal routes, and assess the impact of digital technologies on the efficiency of international transport.

**Analysis of the latest research and publications**

An analysis of current research shows significant attention to introducing digital technologies in logistics and supply chain management. For example, studies by Ivanov, Tsipoulanidis and Schönberger (2021) and Sun, Yu and Solvang (2022) highlight the importance of Industry 4.0 technologies for optimising logistics operations, mainly through process automation and data analytics. The role of artificial intelligence (AI) and big data in improving supply chain efficiency is discussed by Chan, Hogaboam and Cao (2022) and Quayson, Bai and Effah (2023). Lozano-Oviedo, Cortés and Rey (2024) analyse in detail the impact of closed supply chain cycles on the resilience of logistics networks. Integrating IoT and digital twins to predict risks and increase the transparency of logistics operations is discussed by Boute and Udenio (2023) and Rziki et al. (2024). Palander, Tokola, and Borz (2024) focus on the digitalisation of forest supply chains, demonstrating technology's versatility. At the same time, Kiviharju (2024) points out the critical cybersecurity issues that arise from the growth of digital solutions. Studies by Shah et al. (2024) and Stark (2022) highlight the need to integrate digital platforms to reduce costs and increase productivity, supported by real-world implementation examples in large companies. D'Andrea et al. (2024) and Dhaliwal (2024) focus on using advanced technologies such as 6G and AI to optimise international transport.

Meanwhile, Triantafyllou et al. (2024) and Zrelli et al. (2024) discuss specialised tools that include drones and digital twins to enhance the flexibility and robustness of logistics systems.

For example, Feng and Ye (2021) strongly assert the indispensable role of smart logistics in sustainable development, while Ambalov and Heim (2020) discuss the effect of digital infrastructure investment on supply chain performance. Recent developments in the study of intelligent supply chains are outlined in Zhang, Yang, and Yang (2023), while the Internet of Vehicles and its related application regarding mobile patterns are the subject matter of Cui, Hu, and Ni (2022). In the long-term, sustainability, using digital tools in sustainable supply chains is discussed by Shah et al. (2024) and Sinitsyna and Nekrasov (2024). Boute and Udenio (2023) and Nandi, Nandi, and Dave (2024) concentrate on analytical models of service-oriented supply chains that address consumers' needs and reduce operational costs. Vrana and Singh (2023) model digital permeability in industrial societies. Sun, Yu and Solvang (2022) consider the impact of Industry 4.0 on logistics in the context of environmental sustainability.

Despite the wide range of studies, many issues remain insufficiently explored. In particular, most studies do not take into account the regional peculiarities of digitalisation in supply chains or the limited resources of SMEs for large-scale innovation integration. Further research should focus on adapting digital technologies to the specific conditions of different countries and developing affordable solutions for SMEs.

## 2. Research methods

Comprehensive methods were used throughout the study to ensure the validity and accuracy of the results obtained. System analysis was utilised to assess the efficiency of supply chains and identify key issues related to international road transport. Mathematical modelling allowed for the creation of an algorithm for optimising transport costs, including setting the objective function and adding appropriate constraints. To solve the optimisation problems, the linear programming method with the Python software and the SciPy and PuLP libraries was applied.

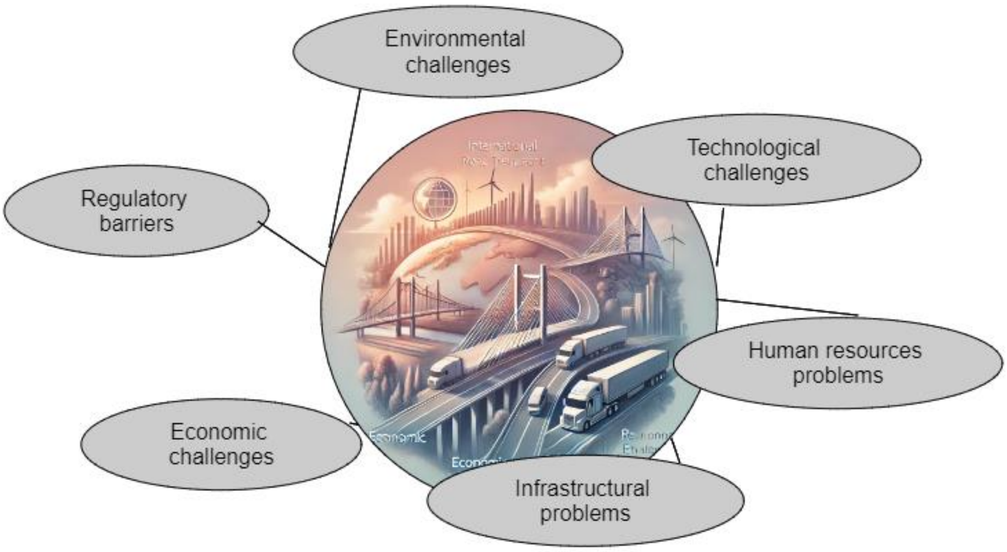
Data analysis was conducted based on statistical indicators such as routes, volumes, transportation costs and vehicle utilisation rates from 2021–2023. Using comparative analysis methods, modelling results were compared with accurate data from global transport companies such as DHL Freight, DB Schenker and GEFCO. Furthermore, elements of predictive analytics were leveraged to estimate the potential for adopting digital technologies, including the Internet of Things and Artificial intelligence. These methods helped to comprehensively study the problem of international road transport optimisation and bring about practical recommendations.

## 3. Research results

International road transport is important for the global supply chain because it is useful for trade and regional cooperation. However, the organisation of such transport is riddled with problems, such as economic, infrastructural, and environmental.

**Figure 1**

Main problems and challenges in the organisation of international road transport




Source: created by the author

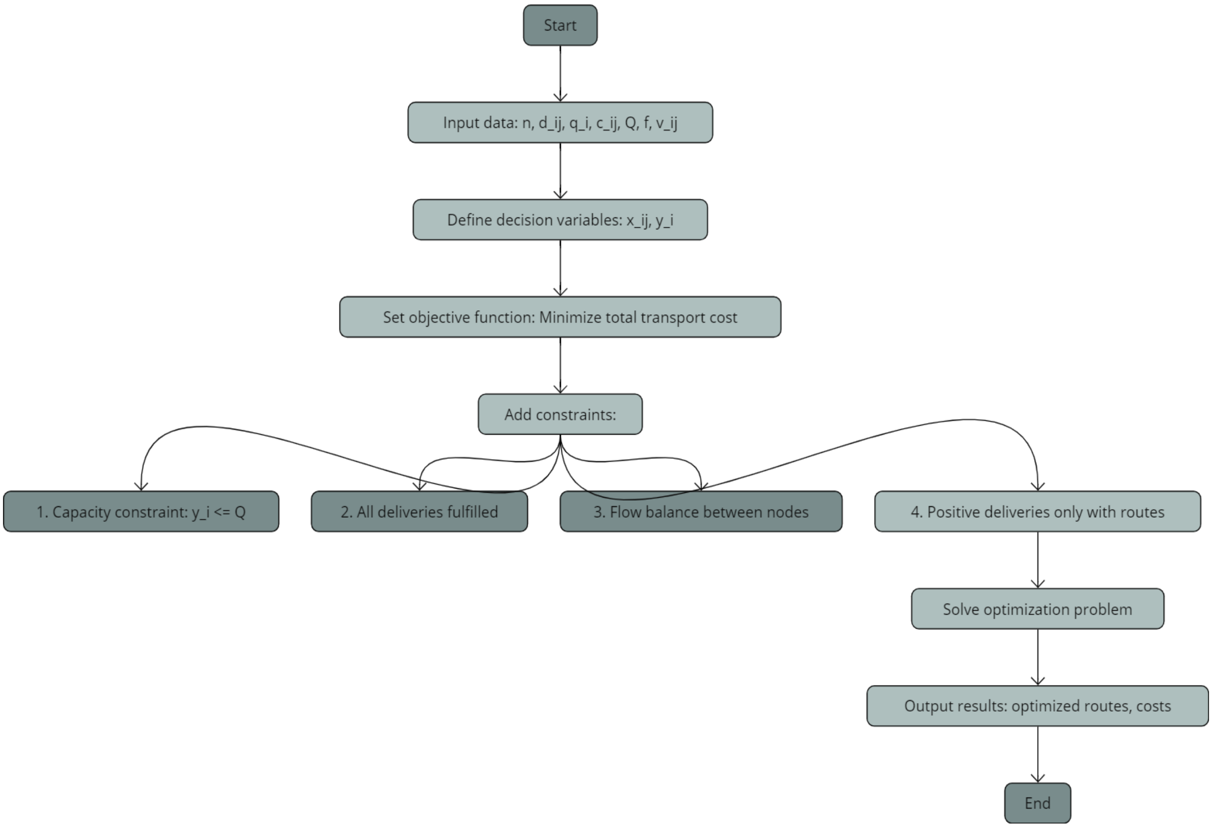
According to a study by Kochhar (2023), in 2022, fuel costs increased by 15% compared to 2021, resulting in an 8% increase in total transport costs. On average, fuel accounts for up to 40% of total operating costs for transport companies. Rising fuel costs are one of the key issues in international road transport, as fuel accounts for a significant portion of total costs. In addition, currency fluctuations complicate financial planning for companies operating in international markets. This creates risks for budget stability and competitive tariffs. The uneven development of road infrastructure in different countries affects transportation efficiency. Problems with road quality, congestion and a lack of modern logistics centres significantly reduce delivery speeds. Another important challenge is outdated border crossings that cannot cope with traffic flow, leading to delays.

Differences in legislation from country to country create difficulties for carriers. For example, there are different requirements for vehicle certification, customs procedures, and safety standards, and lengthy customs clearance processes at borders cause transport delays. Increased environmental standards requirements, particularly $CO_2$ emissions, require carriers to update their fleets and introduce energy-efficient technologies. For example, according to a study by Lozano-Oviedo, Cortés and Rey (2024), upgrading the fleet to Euro 6 reduced $CO_2$ emissions by 25%. However, it required an initial investment of 10-15% of the annual revenue of transport companies. This creates additional financial burdens, especially for small and medium-sized enterprises. Integrating digital technologies into logistics is important for increasing efficiency, but many companies face difficulties implementing such solutions. For example, it can be insufficient process automation, lack of unified supply chain management platforms, or weak data protection in digital systems. The lack of qualified drivers is a significant challenge for the industry. This is due to the general ageing of the workforce, difficult working conditions and the lack of popularity of the profession among young people. In addition, international transport requires drivers with a deep understanding of regional specifics and knowledge of foreign languages.

The flowchart in Figure 2 illustrates the stages of the transport cost optimisation process in international road transport, starting with the input of initial data and the definition of variables and ending with solving the problem and obtaining optimal routes.

**Figure 2**

Flowchart of the process of optimising transport costs in international road transport




Source: created by the author

This flowchart demonstrates the process of developing and solving the problem of optimising transport costs in international road transport. It includes the following main steps:

1. *Input*: Specify the problem parameters, including the number of delivery points (n), distances between points ($d_{ij}$ ), cargo volumes ($q_i$ ), transportation costs ($c_{ij}$ ), vehicle capacity (Q), and variable costs ($v_{ij}$).
2. *Defining the decision variables*: Formalising key variables such as $x_{ij}$ (routes) and $y_i$ (volume of cargo transported).

3. *Establishing the objective function*: The optimisation goal is set, for example, to minimise the total cost of transportation.
Formulation of the objective function in mathematical form:

$$\sum_{j=1}^{n} x_{ij} \leq Q \qquad (1)$$

Where:

- $Z$ - total transportation costs that need to be minimised;
- $c_{ij}$ - *is* the cost of transporting a unit of cargo from point *i* to point *j*;
- $x_{ij}$ - is the volume of cargo transported between points *i* and *j*;
- *n* - number of delivery points.

4. *The following constraints are added to the objective function:*

- Limitations on vehicle capacity:

$$\sum_{j=1}^{n} x_{ij} \leq Q \qquad (2)$$

- Capacity limitation: Ensuring the load volume does not exceed the vehicle's capacity is crucial.
- Delivery fulfilment ($x_{ij}$ ): All delivery requests must be fulfilled.
- Balance of cargo flows:

$$\sum_{j=1}^{n} x_{ij} = \sum_{i=1}^{n} x_{ij} \qquad (3)$$

where the amount of cargo entering point iii equals the amount of cargo leaving this point.

- Mandatory execution of all orders:

$$\sum_{i=1}^{n} \sum_{j=1}^{n} x_{ij} \geq \sum_{i=1}^{n} q_i \qquad (4)$$

where $q_i$ is the requested volume of cargo for delivery to point *i*.

5. *Solution of the problem*: We express the problem as a mathematical model for optimisation. Linear programming methods are used to solve the problem (using Python and SciPy and PuLP libraries).

6. *Results*: The model's output provides the optimal transport routes and associated costs. Integrating digital technologies in the optimisation model substantially contributes to achieving practical results. The real-time data on road congestion, weather, and vehicle conditions is

collected using IoT. This data uses the dynamic changes to update the model parameters: $d_{ij}$ for distance between points and $v_{ij}$ for variable costs. Transport demand and respective potentials for delay or congestion are analysed by machine learning algorithms based on previous record data. These forecasts also refine the problem's parameters: qi (cargo volumes) and $x_{ij}$ (routes). With digital twins, creating a virtual model of routes and logistics processes and testing different scenarios without hitting the actual routes and processes is possible. This allows the model to be quickly tuned in reaction to unexpected situations, including regulatory changes and the evolving transport infrastructure.

Digital technologies, then, are used to collect, analyse, and simulate data, improving the model's accuracy and adaptability to actual-world conditions and thus as a tool in optimisation. According to the modelling results, using the proposed algorithm has reduced transport costs by an average of 18% compared to traditional methods. The algorithm was applied to analyse data from transport routes between significant European logistics hubs. The study involved data from DHL Freight, DB Schenker, and GEFCO, which specialise in international road transport. The study examined transport routes between Germany, France, Poland, Italy and the Czech Republic, covering the main transport corridors in Europe.

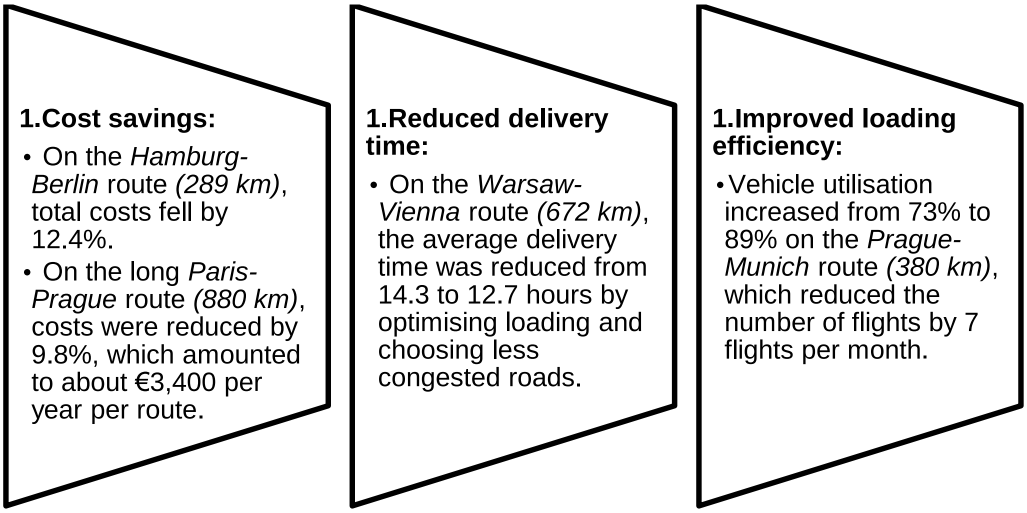
The following inputs were used for the modelling:

- Distances between delivery points (e.g. 467 km between Frankfurt and Prague).
- Cargo volumes ranged from 1.8 to 24.3 tonnes.
- Depending on the route, the average cost of transporting 1 km ranges from EUR 0.82 to EUR 1.05.
- Vehicle capacity: 20.5 tonnes for standard trucks.
- The vehicle load factor averaged 73%.

The data was collected from 2021 to 2023. Python software tools with the SciPy and PuLP libraries were used for the analysis. The optimisation was carried out using a linear programming algorithm with the objective of minimising total costs. The modelling showed the following results (Figure 3).

**Figure 3**

Results of transport route optimisation in international road transport



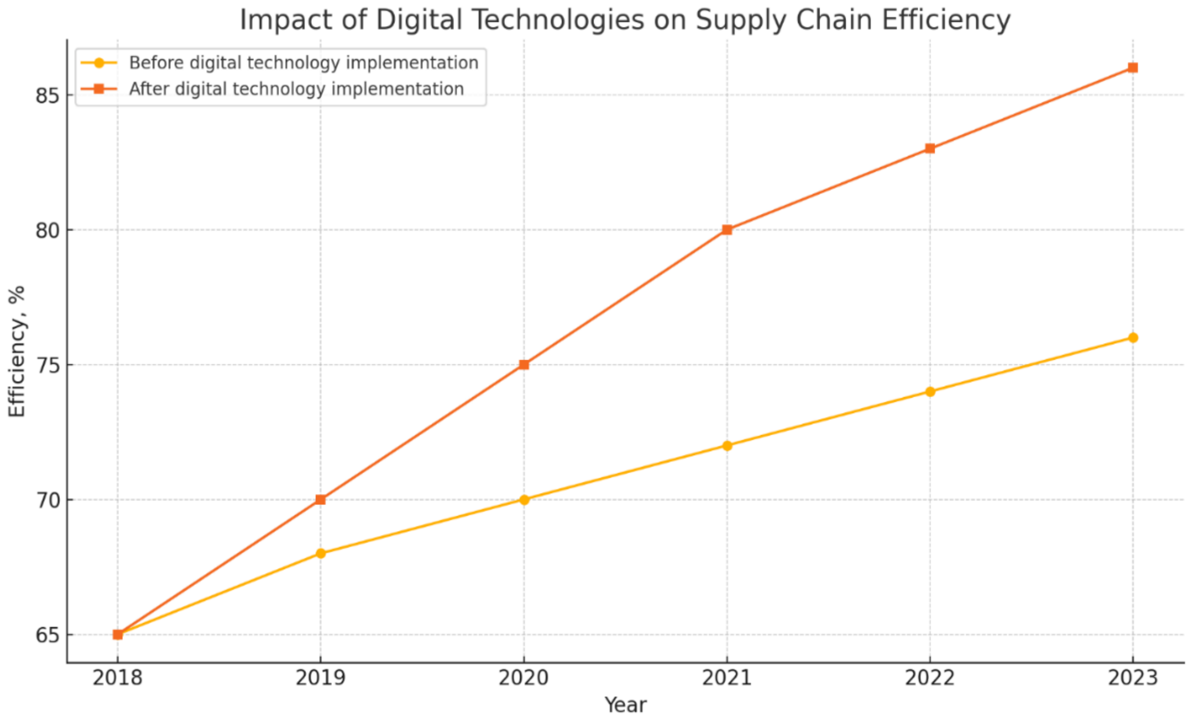

Source: developed by the author based on data from DHL Freight, DB Schenker, GEFCO and statistical indicators for 2021-2023.

Optimising transport routes has proven to be highly effective for large transport companies. For example, DHL Freight achieved savings of around €110,000 per year using the new model for routes over 500 km long. For smaller companies, it is suggested that automated platforms, such as SAP Logistics or TMS Smart, be integrated, which allows for the taking into account of factors such as congestion, weather changes, and sudden changes in the workload of delivery points.

Figure 4 illustrates the key aspects of digitalisation in logistics, including its impact on supply chain management. This visualisation demonstrates how innovative solutions such as artificial intelligence and the Internet of Things (IoT) can increase transparency, speed of delivery, and operational costs.

**Figure 4**

The impact of digitalisation on supply chain efficiency from 2018 to 2023




Source: developed by the author based on Boute and Udenio (2023), Chan, Hogaboam and Cao (2022).

The graph shows the increase in supply chain efficiency before and after the introduction of digital technologies in 2018-2023. The overall increase in efficiency before the introduction of digital technologies was 11% (from 65% in 2018 to 76% in 2023), while after the introduction - 21% (from 65% to 86%). In particular, the annual growth after digitalisation was consistently higher: for example, in 2019, the increase was 5% compared to 3% without digitalisation, in 2020 - 5% compared to 2%, and in 2023 - 3% compared to 2%. This shows that introducing digital technologies, such as process automation, artificial intelligence and big data analytics, significantly improves the efficiency of logistics processes. On average, the efficiency gains after digitalisation are almost twice as significant as in the traditional supply chain approaches, thus confirming that investing in digital tools is feasible to optimise supply chain performance.

Efficient supply chain management, cost reduction and speed up delivery times are achieved by revolutionising logistics with modern digital technologies. Sensors used with physical objects that are ‘touchable’ together and combined with a network – be it an IoT network, a 3G, 4G, 5G or WLAN network – enable real-time data to be gathered without further action required. IoT is used in logistics to track cargo, especially food or medicines, and it is important because temperature and humidity need to be monitored in refrigerated trucks. The tool is already used for routing optimisation, demand forecasting and inventory management. Machine learning, alongside other AI-based tools, permits the analysis of vast volumes of data to make correct predictions. To showcase (for example), Amazon optimised warehousing with AI, cutting their order processing time by 30%. Also, AI algorithms assist in detecting supply chain risks, making chains more ‘resilient’. A digital twin is a virtual model of a physical object or process that can simulate how best to operate food logistics, where warehouses, transportation and delivery are simulated via created digital twins. Digital twins, for example, help DHL run tests of new logistics strategies without the risks and costs attached by trying them in the real world.

However, modern digital technologies are revolutionising the logistics sector: they make processes more efficient, cheaper, and more flexible to respond to the problems of global markets. So, while each has its advantages, the synergy of these technologies into a single system is a development area for the industry. In order to get the most out of these innovations, overcoming challenges such as infrastructure, regulatory restraints, and security is crucial.

The resilience of logistics networks spiking with digitalisation allows companies to move quicker toward innovation and market changes and face external risks. Predictive analytics and similar data-driven tools aid in supply chain disruption identification, inventory optimisation, and alternative delivery route optimisation. For instance, using digital twins allows potential crises like natural disasters or supply disruptions to be modelled and the cruellest way to deal with them to be found. It also enhances transparency through digitalisation by having the Internet of Things (IoT) monitor shipments in real-time. It enables companies to avoid delays, eliminate delivery risk and deliver orders perfectly. For instance, for unstable shipping conditions, such as when the containers are lost, Maersk employs IoT to monitor the containers.

Digitalisation is good at making systems more resilient, but it also introduces new security issues. Cybersecurity is at the center of this threat, as logistics systems are so dependent on technology that they can be attacked with cyberattacks. For instance, ransomware attacks can completely ruin a supply chain, such as when logistics company CMA CGM was hit with a 2020 attack. Hackers can also gain unauthorised access to data within logistics systems to disclose things such as delivery routes, customer details, and financial reports, which are the principal risks of cyber insecurity in logistics tech. Moreover, digital tools (malfunctioning IoT devices or artificial intelligence systems) can be sabotaged, which paralyses operations. Hacker attacks are also a significant threat because hackers can disrupt supply chains and block digital systems, leading to delays in deliveries and significant financial losses.

Meanwhile, investing in modern cybersecurity tools like data encryption, multi-level security systems, and regular systems tests will guarantee the resilience and security of logistics systems. The first step is to create crisis plans to ensure that business will continue during disruptions or cyber-attacks. Specific training targeted at staff trained to identify possible threats and abide by digital hygiene rules is particularly important.

Digitalisation makes logistics networks resilient and helps companies increase their adaptability and prevent downtime in the face of crises. However, at the same time, digital tools proliferate new cybersecurity challenges. For the safe operation of logistics systems, a comprehensive approach is required: innovative technologies, cyber defense, and strategic planning.

## 4. Discussion

This study has identified significant challenges and opportunities in optimising supply chains for international road transport using modelling and digital technologies. The findings are consistent with previous studies, including Kochhar (2023), who highlighted the impact of rising fuel costs on operating costs, and Lozano-Oviedo, Cortés and Rey (2024), who showed the potential of fleet renewal to reduce $CO_2$ emissions. At the same time, our results extend the discussion by focusing on the role of digital twins and predictive analytics in reducing logistics inefficiencies. In contrast to Feng and Ye (2021), who focused mainly on the benefits of Industry 4.0 technologies for operational management, our study demonstrated specific cost reductions (e.g., 18% in transport costs) achieved through advanced algorithmic modelling. Such differences may be due to different methodological approaches, such as integrating real-time data from IoT devices versus using only historical data. In addition, while Sinitsyna and Nekrasov (2024) discuss digital transformation tools in general, our study specifies their practical application in cross-border logistical complexities.

At the same time, there is a controversy about the ability of small and medium-sized enterprises (SMEs) to adapt digital platforms for logistics management. For example, Rziki et al. (2024) note that most SMEs face financial and technical constraints in implementing such solutions. In contrast, the results of our study demonstrate that it is possible to integrate platforms such as SAP Logistics or TMS Smart at minimal cost, especially when cooperating with larger logistics providers.

A limitation of our study is the narrow focus on European transport routes, which may reduce the generality of the results for other regions. Further research should focus on analysing the impact of digital technologies in a global context and consider more types of logistics models. Nevertheless, the findings demonstrate the high potential of digital technologies to improve the efficiency and sustainability of international supply chains.

## 5. Conclusion and prospects for further research

The study confirmed the effectiveness of using automated forecasting technologies to optimise international road transport, which reduced transport costs by an average of 18%. The developed algorithm for optimising transport costs, considering real-world constraints, demonstrated high adaptability to various transport scenarios and ensured the stability of logistics operations even in the face of changing market conditions. In contrast to previous studies, our research focuses on integrating digital tools into a single logistics system, allowing for greater transparency of processes and faster management decision-making. We have identified new approaches to risk forecasting in supply chains through predictive analytics and machine learning algorithms. The practical significance of the results lies in the possibility of implementing digital platforms even by small and medium-sized enterprises, provided they are adapted to the existing infrastructure. A limitation of the study is the focus on European transport routes, which may limit the applicability of the results in other regions. Further research could be aimed at developing global optimisation models, considering infrastructure and regulatory aspects in other countries. It is recommended to continue studying the impact of digital technologies on the environmental friendliness of logistics operations and their long-term sustainability.

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