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Veleučilište u Rijeci
University of Applied Sciences of Rijeka, Rijeka

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Konferencija se organizira kao međunarodni znanstveni skup te ima međunarodni programski odbor sastavljen od članova iz više država i institucija. Svi radovi objavljeni u ovom zborniku bili su podvrgnuti postupku dvostruko slijepe recenzije.

The conference is organized as an international scientific conference and has an International Program Committee composed of members from multiple countries and institutions. All papers published in the proceedings have undergone a double-blind peer review process.

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PREDGOVOR

S osobitim zadovoljstvom predstavljamo zbornik radova međunarodne znanstvene konferencije *Transport and Logistics 2026*, održane 16. i 17. travnja 2026. godine u Opatiji i Rijeci. Ovaj zbornik rezultat je zajedničkog znanstvenog i stručnog promišljanja suvremenih izazova, razvojnih procesa i budućih smjerova prometa i logistike, kao jednog od ključnih područja gospodarskog i društvenog razvoja.

Konferenciju su zajednički organizirali Hrvatsko znanstveno društvo za promet i Veleučilište u Rijeci, čime je potvrđena važnost suradnje znanstvenih, obrazovnih i stručnih institucija u promicanju istraživanja, razmjene znanja i razvoja inovativnih rješenja u području prometa i logistike. Posebnu važnost ovom skupu daje činjenica da je njegov pokrovitelj Ministarstvo mora, prometa i infrastrukture Republike Hrvatske, čime je dodatno potvrđena njegova stručna, društvena i institucionalna relevantnost.

Na konferenciji su predstavljena 42 rada, koja su prethodno prošla postupak dvostruko slijepe recenzije, čime je osigurana znanstvena kvaliteta i vjerodostojnost izloženih istraživanja. Odlukom Organizacijskog odbora konferencije četiri su rada izdvojena i predložena za objavu u časopisu *Journal of the Polytechnic of Rijeka* (WoS Q3). Ta činjenica dodatno potvrđuje znanstvenu kvalitetu i relevantnost radova predstavljenih na konferenciji, kao i nastojanje organizatora da najvrjedniji doprinosi budu dodatno afirmirani u međunarodno prepoznatljivom znanstvenom okruženju.

U radu konferencije sudjelovalo je više od 100 autora i koautora iz 12 zemalja: Hrvatske, Slovenije, Srbije, Bosne i Hercegovine, Crne Gore, Sjeverne Makedonije, Slovačke, Njemačke, Italije, Portugala, Turske i Kine. Takva međunarodna zastupljenost autora i institucija potvrđuje prepoznatljivost konferencije te njezinu ulogu kao važnog mjesta susreta različitih istraživačkih pristupa, znanstvenih tradicija i praktičnih iskustava. U ovom je zborniku objavljeno 38 radova.

Tematski sadržaj radova obuhvaća niz aktualnih i međusobno povezanih područja, među kojima se osobito izdvajaju ekonomika prometa i prometna politika, javni prijevoz, logistika i lanci opskrbe, digitalna transformacija prometnih i logističkih sustava, sigurnost prometa, željeznički i intermodalni sustavi, održiva mobilnost te razvoj prometne infrastrukture i koridora. Takva tematska raznolikost potvrđuje da se promet i logistika danas ne mogu promatrati usko i parcijalno, nego kao složeni razvojni sustavi u kojima se isprepliću tehnologija, sigurnost, održivost, ekonomija i kvaliteta upravljanja.

Radovi objavljeni u ovom zborniku potvrđuju da budućnost prometa i logistike počiva na povezivanju tehnoloških inovacija, ekonomske učinkovitosti, sigurnosnih standarda, održivog razvoja i odgovornog upravljanja. U tom smislu, ovaj zbornik ne predstavlja samo pregled aktualnih istraživačkih tema, nego i vrijedan doprinos daljnjem razumijevanju suvremenih prometnih i logističkih procesa na nacionalnoj i međunarodnoj razini.

Uredništvo zbornika izražava iskrenu zahvalnost svim autorima na njihovim znanstvenim i stručnim doprinosima. Posebnu zahvalnost upućujemo recenzentima, čiji su stručnost, savjesnost i predanost u recenzijskom postupku dali važan doprinos znanstvenoj kvaliteti i vjerodostojnosti ovoga zbornika. Zahvaljujemo i članovima Organizacijskog i Programskog odbora na predanom angažmanu u pripremi i provedbi konferencije. Vjerujemo da će ovaj zbornik biti trajan zapis o uspješnosti skupa, ali i poticaj daljnjim istraživanjima, novim suradnjama i razvoju suvremenih rješenja u području prometa i logistike.

Opatija–Rijeka, travanj 2026.

Bojan Hlača
Marino Golob
Drago Pupavac
Urednici

PREFACE

It is our great pleasure to present the proceedings of the international scientific conference *Transport and Logistics 2026*, held on 16 and 17 April 2026 in Opatija and Rijeka. These proceedings are the result of a shared scientific and professional reflection on contemporary challenges, developmental processes, and future directions in transport and logistics, one of the key domains of economic and social development.

The conference was jointly organized by the Croatian Scientific Society for Transport and the Polytechnic of Rijeka, thereby reaffirming the importance of cooperation among scientific, educational, and professional institutions in promoting research, knowledge exchange, and the development of innovative solutions in the field of transport and logistics. The significance of this conference is further underscored by the patronage of the Ministry of the Sea, Transport and Infrastructure of the Republic of Croatia, which additionally confirms its professional, social, and institutional relevance.

A total of 42 papers were presented at the conference, all of which had previously undergone a double-blind peer review process, thus ensuring the scientific quality and credibility of the research presented. By decision of the Conference Organizing Committee, four papers were selected and recommended for publication in the *Journal of the Polytechnic of Rijeka* (WoS Q3). This further attests to the scientific quality and relevance of the papers presented at the conference, as well as to the organizers' commitment to providing additional recognition for the most valuable contributions within an internationally recognized scientific environment.

The conference brought together more than 100 authors and co-authors from 12 countries: Croatia, Slovenia, Serbia, Bosnia and Herzegovina, Montenegro, North Macedonia, Slovakia, Germany, Italy, Portugal, Turkey, and China. Such international representation of authors and institutions confirms the conference's visibility and its role as an important meeting point for diverse research approaches, scientific traditions, and practical experience. A total of 38 papers are included in these proceedings.

The thematic scope of the papers covers a range of current and interconnected fields, particularly transport economics and transport policy, public transport, logistics and supply chains, the digital transformation of transport and logistics systems, transport safety, railway and intermodal systems, sustainable mobility, as well as the development of transport infrastructure and corridors. Such thematic diversity confirms that transport and logistics can no longer be viewed in a narrow or fragmented manner, but rather as complex development systems in which technology, safety, sustainability, economics, and quality of governance are closely intertwined.

The papers published in these proceedings demonstrate that the future of transport and logistics rests on the integration of technological innovation, economic efficiency, safety standards, sustainable development, and responsible management. In this sense, these proceedings provide not only an overview of current research topics, but also a valuable contribution to a deeper understanding of contemporary transport and logistics processes at both the national and international levels.

The Editorial Board extends its sincere gratitude to all authors for their scientific and professional contributions. Special thanks are also due to the reviewers, whose expertise, conscientious work, and dedication to the review process made a significant contribution to the scientific quality and credibility of these proceedings. We also express our appreciation to the members of the Organizing Committee and the Programme Committee for their dedicated efforts in the preparation and implementation of the conference. We believe that these proceedings will serve as a lasting record of the conference's success and as an incentive for further research, new collaborations, and the development of contemporary solutions in the field of transport and logistics.

Opatija–Rijeka, April 2026

Bojan Hlača
Marino Golob
Drago Pupavac
Editors

I. TRANSPORT INFRASTRUCTURE, PORTS AND LOGISTICS CORRIDORS

I. PROMETNA INFRASTRUKTURA, LUKE I LOGISTIČKI KORIDOR

Preliminary communication

THE DEVELOPMENT OF TRANSPORT INFRASTRUCTURE IN MONTENEGRO AS A PREREQUISITE FOR THE VALORIZATION OF THE PORT OF BAR

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ABSTRACT

The Port of Bar, positioned in the Southern Adriatic, holds significant geographical advantages that could enable it to function as a major logistical gateway for the markets of Central and Southeastern Europe. Yet the realization of this potential depends less on its coastal location alone and more on the quality, efficiency, and capacity of the transport infrastructure that connects the port to its hinterland. This paper analyzes the link between national infrastructure modernization and the port's competitive position within the Adriatic transport basin.Attention is given to the combined role of two key transport corridors: the Bar–Boljare–Belgrade highway and the Belgrade–Bar railway. Although the port benefits from a favorable natural position, its performance is constrained by operational bottlenecks. These stem primarily from technical and capacity limitations on the railway and from the incomplete integration of road links with Pan-European corridors. Using both qualitative assessments and quantitative indicators such as cargo throughput and transit times, the research shows that upgrading port terminals alone is insufficient to secure a competitive regional position. Instead, competitiveness requires a comprehensive intermodal transport strategy that connects maritime, rail, and road systems in a coordinated manner. Key findings indicate that completing the highway and undertaking a full-scale modernization of the railway are essential for lowering logistics costs, improving reliability, and making the port more attractive to major shipping lines. The paper also highlights the importance of developing "dry ports" and integrated logistics zones to enhance the port's gravity area. In conclusion, the paper proposes a strategic framework for decision-makers, arguing that transport network modernization is a true "conditio sine qua non" for transforming the Port of Bar from a modest regional transit point into an efficient, sustainable maritime-logistics hub. Such a transformation would generate meaningful multiplier effects for Montenegro's economy and contribute to long-term national growth.

Key words: *Port of Bar, Transport Infrastructure, Hinterland Connectivity, Intermodal Logistics*

1. INTRODUCTION

For countries with maritime access, economic development is closely linked to the operational efficiency of their ports and the degree to which these ports are integrated into global supply chains. In Montenegro, the Port of Bar constitutes a strategic national asset; however, its overall performance depends largely on the quality and reliability of the transport infrastructure that supports it. Although the port benefits from a favorable geographic position

and deep-water capacity, its operational efficiency continues to be constrained by bottlenecks in the surrounding road and rail networks (Montenegro Business Portal, 2025).

Montenegro's geographic location at the intersection of major European transport corridors—particularly in the context of the extension of the Trans-European Transport Network (TEN-T) into the Western Balkans—creates new expectations for the national transport system. The Port of Bar is increasingly recognized as an important regional logistics node, yet its long-term competitiveness depends on the efficiency of multimodal transport systems and the effective coordination between maritime, rail, and road infrastructure. Upgrading these transport links is essential for transforming Bar from a predominantly domestic port into an internationally relevant logistics hub capable of competing with larger Adriatic ports such as Rijeka and Koper.

Two major national infrastructure projects form the core of this transformation: the Bar–Boljare Highway and the Belgrade–Bar Railway. The highway, Montenegro's most ambitious infrastructure project to date, is intended to overcome challenging mountainous terrain and provide a faster and safer connection to Serbia and the wider Central European region. At the same time, the modernization of the Belgrade–Bar Railway (Route 4), which has suffered from decades of underinvestment, is essential for supporting the efficient movement of heavy cargo and containerized freight. Current initiatives, including the EU-funded €175 million reconstruction of the Bar–Golubovci section, are expected to improve travel speeds, enhance reliability, and strengthen the connection between the port and its natural hinterland markets (EU, 2025).

According to the Transport Development Strategy 2019–2035, the Government of Montenegro has placed strong emphasis on integration with the European Union market, improvements in transport safety standards, and the promotion of economic growth through more efficient infrastructure. These priorities are further supported by the EU Economic and Investment Plan, which provides grant financing for key road and rail projects. Nevertheless, realizing the full potential of these investments remains challenging due to the high construction costs associated with Montenegro's mountainous terrain, the need for institutional modernization, and the requirement to further professionalize port management practices (European Commission, 2022).

This study examines how strategic investments in key transport corridors can enhance the economic impact of the Port of Bar on Montenegro's national development. It identifies existing infrastructure constraints, reviews current and planned development initiatives, and evaluates the extent to which a modernized road and railway network can stimulate foreign direct investment and support the development of logistics clusters. The central argument of the study is that strengthening hinterland connectivity—particularly through the modernization of rail and road infrastructure—represents the most reliable pathway toward sustainable economic growth and the positioning of Montenegro as an important logistics platform on the Adriatic coast (WBIF, 2023; European Commission, 2022).

Realizing the full economic potential of the Port of Bar requires more than improvements to maritime infrastructure alone; it depends on the transformation of its hinterland into an integrated and efficient logistics ecosystem. Rather than functioning solely as a transit hub, the port should evolve into a value-added logistics center where goods can be stored, processed, and redistributed. The establishment of the Port of Bar Free Zone provides an institutional framework for attracting foreign investment; however, its long-term effectiveness depends on efficient integration with major European transport corridors (Government of Montenegro, 2021; European Commission, 2023).

The proposed Corridor XI, linking Bari in Italy with Bar, Belgrade, and Bucharest, further strengthens the strategic importance of the Port of Bar as a potential gateway for Central and

Southeastern Europe. The inclusion of this corridor within the Trans-European Transport Network (TEN-T) framework would enable Montenegro to access key European financing instruments, particularly those available through the Western Balkans Investment Framework (WBIF). Such financial support is essential for implementing complex infrastructure modernization projects, especially given Montenegro's challenging mountainous terrain and the high costs associated with transport development (European Commission, 2022; WBIF, 2023). Key benefits of this integration include:

- **Multimodal Synergy**: The completion of the Bar-Boljare motorway, paired with the full modernization of the Bar-Vrbnica railway, drastically reduces transit times and logistics costs. This makes Bar a viable, high-speed alternative to North Adriatic ports for cargo destined for the Balkans and beyond.

- **Creation of "Dry Ports"**: Developing modern intermodal terminals in inland hubs like Podgorica or Bijelo Polje would allow for the creation of "dry ports." This decentralizes logistics operations, alleviates congestion at the shoreline, and increases the overall throughput capacity of the maritime gateway.

- **Digitalization and Green Logistics**: Aligning with the EU Green Agenda for the Western Balkans, infrastructure upgrades must prioritize decarbonization. Shifting freight from road to rail is not only an environmental necessity but a requirement for long-term integration into the European logistics market.

Without full integration into the proposed Corridor XI, the Port of Bar risks remaining only a limited regional gateway rather than a major international logistics node. By deliberately developing logistics clusters, Montenegro can turn its geographic position into a strategic advantage, transforming the country into a key Balkan distribution center that links maritime trade routes with the core of the European continent. To fully grasp the importance of infrastructure upgrades, the Port of Bar must be evaluated within the competitive context of the Adriatic market. Ports such as Rijeka in Croatia and Koper in Slovenia already benefit from strong connections to established European transport corridors, while Bar simultaneously faces increasing pressure from the Port of Durres in Albania. Durres is undergoing a significant redevelopment effort, supported by both UAE and EU investment, and is being positioned as a major node along Corridor VIII, which spans the Eastern and Western Balkans.

Despite this intensifying competition, Bar maintains two critical advantages: its deep natural harbor, capable of accommodating large vessels, and its direct railway connection that extends deep into the hinterland. However, without the timely completion of the Bar–Boljare motorway and the modernization of the Bar–Belgrade railway—anticipated by 2030—the Port of Bar risks losing cargo flows destined for Serbia, Hungary, and Romania. In short, Bar's long-term competitiveness depends on aligning maritime capacity with reliable, high performance inland connectivity

2. LITERATURE REVIEW

High quality inland transport (rail/barge) reduces distance barriers and expands hinterlands, strengthening port attractiveness and throughput (Guerrero, 2019). Behdani et al. (2020) highlights that hinterland transport accounts for ~60% of maritime supply chain costs, making inland infrastructure critical for reducing bottlenecks and increasing port throughput. Port competitiveness and throughput rely heavily on efficient inland connections, and poor hinterland links become major constraints even when port side operations are modernized (OECD/International Transport Forum 2015). Rožić et al. (2025) shows that inland terminals ("dry ports") strengthen port–hinterland integration, improving cargo flow efficiency and supporting increased port throughput while Merk and Notteboom (2015) state that expanded

multimodal inland infrastructure is essential to avoid bottlenecks and support port capacity growth and throughput increases.

Liang & Liu (2020) demonstrates that improved port infrastructure connectivity enhances logistics performance, which in turn boosts seaborne trade (linked to higher throughput). Empirical evidence from Sierra Leone demonstrates that targeted infrastructure investment yields measurable increases in port throughput. Upgrades such as berth expansion, modernization of handling equipment, and improved ICT (Information and Communication Technology system) systems produced a 30% increase in annual container throughput and a 25% reduction in vessel turnaround times at Queen Elizabeth II Quay (Kamara et al.,2025). Similarly, Brancaccio et al. 2024, develop an infrastructure–trade model showing that infrastructure investments generate significant welfare and trade gains, though benefits vary by port location and require correct targeting. The study confirms positive returns to infrastructure investment at a subset of ports, reinforcing the link between inland capacity, port performance, and national trade volumes. Ensslin et al. 2025, further emphasize that infrastructure-related variables—such as yard layout, berth capacity, and the number of ship to shore cranes—are direct drivers of port throughput and container-handling efficiency. Their findings underscore the need for modernization and strategic investments aligned with port size and cargo mix.

Dry ports have emerged as a powerful mechanism to relieve seaport congestion, improve inland penetration, and expand hinterland reach. Khaslavskaya's systematic review shows that dry ports enhance seaport competitiveness by offering inland nodes where cargo can be consolidated, cleared, or staged, effectively extending the seaport into the hinterland. This reinforces stable cargo flow and improves overall supply chain efficiency (Khaslavskaya and Roso, 2020). Li et al., 2020 show that dry ports improve accessibility across regional hinterlands, although benefits vary by geography, rail frequency, and cargo characteristics. Their modeling demonstrates that dry ports can reduce transport costs and improve port hinterland connectivity, but the distribution of benefits depends on each region's logistics structure.

Advanced modeling approaches reveal the mechanisms by which inland infrastructure affects port throughput. Kunambi and Zheng (2025) use Markov processes, max flow models, and traffic flow simulation to evaluate the Dar es Salaam hinterland system. Their findings identify severe inland bottlenecks—especially for destinations like Lubumbashi, which faces a 500 ton/day shortfall in capacity due to weak road and rail links, directly restricting port throughput. GIS based analysis by Gurav and Patel demonstrates how optimal siting of dry ports—based on population density, accessibility, rail connectivity, and land suitability—can significantly reduce inland congestion and improve cargo flows to and from seaports. This reduction in transport costs and greenhouse gas emissions illustrates how hinterland planning impacts port throughput and sustainability. Liang and Liu 2020, provide empirical evidence showing that improved port infrastructure connectivity enhances logistics performance, which in turn accelerates seaborne trade and economic development. Their structural equation model highlights the indirect but powerful effects of hinterland infrastructure on trade volumes moving through ports.

Munim and Schramm similarly show that improved port infrastructure enhances logistics performance, generating higher seaborne trade flows—a key proxy for port throughput. Their analysis of 91 countries demonstrates that improvements to port and inland infrastructure have strong, positive, and statistically significant effects, especially in developing economies. Behdani et al. 2020., also note that containerization and intermodal infrastructure have revolutionized hinterland logistics, enabling larger ships and ports to function efficiently—but only when supported by inland terminals, rail corridors, and distribution centers. Without inland integration, mega ports face recurrent congestion and throughput constraints. Koritarov and Dimitrakiev (2020), emphasize evolving definitions of the hinterland, describing it not merely as a geographic space but a dynamic system of economic, social, and infrastructural linkages. Their study notes that infrastructure quality, freight volumes, modal

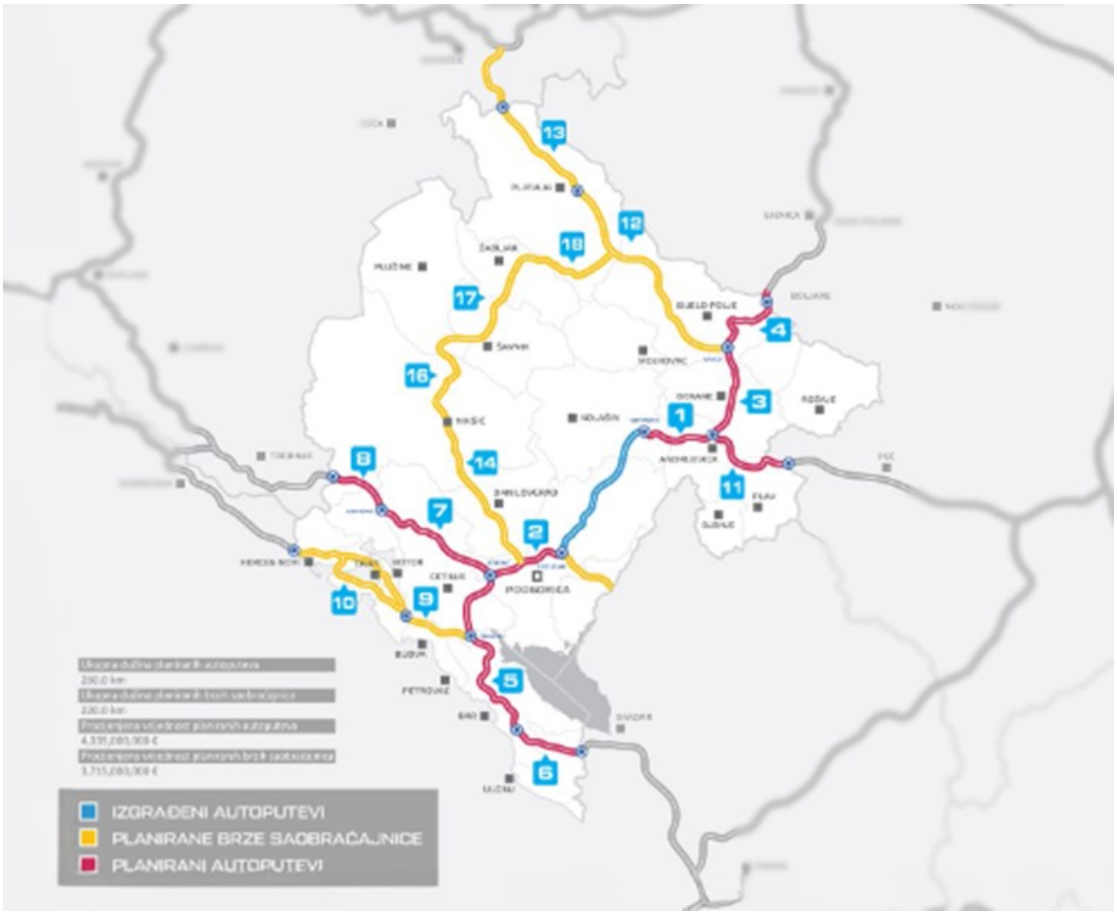
split, and logistics performance all shape the functional reach of ports and their ability to grow throughput.

Finally, the OECD finds that the growing sizes of ships and the rise of maritime hub and spoke systems increase demands on hinterland networks. Without synchronized development, inland infrastructure becomes the primary point of friction, constraining the throughput potential of even the most technologically advanced ports (Rožić et al. 2025).

3. RESEARCH AND DISCUSSION

The European Union, through the Western Balkans Investment Framework (WBIF), funds the development of transport infrastructure in all Western Balkan countries and in Montenegro, in cooperation with the European Bank of Reconstruction and Development (EBRD) and the European Investment Bank (EIB). Montenegro's current investment program for transport infrastructure development amounts to an ambitious €9 billion, creating significant opportunities for investments and partnerships within Montenegro and the Western Balkans region (WBIF,2025).

Graph 1. Planned roads with an investment plan of 9 billion euros



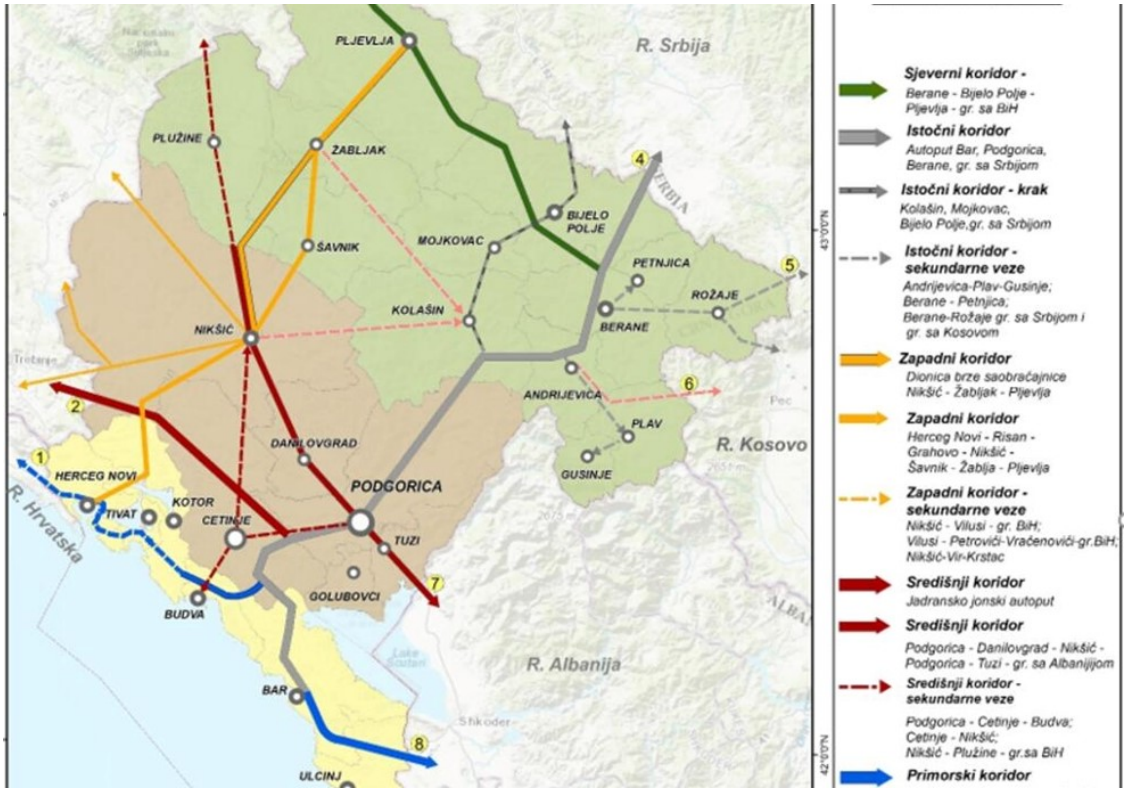
Source: https://investitor.me/2025/01/15/u-2026-planiran-pocetak-gradnje-480-kilometara-auto-puteva/

The investment cycle of 9 billion euros includes the construction of 260 km of highways and 220 km expressways in Montenegro. Graph 1 shows a map of the planned traffic routes, of which the Bar-Belgrade highways and the Adriatic-Ionian highway that passes through Montenegro are key.

On the Graph 1, the already constructed part of the Bar-Boljari highway is marked in blue. Highways that are planned to be built are marked in red, while planned expressways are

marked in yellow. The spatial plan foresees that Montenegro will have 623 kilometers of highways and expressways in 2040. Of that, 270 kilometers refer to the two highway corridors Bar - Boljare (A1) and Adriatic - Ionian (A2), and 353 kilometers are expressways in five directions - Budva - border with Croatia (B1), Crnča - Pljevlja - border with Bosnia and Herzegovina (B2), Smokovac - Tuzi - Božaj (B3), Podgorica - Nikšić - Šavnik - Žabljak - Pljevlja (B4) and Andrijevica - border with Kosovo. (B5). Graph 2 shows the network of future highways and expressways in Montenegro with a total length of 623 km, which are foreseen in the spatial plan until 2040 (Službeni list Crne Gore, 2025).

Graph 2. Highways and express ways in 2040



Source: https://investitor.me/2025/06/20/evo-kako-ce-izgledati-putevi-crne-gore-2040-mreza-623-km-auto-puteva-i-brzih-saobracajnica/

Rail transport plays a crucial role in ensuring Montenegro's seamless integration into the European freight network. The Bar-Belgrade railway serves as the main corridor for cargo transport, enabling efficient movement of goods between Montenegro and Serbia, and further into Central Europe.

Rail transport offers several advantages over road transport, including lower costs for bulk shipments, reduced traffic congestion, and decreased environmental impact due to lower carbon emissions. With total length of 327 km if railroads Montenegro cargo transport offers investors good connection with Port of Bar and further with Serbia and Central Europe. The Niksic – Podgorica railway is 56.6 km long and it is used mainly for passengers and cargo transport (bauxite). The railway was thoroughly reconstructed and electrified in 2006–2012 period, with passenger service reintroduced (MIA, 2025). Graph 3. shows the railway network in Montenegro.

Graph 3. Railway network in Montenegro

Source: Ibid

Montenegro's 2026 railway development strategy places strong emphasis on modernizing the national rail system and aligning it with the Trans-European Transport Network (TEN-T). Central to this plan is the reconstruction of the Bar–Golubovci railway section, the most substantial rail infrastructure investment undertaken in Montenegro in several decades. The project's total value is estimated at €230.8 million, with the European Union contributing €175 million through grants and concessional financing. The modernization aims to operational speed, reliability, and safety, while also expanding capacity to accommodate up to 1.3 million passengers annually. As part of a key international corridor, this upgraded segment strengthens Montenegro's connection between the Port of Bar, Belgrade, and the wider Central European transport network (Railway Pro, 2026). The Government of Montenegro is implementing the National Railway Infrastructure Program for the period 2024-2026. The strategy relies on the following pillars:

- Green transition: Transition from road to rail traffic in order to reduce CO2 emissions by over 50% by 2037.
- Removal of "bottlenecks": The focus is on rehabilitation of critical points that slow down traffic and reduce railway competitiveness.
- Interoperability: Harmonization of technical standards with EU standards to enable smooth international traffic (Portal Vijesti, 2024).

In addition to infrastructure, the strategy also includes the modernization of the vehicle fleet:

- Procurement of new trains: The procurement of new passenger trains is planned with the support of the EBRD, which will directly affect the quality of service and environmental sustainability.

- Digitization: Introduction of modern systems for traffic management and passenger information.

- The long-term goal is for the railway to become the backbone of economic and tourist development, fully integrated into the unique European railway area (ZICG, 2023).

Regional connection

In order for investments in the road and railway infrastructure of Montenegro to make sense, it is necessary for the neighboring countries to plan a connection with Montenegro. The key connection in this sense is the corridor Bar - Belgrade - Budapest, as well as the connection between Sarajevo and the Montenegrin border. It should provide an alternative route to Budapest as a central European hub.

Work on the transport route commonly referred to by experts as Corridor XI – Bari–Bar–Belgrade–Bucharest – began in Serbia in 2012 with the launch of the first construction site on the Ljig–Preljina section. Although it has not yet been formally integrated into the TEN T European network, this corridor is already recognized as an international infrastructure project currently under development and serves as the foundation for future connectivity among four countries across the Adriatic. Its main components are Serbia's A2 "Miloš Veliki" highway and Montenegro's Bar–Boljare highway.

To date, Serbia has reconstructed 77 km of railway between Belgrade and Valjevo. The remaining 210 km of track along the Montenegrin border still requires renovation. As part of the National Program extending to 2029, Serbia plans a full modernization of these remaining sections of the railway to Montenegro. Priority will be given to the following areas:

- Reconstruction of the section Valjevo-Vrbnica as a key part of the plan that includes 210 kilometres of railway from Valjevo to the border with Montenegro.

- Technical documentation is being prepared, and the project includes the modernization of signalling, bridges and tunnels in order to enable higher speeds (up to 100-120 km/h) and higher load capacity.

- Serbia applied for funding for this project from the European Union through the Western Balkans Investment Framework (WBIF). The estimated value of the works is over 1.5 billion euros.

- A unique performance: Serbia and Montenegro signed a joint letter of intent to the European Commission in September 2024. The goal is to treat the Belgrade-Bar railway as a single corridor, which makes it easier to obtain grants and favourable loans for the complete reconstruction from Belgrade to Bar (Portal eKapija, 2024).

The planned works on the entire corridor aim to:

- Reduction of travel time: It is estimated that after the completion of all works, the journey from Belgrade to Bar could take about 7 to 8 hours (instead of the current 11+ hours).

- Increasing cargo capacity: Modernization is key to connecting the Port of Bar with industrial centres in Serbia and further to Central Europe.

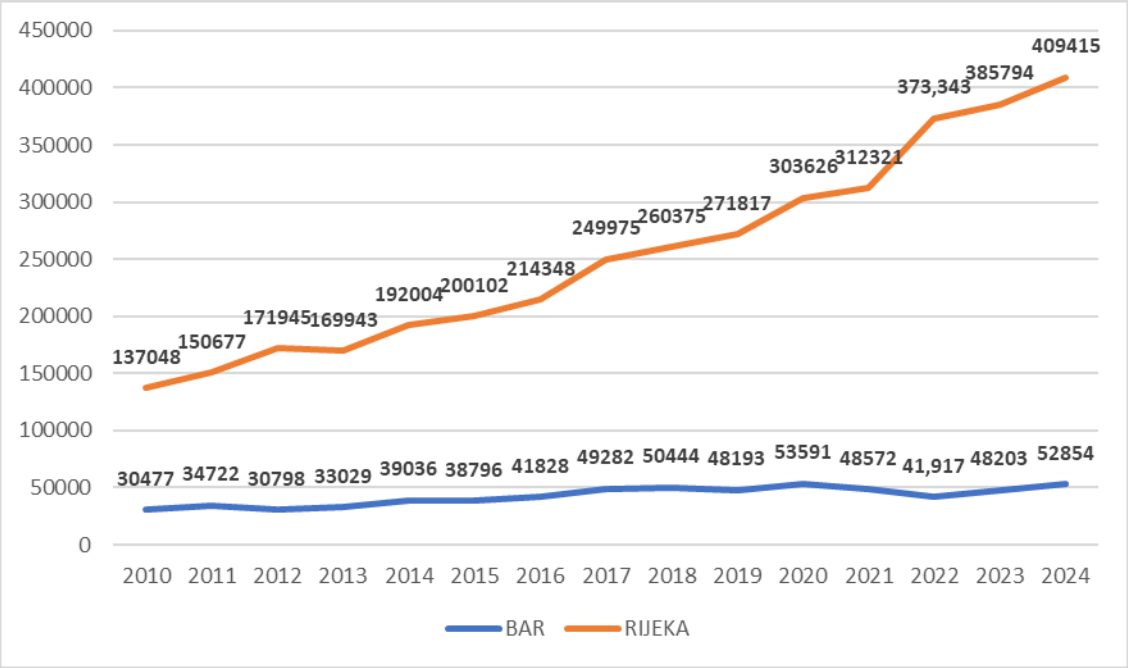
- Safety: Special emphasis was placed on the rehabilitation of damaged bridges and tunnels on the most demanding sections through mountainous areas.

- Although the reconstruction of the Belgrade-Bar railway is marked as a priority, the real start of massive works on the section from Valjevo to the border depends on the completion of negotiations on financing with international partners (DB Engineering & Consulting, 2020).

The completion of the road-railway transport corridor Bar-Belgrade-Budapest is key for Montenegro.

The main source of cargo for the Adriatic ports of Rijeka and Bar is the country of Serbia. In intermodal transport, Serbia uses those two ports for over 90% of its imports and exports. However, precisely because of the poor condition of the railway line between Bar and Belgrade in relation to the railway route Rijeka - Belgrade, most of the Serbian cargo uses the logistics route via Croatia. The carrying capacity of the Bar-Belgrade railway line is 1060t, while from the direction of Rijeka to Belgrade it is 1800t. The Serbian economy in 80% of cases for its needs in international transport uses the logistics route via the Port of Rijeka, while the logistics route via the Port of Bar is used in about 12% of the cases (Pelevic, 2021). The orientation of the Serbian market towards the port of Rijeka in the last two decades is one of the main reasons for the prosperity of the Croatian port and the stagnation of the port of Bar.

Graph 5. Container throughput Rijeka vs Bar (2010-2024) in TEU



Source: Pelević, 2025

Despite the shorter distance from Belgrade to Bar compared to the distance to the northern Adriatic ports, including Rijeka, for about 1/3 of the total route, goods bypass the direction towards Bar (Pelević et al.,2024). In addition to the markets of Serbia and Bosnia and Herzegovina, it represents a potential for the Port of Bar, which is now very little used. In

order to have a clear insight into the importance of certain markets for the port at least and therefore to work on priority connections, table 1 presents the potential of Montenegrin neighbors in TEU units. Based on the information in Table 1, the absolute priority of Montenegro should be infrastructural connection with Serbia and after that with Bosnia and Herzegovina. The market of Kosovo is connected with the ports of Durres and Thessaloniki by a quality infrastructure, so the Montenegrin logistics community should focus on the markets of Serbia and then the markets of Bosnia and Herzegovina.

Table 1. Potentional hinterland of Bar port in 2024 (in TEU unit)

Country	Yearly TEU capacity	Share
Montenergo	10000	3.4%
Bosna and Hercegovina	70000	23.7%
Serbia	185000	62.7%
Kosovo	30000	10.2%
	295000	100.0%

Source: Ibid

Graph 6. illustrates the potential links between the Port of Bar and medium and long range dry ports in the region, which could channel regional cargo toward the Montenegrin logistics corridor, specifically through the Port of Bar.

Graph 6. Example of Potential Connection of the Port of Bar with Dry Ports of Long and Medium Range in the Region

Source: Pelević, 2020

A suitable example of a medium distance dry port for the Port of Bar would be the dry ports located in Belgrade and Niš. These facilities, positioned within roughly 500 km of a seaport,

operate in areas primarily served by road transport. However, because of the large cargo volumes, shifting freight from road to rail would help ease road congestion and provide a more efficient connection with the seaport (Roso et al., 2009). Long-range dry port would be placed in Budapest and Bucharest. Quality infrastructure in the hinterland of the port of Bar would attract significant cargo to the logistics route via Montenegro, which would interest the world's large logistics companies for investments in Montenegro, especially the Port of Bar. The Port of Bar currently uses only a small share of its real market potential, meaning Montenegro loses significant revenue that instead goes to competing ports like Rijeka. If the Bar–Belgrade–Budapest corridor is developed, intermodal transport could grow from today's €20–30 million to more than €500 million annually, creating thousands of jobs and strongly diversifying Montenegro's economy (Pelević, 2025).

4. CONCLUSION

The analysis indicates that the economic valorization of the Port of Bar is fundamentally dependent on the modernization of Montenegro's transport infrastructure. Despite its advantageous geographic position and natural deep-water capacity, the port cannot achieve sustainable regional competitiveness without reliable and high-performance connections to its hinterland. The completion of the Bar–Boljare–Belgrade motorway and the comprehensive reconstruction of the Belgrade–Bar railway emerges as essential prerequisites for reducing logistics costs, shortening transit times, and attracting cargo flows that currently bypass Montenegro in favor of better-connected Adriatic ports.

The study further demonstrates that partial improvements to port terminals alone are insufficient. Only the development of an integrated intermodal transport system—encompassing road and rail infrastructure, dry ports, and logistics zones—can fully unlock the port's market potential. The establishment of medium- and long-distance dry ports, particularly in Serbia and Central Europe, would significantly expand the Port of Bar's gravitational area and facilitate the redirection of cargo volumes presently routed through Rijeka and other competing ports.

EU-supported investments, green transition policies, and the strategic inclusion of Corridor XI within the broader Trans-European Transport Network framework create a historic opportunity for Montenegro. If fully implemented, these infrastructure developments could transform the Port of Bar into a modern, efficient, and sustainable logistics hub, capable of generating substantial economic spillover effects and positioning Montenegro as a key distribution gateway between the Adriatic region and Central and Southeastern Europe.

Ultimately, the modernization of Montenegro's transport infrastructure is not merely advantageous but represents a conditio sine qua non for unlocking the full potential of the Port of Bar and ensuring long-term national economic growth.

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Prethodno priopćenje

RAZVOJ SAOBRAĆAJNE INFRASTRUKTURE U CRNOJ GORI KAO PREDUSLOV VALORIZACIJE LUKE BAR

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SAŽETAK

Luka Bar, smještena na južnom dijelu Jadrana, posjeduje značajne geografske prednosti koje joj omogućavaju da funkcioniše kao važna logistička kapija za tržišta Centralne i Jugoistočne Evrope. Međutim, ostvarivanje ovog potencijala ne zavisi prvenstveno od njenog primorskog položaja, već od kvaliteta, efikasnosti i kapaciteta saobraćajne infrastrukture koja luku povezuje sa njenim zaleđem. Ovaj rad analizira vezu između modernizacije nacionalne infrastrukture i konkurentske pozicije Luke Bar u okviru jadranskog transportnog bazena. Posebna pažnja posvećena je objedinjenu djelovanju dva ključna saobraćajna koridora: autoputa Bar–Boljare–Beograd i željezničke pruge Beograd–Bar. Iako luka raspolaže povoljnim prirodnim položajem, njeni razvojni rezultati ograničeni su postojećim operativnim uskim grlima. Ona prije svega proizlaze iz tehničkih i kapacitetskih ograničenja željezničke infrastrukture, kao i iz nedovoljne integrisanosti putne mreže sa panevropskim saobraćajnim koridorima. Korišćenjem kvalitativnih analiza i kvantitativnih pokazatelja, kao što su obim pretovara robe i tranzitna vremena, istraživanje pokazuje da unapređenje lučkih terminala samo po sebi nije dovoljno za obezbjeđivanje konkurentne regionalne pozicije. Naprotiv, konkurentnost zahtijeva sveobuhvatnu intermodalnu strategiju koja na koordinisan način povezuje pomorski, željeznički i drumski saobraćaj. Ključni nalazi ukazuju da su završetak autoputa i sveobuhvatna modernizacija željezničke pruge od presudnog značaja za smanjenje logističkih troškova, unapređenje pouzdanosti transporta i povećanje atraktivnosti luke za velike brodarske kompanije. Rad takođe naglašava značaj razvoja „suvih luka“ i integrisanih logističkih zona u cilju proširenja gravitacionog područja Luke Bar. U zaključku se predlaže strateški okvir namijenjen donosiocima odluka, uz argument da modernizacija saobraćajne mreže predstavlja istinski conditio sine qua non za transformaciju Luke Bar iz skromne regionalne tranzitne tačke u efikasan i održiv pomorsko-logistički centar. Takva transformacija generisala bi značajne multiplikativne efekte za privredu Crne Gore i doprinijela dugoročnom nacionalnom ekonomskom rastu.

Ključne riječi: *Luka Bar, saobraćajna infrastruktura, povezanost zaleđa, intermodalna logistika*

Preliminary Communication

DIGITAL TWIN FRAMEWORK FOR CONTAINER TRANSPORT ACROSS A NETWORK OF CONTROL TOWERS: CASE STUDY OF THE ATLANTIC CORRIDOR

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ABSTRACT

Globalisation has intensified the flow of containerised freight across global supply chains, making container transport networks more operationally and coordinatively complex. Ports and container terminals function as critical logistics nodes within these networks, shaping overall supply chain performance. As convergence points for multiple transport routes, ports bring together a wide range of stakeholders, some of whom may have aligned objectives and some of whom may have conflicting objectives. This directly influences the efficiency and reliability of container flows. The growing complexity of interactions at port level means that locally optimised, fragmented decision-making is becoming increasingly inadequate. To ensure continuity and performance across the supply chain, a more integrated management approach is needed. In logistics and supply chain management, this role is often referred to as the 'Control Tower', and enables end-to-end visibility, coordinated decision-making and real-time alignment among stakeholders. When applied at port level, a Control Tower supports the orchestration of local container operations while maintaining awareness of the effects of decisions made at other interconnected ports. When multiple Port Control Towers are interconnected, they form an adaptive, complex logistics system through which local decisions propagate across the wider container transport network. Understanding these propagation effects is crucial for predicting disruptions, managing the repositioning of empty containers, and enhancing network-wide performance. Digital Twin (DT) technology is a suitable framework for representing such systems because it enables the dynamic modelling of physical assets, information flows and decision rules within supply chains. This paper proposes a Digital Twin framework designed to capture control tower decision-making processes and assess their impact on container transport performance at a network level. The framework has been applied to the Atlantic Corridor of the Trans-European Transport Network (TEN-T), taking into account the variety of cargo flows across terminals, including containers with predefined destinations and empty containers. This demonstrates its potential for supporting sincrotimodal transport and supply chain management.

Key words: *Digital Twin, Control Tower, Sincromodal Transport, Atlantic Corridor, TEN-T.*

1. INTRODUCTION

Cargo transport is a critical area for intervention due to its increasing contribution to global emissions. It is estimated that freight transport accounts for around 7% of global CO_2 emissions, a figure which is expected to rise as demand for the transportation of goods increases (World Bank, 2017). In addition to its climate impact, freight transport significantly contributes to local air pollution through the emission of nitrogen oxides (NO_x), particulate matter and other harmful pollutants. According to the European Environment Agency, road transport is a major source of air pollutant emissions in urban areas, which negatively affects air quality and poses serious risks to public health (European Environment Agency, 2020). Furthermore, the increase in heavy-duty vehicle traffic has exacerbated congestion on road networks and in major ports, resulting in delivery delays, elevated operational expenses, and diminished efficiency throughout supply chains (International Energy Agency, 2021).

Multimodal transport is widely recognised as a promising strategy for improving the sustainability of freight transport systems. When implemented effectively, it can contribute to significant emission reductions by enabling the shift of freight from high-emission modes, such as road transport, to more energy-efficient alternatives (Eng-Larsson & Kohn, 2012). However, despite its recognised potential, the effectiveness and operational implications of multimodal freight systems remain relatively unexplored in the literature. Frequently highlighted advantages include the economies of scale associated with rail transport and the environmental benefits resulting from reduced reliance on road-based freight (Baykasoğlu and Subulan, 2016; Limbourg and Jourquin, 2009). In line with the strategic objectives of the European Green Deal and related EU transport strategies, policymakers are increasingly encouraging a modal shift from road freight to rail, inland waterways and short-sea shipping, as this is seen as a key pathway for reducing transport emissions (European Commission, 2019; Perissi et al., 2021). Such modal integration can substantially reduce the environmental footprint of freight transport systems. For instance, rail transport is significantly more energy efficient and generates lower CO_2 emissions per tonne-kilometre than road transport, while maritime transport can provide even greater efficiency for long-distance freight movements (World Bank, 2017).

The increasing globalisation of transport networks has amplified the need for integrated, efficient approaches to transporting goods. This requires the strategic use of multiple transport modes to overcome logistical challenges and optimise cargo flows. According to Baykasoğlu and Subulan (2016), cargo transportation comprises three main stages: pre-transport, long-haul transport and final delivery, each of which is associated with a particular mode of transport. While trucks are commonly used for pre-transport and final delivery, long-haul transport is often carried out by sea, rail or air (SteadieSeifi et al., 2014). The use of various transport modes is driven by multiple reasons, including business considerations, safety, and environmental impact. Shifting from faster, more polluting modes such as trucks to slower, lower-emission alternatives such as rail is increasingly regarded as an environmentally responsible decision (Flodén, 2007). Depending on their combination, transport organisations can leverage the advantages of each modality and follow multimodal, intermodal, co-modal or synchromodal approaches to cargo handling and collaboration (SteadieSeifi et al., 2014). Synchromodality involves the intelligent planning of cargo movements across available modes, aiming to reduce costs and promote sustainability (Delbart et al., 2021; Rentschler et al., 2022; Zhang et al., 2025).

Digital twins (DTs) are virtual representations of physical systems that can function independently. They continuously collect sensor data and exchange information with their physical counterparts throughout the system lifecycle. In logistics and transportation, digital twins play a crucial role in enhancing system visibility and enabling real-time monitoring, simulation and operational optimisation. By bridging the physical and digital domains, DT facilitate the use of real-time traffic information to manage congestion, optimise cargo flows and improve mobility infrastructure through smart sensors (Javaid et al., 2023; Li & Wang, 2025).

The aim of DT is to integrate technologies, processes and human expertise in order to create highly realistic digital systems that support the management of transport networks, improving cost-efficiency, quality, reliability and responsiveness in the process. The concept of DT has recently gained considerable attention, as organisations increasingly recognise its value in supply chain management (Le & Fan, 2024). DT provides deep operational insights, incorporates multiple system dynamics and offers predictive capabilities, including real-time monitoring and prediction, simulation and optimisation, and data integration and management.

Control towers serve as centralised decision hubs, gathering information from multiple sources and modelling states from multiple twins. They provide a consolidated operational overview, enabling interventions to be prioritised based on predictive alerts and early warnings of transport or cargo delays (Lu et al., 2024). By composing a network of control towers, transport managers can gain visibility across the entire transportation network (Busse et al., 2021).

Digital twins enhance the capabilities of control towers by enabling variance-based route optimisation, which prioritises consistency and predictability over speed. Adopting a network perspective enables the dynamic adjustment of routes across different stakeholders, thereby improving resilience in the face of disruptions. Furthermore, integrating predictive insights from planning models, such as demand forecasting, enables the Control Tower network to manage complex transport flows more effectively (Zaidi et al., 2024).

Despite their clear advantages, research into the use of DT in logistics is currently largely limited to proof-of-concept studies (Sakti et al., 2023). This highlights the need for more applied and comprehensive investigations. This study proposes a Digital Twin framework for the practical deployment of transportation systems to demonstrate their potential to improve sustainability, operational efficiency and decision-making in complex transport networks.

2. METHODOLOGY

The primary goal of a transport network is to deliver cargo at the agreed time and location (customer request), while minimising transport costs (service provider request) and providing sustainable transport (societal request). A transport network can be represented as a system of nodes (terminals or warehouses) and links (transport connections). A Control Tower can be assigned to each node to manage operations, particularly the local cargo assignment problem.

2.1 Digital Twin Framework

The overall management challenge in the network is to ensure cooperation among the multiple agents present in the transport network (merchants, forwarders, terminal managers, shippers, infrastructure owners, etc.) towards a more sustainable and reliable transport system, based on known transport demand from a source location to a destination location. In order to create the Digital Twin composed of Control Towers, it is necessary to have information on the following:

Network Configuration: This is the base configuration required to start the Digital Twin. In particular, it specifies the available terminals that can be reached within the system and the time step that is considered suitable for capturing the main dynamics of the network transport.

Network Parametrization: after constructing the transport network using this framework, it is possible to define the following:

i) the transport options available at each location,
ii) the schedules for each connection between two locations,
iii) the transport time for each connection,
iv) the heuristic to allocate cargo,

v) the transport demand.

The proposed Digital Twin framework will provide a real-time, virtual representation of the operations of a transport network spread over a large geographical area. At each time step, the digital twin will perform the following operations:

Acquire Data: Receive updated data from the field. Using this information, we can analyse the difference between the real system and the predicted state of the Digital Twin. This can be used to identify discrepancies and evaluate the risk to the current transport network.

Update Information: The information to be used in the next simulation step will be updated according to the data collected from the real system.

Performance Evaluation: A set of simulations will be run to test different transport organisation strategies, from low to high integration between multimodal control towers, and/or different transport organisation factors such as schedules, transport capacity and frequency.

Export Data: After the simulations, a set of data and key performance indicators will be made available to transport managers to support wise decision-making.

2.2 Digital Twin Components

Transport network players face the challenge of satisfying customer requests while reducing transport costs in order to remain competitive in a competitive sector and be sustainable at the same time. The management challenge is to ensure cooperation among the multiple agents present in the supply chain (merchants, forwarders, terminal managers, shippers, infrastructure owners, etc.) to create a more sustainable and reliable transport system, given known transport demand from a source location to a destination location.

A node model should capture the necessary information to support analysis of the transport network, with the aim of achieving a more sustainable transport system. Reducing transport costs depends on choosing the right route within the network, depending on the context. For example, if there is not much time to deliver, a quick transport mode can be used to ensure timely delivery, whereas if there is enough time, transport management can be planned using multiple transport modalities to promote more sustainable, less polluting transport. To accomplish this, it is important to categorise goods according to their final destination. The destination can be interpreted as a pick-up point without compromising client information, which can be critical in a business context. In this study, the destination of a container is the final terminal it should visit before being transported by truck to the customer. This guarantees the privacy of the client. In this approach, containers are categorised according to:

Loaded cargo: The container may be empty with no destination, or it may be loaded with cargo and have a known destination. This information is relevant when choosing connections, to ensure the container is moved towards its final destination.

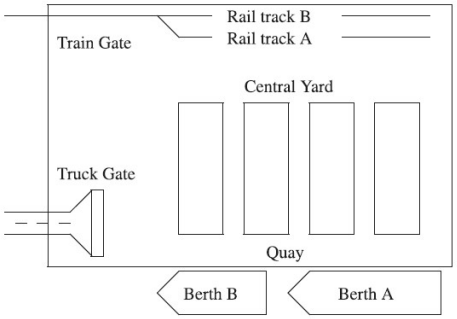
Physical properties: A physical property is a vital characteristic of the container that impacts the transport operation. Examples include weight, size and reefer type.

The dynamics of a node (terminal) are modelled using a discrete state-space approach. The state-space is defined as the number of containers of a given category, and the decisions are defined as the number of containers of a given category to be loaded onto an available connection at the terminal.

Decisions within the transport network relate to loading a specific container onto a transport connection with a known departure time from the terminal. The decision to load a container considers its final destination and physical properties. This decision can be made either locally by the Control Tower using local information, or centrally using information from the entire transport network, thereby fostering cooperation among stakeholders. Terminal operations relate to the movement of cargo, i.e. loading and unloading cargo from and to transport connections, as well as reshuffling cargo within the terminal to prepare for future operations. Graph 1 shows a terminal served by three transport modalities.

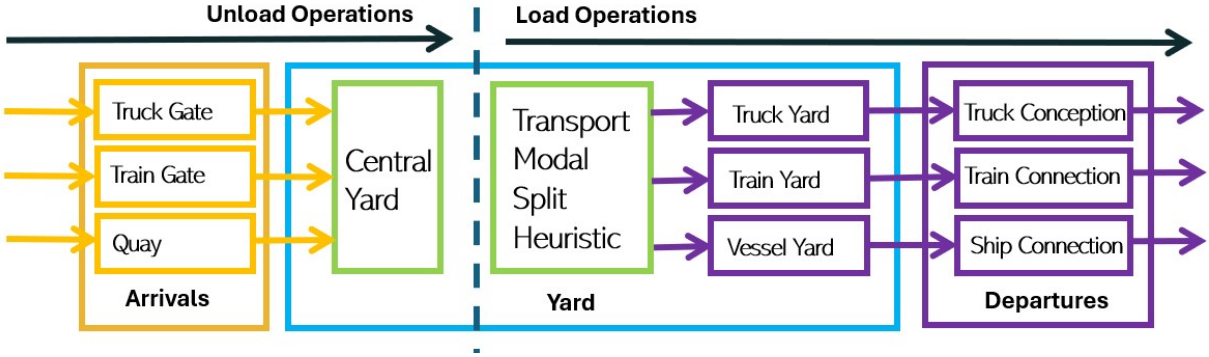
For the operations of the Control Towers in a Digital Twin, a heuristic was developed to address the automatic allocation of cargo for transport connections available at the terminal. This heuristic is applied locally at each control tower, which has access only to the existing cargo at the terminal and the visiting connections (and, respectively, the destinations reachable by each connection). This push-based approach involves loading containers onto connections towards the destination as soon as a connection becomes available, allowing the cargo to approach the destination. A Transport Modal Split guideline is included for each destination at each terminal to promote sustainability awareness. Knowing the destination of a given container at each terminal is critical for the wise allocation of cargo, enabling the container to be moved closer to the desired destination (provided there are no network congestion or bottlenecks at that time). This approach makes it possible to determine whether a transport modality is available or not, and to express a preference for more sustainable transportation using a Transport Modal Split guideline. The use of Sustainable Awareness Cargo Allocation (SACA) in terminal operations, which follows Transport Modal Split Heuristics, is presented in Graph 2 (Nabais et al., 2025).

Graph 1. General overview of a terminal operation areas in a transport network.



Source: Nabais et al. (2015)

Graph 2. General representation of the Transport Modal Split Heuristic at the terminal.



Source: Nabais et al. (2025)

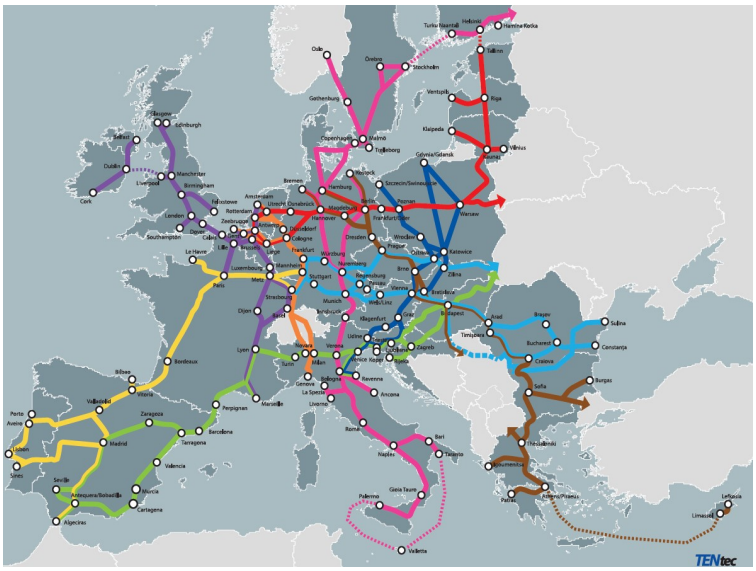
In order to create the Digital Twin, it is necessary to have information on the network configuration, particularly the locations to be visited. Once the transport network has been constructed using this framework, it is possible to define the following: i) the transport

modalities available at each terminal; ii) the schedules for each connection between two terminals; iii) the transport time for each connection; iv) the heuristic for allocating cargo; v) the transport demand. The proposed Digital Twin framework provides a real-time virtual representation of transportation network operations. By integrating operational data, logistical information and environmental parameters, the platform aims to provide valuable insights to optimise operational efficiency and address specific challenges related to intermodal terminal capacity and schedule frequency and capacity.

3. CASE STUDY: THE ATLANTIC CORRIDOR

The Atlantic Corridor is part of the Trans-European Network for Transport (TEN-T) and initially connected Portugal, Spain and France. It was later extended to include Germany (see Graph 3). Important European cities such as Lisbon, Sines, Madrid, Bilbao, Paris, Le Havre, Bordeaux, Strasbourg and Mannheim are part of this corridor, which aims to create a high-capacity railway and road network connecting Portugal, Spain, France and Germany. The Atlantic Corridor aims to overcome technical and operational barriers and promote interoperability among the railway systems of the countries involved. This corridor's strength lies in its strategic location, connecting southern Portugal to northern France and Germany via Spain. The railway connection is complemented by the option of using waterways for such a long route. In summary, the Atlantic Corridor plays a vital role in European goods transportation, promoting collaboration between countries and improving logistical efficiency along the Atlantic coast (Atlantic Corridor 2025).

Graph 3. General representation of the TEN-T and the Atlantic Corridor within it (yellow).



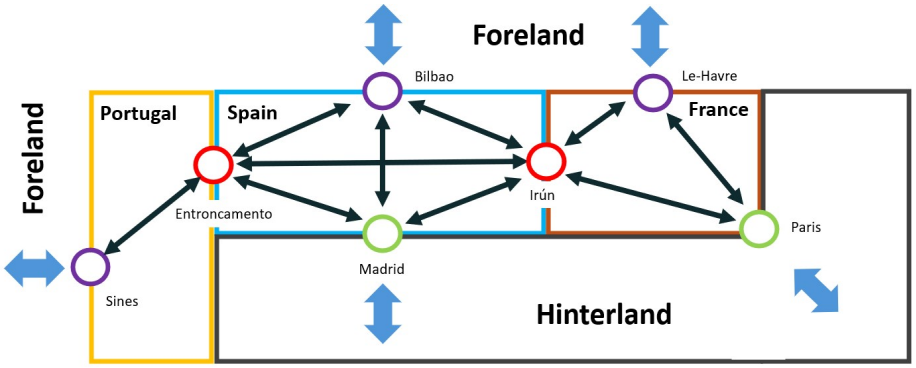
Source: Atlantic Corridor (2025)

3.1 Configuration of the Digital Twin for the Atlantic Corridor

The Atlantic Corridor comprises many facilities and terminals. To illustrate the use of the Digital Twin framework for the Atlantic Corridor, a subset of locations is considered for the sake of simplicity. The simplified Atlantic Corridor addressed in this paper comprises seven locations where logistics operations take place: two in Portugal (Sines and Entroncamento), three in Spain (Madrid, Bilbao and Irún), and two in France (Le Havre and Paris). Therefore, the chosen sample takes into account the corridor's major characteristics: i) it connects southern Portugal to northern France; ii) it is possible to complete this long journey using maritime transport; iii) the rail connection between Spain and France is only available at Irún; iv) connections to other corridors are available at Madrid and Paris (see Graph 4). In this structure, the connection between the endpoints (Sines and Paris) can be made using

different modes: i) road only, ii) train only, or iii) maritime to Le Havre, followed by a final connection using either road or rail. Connections using railways or waterways depend on the available infrastructure and geography.

Graph 4. Simplified scheme of the Atlantic Corridor with foreland and hinterland connections.



Source: author

The estimated transport times were calculated using the available information as a reference. For road connections, the distance between locations was used. For train connections, the available schedules were used as a starting point. For maritime connections, the distances between locations were used to establish regular service lines (see Tables 1 and 2).

Table 1. Road transportation time (in hours).

	Portugal		Spain			France	
	Sines	Entron.	Madrid	Bilbao	Irún	Le-Havre	Paris
Sines	-	3	8	14	17	28	26
Entroncamento	3	-	7	11	12	24	23
Madrid	8	7	-	5	6	18	17
Bilbao	14	11	5	-	2	14	13
Irún	17	12	6	2	-	13	12
Le-Havre	28	24	18	14	13	-	3
Paris	26	23	17	13	12	3	-

Source: author

Table 2. Train and vessel transportation time (in hours), only direct connections measured in hours expressed in the pair (train ; vessel).

	Portugal		Spain			France	
	Sines	Entron.	Madrid	Bilbao	Irún	Le-Havre	Paris
Sines	-	(5 ; ND)		(ND ; 72)		(ND ; 120)	
Entroncamento	(5 ; ND)	-	(6 ; ND)	(15 ; ND)	(19 ; ND)		
Madrid		(6 ; ND)	-	(6 ; ND)	(7 ; ND)		
Bilbao	(ND ; 72)	(15 ; ND)	(6 ; ND)	-	(2 ; ND)	(ND ; 48)	
Irún		(19 ; ND)	(7 ; ND)	(2 ; ND)	-	(19 ; ND)	(17 ; ND)
Le-Havre	(ND ; 120)			(ND ; 48)	(19 ; ND)	-	(4 ; ND)
Paris					(17 ; ND)	(4 ; ND)	-

Source: author

3.2 Illustrative Scenarios

The Digital Twin of a set of Control Towers along the Atlantic Corridor has two sets of parameters that change to emphasise system performance: i) transport demand (Scenarios 1–3); ii) decisions taken at some Control Towers (TMS 1–3). The illustrative scenarios were

constructed to demonstrate how operations within the Digital Twin could be challenged, for example by cargo lows spreading their impact to all locations in the transport network.

Transport demand can be interpreted as a transport request from agents outside the Atlantic Corridor and, for illustrative purposes, is categorised depending on the location of arrival: i) seaports (Sines – PT, Bilbao – ES and Le Havre – FR) and ii) intermodal locations (Madrid and Paris). The Entroncamento and Irún locations are critical for the railway infrastructure, ensuring smooth connectivity between train schedules and facilitating the change from Iberian to European gauge at Irún. Scenarios 2 and 3 are obtained by applying factors of 1.25 and 1.5 to the transport demand arriving at the Sines and Le Havre control towers, respectively (see Table 3). Transport demand arrives at seaports during the first week of the simulation. For the hinterland gateways of Madrid and Paris, the transport demand occurs during the first 30-day period, from Monday to Saturday. After the first 30 days (720 hours), no further transport demand is added to the transport network. Cargo allocations continue to be made using the SACA approach, as previously mentioned, and will stop once all containers have been delivered to their final destination (using road, rail or waterways). The final stage, involving trucks, is then performed to deliver the containers to the final client.

Table 3. Transport demand for Scenario 1 (in TEU).

	Source	Destination							Total
		Portugal		Spain			France		
		Sines	Entron.	Madrid	Bilbao	Irún	Le-Havre	Paris	
Foreland	Sines	80	40	280	260	40	1200	500	2400
Foreland	Bilbao	120	50	400	100	80	200	100	1050
Foreland	Le-Havre	800	0	500	160	0	160	600	2220
Hinterland	Entroncamento	0	0	0	0	0	0	0	0
Hinterland	Madrid	910	0	0	910	0	0	1170	2990
Hinterland	Irún	0	0	0	0	0	0	0	0
Hinterland	Paris	390	0	910	650	0	0	0	1950
	Total	2300	90	2090	2080	120	1560	2370	10610

Source: author

A Control Tower is assigned to each location and is responsible for interactions with transport agents and terminals for both foreland and hinterland transport. Each Control Tower allocates cargo using the SACA approach and the transport modal split (TMS) per destination, as indicated in Table 4.

Table 4. The TMS for all Control Towers to use in a SACA approach.

	Portugal		Spain			France	
	Sines	Entron.	Madrid	Bilbao	Irún	Le-Havre	Paris
Sines	(1.0 ; 0.0 ; 0.0)	(0.0 ; 1.0 ; 0.0)	(0.5 ; 0.5 ; 0.0)	(0.0 ; 0.3 ; 0.7)	(0.0 ; 1.0 ; 0.0)	(0.0 ; 0.0 ; 1.0)	(0.0 ; 0.2 ; 0.8)
Entron.	(0.2 ; 0.8 ; 0.0)	(1.0 ; 0.0 ; 0.0)	(0.2 ; 0.8 ; 0.0)	(0.2 ; 0.8 ; 0.0)	(0.2 ; 0.8 ; 0.0)	(0.0 ; 1.0 ; 0.0)	(0.5; 0.5 ; 0.0)
Madrid	(0.2 ; 0.8 ; 0.0)	(0.1 ; 0.9 ; 0.0)	(1.0 ; 0.0 ; 0.0)	(0.2 ; 0.8 ; 0.0)	(0.2 ; 0.8 ; 0.0)	(0.2 ; 0.8 ; 0.0)	(0.2 ; 0.8 ; 0.0)
Bilbao	(0.2 ; 0.3 ; 0.5)	(0.2 ; 0.8 ; 0.0)	(0.2 ; 0.8 ; 0.0)	(1.0 ; 0.0 ; 0.0)	(0.2 ; 0.8 ; 0.0)	(0.2 ; 0.3 ; 0.5)	(0.2; 0.6 ; 0.2)
Irún	(0.2 ; 0.8 ; 0.0)	(0.2 ; 0.8 ; 0.0)	(0.2 ; 0.8 ; 0.0)	(0.2 ; 0.8 ; 0.0)	(1.0 ; 0.0 ; 0.0)	(0.2 ; 0.8 ; 0.0)	(0.0 ; 1.0; 0.0)
La-Havre	(0.0 ; 0.0 ; 1.0)	(0.3 ; 0.7 ; 0.0)	(0.3 ; 0.7 ; 0.0)	(0.1 ; 0.2 ; 0.7)	(0.2 ; 0.8 ; 0.0)	(1.0 ; 0.0 ; 0.0)	(0.2 ; 0.8 ; 0.0)
Paris	(0.2 ; 0.8 ; 0.0)	(0.2 ; 0.8 ; 0.0)	(0.2 ; 0.8 ; 0.0)	(0.2 ; 0.8 ; 0.0)	(0.2 ; 0.8 ; 0.0)	(0.2 ; 0.8 ; 0.0)	(1.0 ; 0.0 ; 0.0)

Source: author

To illustrate the impact of the control tower on the performance of a transport network, such as the Atlantic Corridor, the control towers of Sines and Le Havre are given the ability to use different transport modal splits. Using the TMS shown in Table 4 as a reference, the Sines and Le Havre Control Towers apply different transport modal splits for certain destinations (Madrid, Bilbao and Paris), creating new sets named TMS 2 and TMS 3 (see Table 5). The evolution from TMS 1 to TMS 3 at the Sines and Le Havre control towers ensures that the most sustainable transport modalities are favoured. For TMS 3, cargo destined for Madrid or Bilbao can depart from either Sines or Le Havre using only one transport modality. For TMS

3 at Sines, all cargo destined for Paris is loaded onto a vessel that will either go to Bilbao or Le Havre, and from there the final destination will be reached.

Table 5. Variable Transport Modal Splits at the Control Towers of Sines and Le-Havre.

	Sines			Le-Havre		
	Madrid	Bilbao	Paris	Madrid	Bilbao	Paris
TMS 1	(0.5 ; 0.5 ; 0.0)	(0.0 ; 0.3 ; 0.7)	(0.0 ; 0.2 ; 0.8)	(0.3 ; 0.7 ; 0.0)	(0.1 ; 0.2 ; 0.7)	(0.2 ; 0.8 ; 0.0)
TMS 2	(0.2 ; 0.8 ; 0.0)	(0.0 ; 0.2 ; 0.8)	(0.0 ; 0.1 ; 0.9)	(0.1 ; 0.9 ; 0.0)	(0.0 ; 0.1 ; 0.9)	(0.1 ; 0.9 ; 0.0)
TMS 3	(0.0 ; 1.0 ; 0.0)	(0.0 ; 0.0 ; 1.0)	(0.0 ; 0.0 ; 1.0)	(0.0 ; 1.0 ; 0.0)	(0.0 ; 0.0 ; 1.0)	(0.0 ; 1.0 ; 0.0)

Source: author

4. RESULTS AND DISCUSSIONS

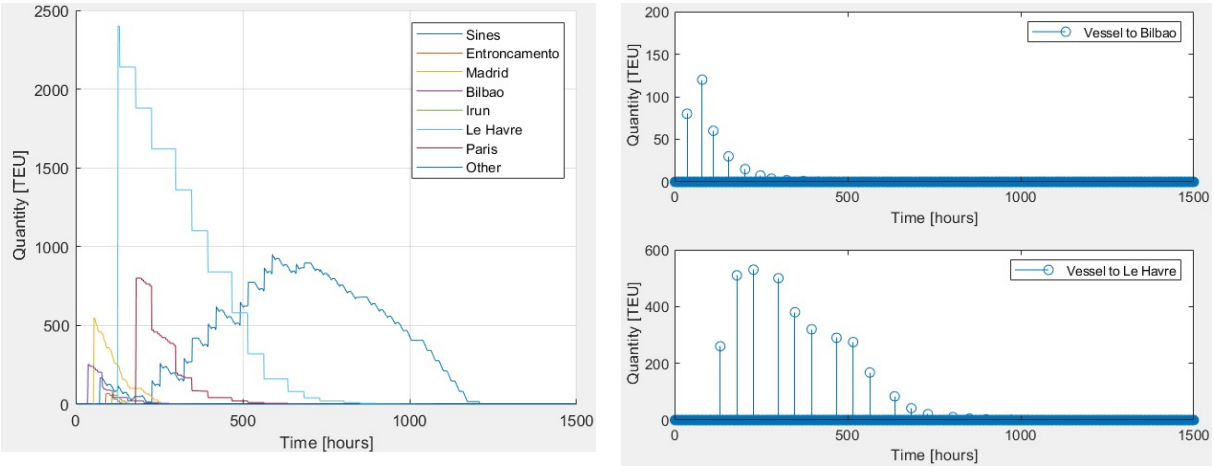
The experiments were conducted using ©Matlab 2021a and Simulink on an 11th Gen Intel® Core™ i7-1165G7 @ 2.80 GHz laptop with 16 GB of installed RAM. The sample time for the experiments was set to 1 hour, with each experiment considering 3,000 hours, which corresponds to 125 days. Table 6 shows the overall impact on inventory across the Atlantic Corridor and the sum of daily inventory levels at each location throughout the simulation. This indicator provides an overview of the operational intensity at the node and the time taken to complete the process. The biggest impact is on Le Havre and Sines, the seaports with the highest container throughput. An increase in inventory is expected from Scenario 1 to Scenario 3 due to an increase in transport demand. A significant increase also occurs when comparing TMS 3 to TMS 1 for the same scenario, particularly at Le Havre, as Sines is loading all cargo destined for Paris via Le Havre and Bilbao (see Graph 5).

Table 6. Sum of daily inventory levels at the Atlantic Corridor locations.

		Portugal		Spain			France	
		Sines	Entron.	Madrid	Bilbao	Irún	Le-Havre	Paris
TMS 1	Scenario 1	395.393	115.606	152.361	102.076	263.516	496.212	51.263
	Scenario 2	789.092	120.739	156.346	154.711	377.418	1.038.298	55.476
	Scenario 3	1.234.722	128.035	160.357	223.425	486.780	1.834.110	58.432
TMS 2	Scenario 1	404.212	116.428	158.390	112.091	246.090	688.280	52.048
	Scenario 2	811.994	122.129	161.704	180.062	352.810	1.382.060	56.432
	Scenario 3	1.270.101	129.761	163.169	264.567	458.436	2.407.156	59.260
TMS 3	Scenario 1	418.129	117.170	161.563	118.203	250.199	625.365	52.903
	Scenario 2	843.867	125.060	162.673	195.992	361.709	1.388.740	56.356
	Scenario 3	1.321.321	135.030	164.697	288.346	473.960	2.560.399	59.295

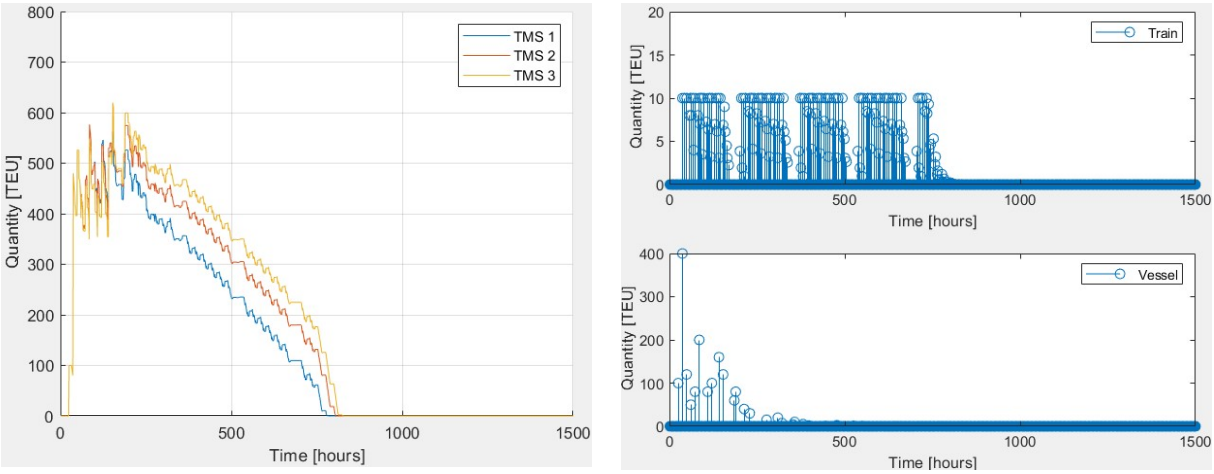
Source: author

Graph 5. Inventory (left) and vessel deparutres (right) for Scenario 3 and TMS 3 at Sines.



Source: authors

Graph 6. Inventory for Scenario 3 (left) and arrivals for TMS 3 with Scenario 3 at Bilbao.



Source: authors

At Sines, the completion time for the operation increases from TMS 1 to TMS 3, as there is naturally more cargo to allocate, but the options for allocating cargo are also more restrictive. Remember that, with TMS 3 at the Sines Control Tower, destinations such as Madrid, Bilbao and Paris can only depart the seaport using one transport modality (see Graph 6). At Bilbao, a seaport, the impact of the Control Tower's allocation decisions on Scenario 3 is a slight increase in inventory, as Bilbao is an option for cargo routes (see Graph 6).

Irún is a unique location in the Atlantic Corridor, as it is the only place where the Spanish and French railways connect. Decisions made by the control towers in Sines and Le Havre to promote the use of railways affect operations at Irún for destinations requiring crossing the Pyrenees. All cargo arrives at Irún by train, and most departures are also by train (see Table 7).

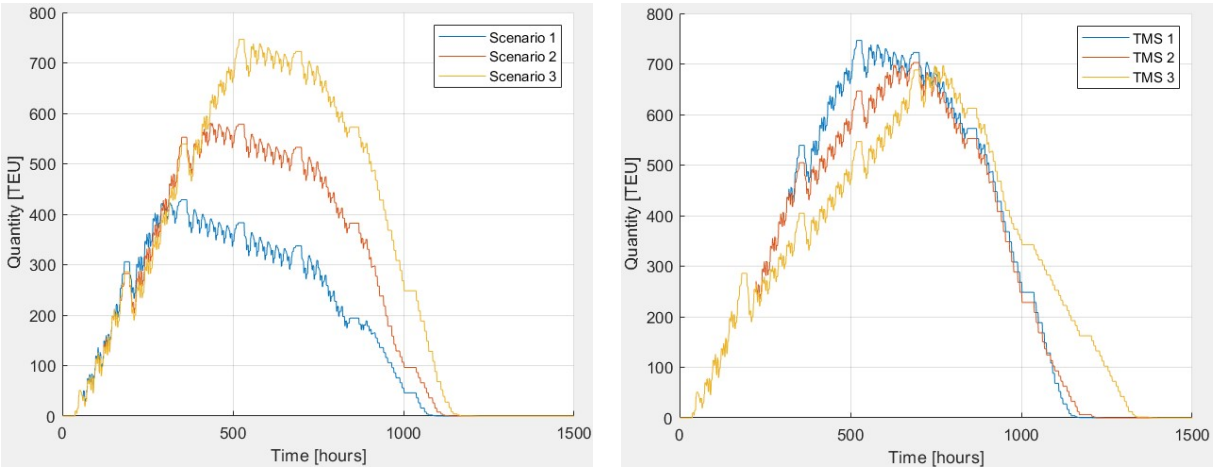
Table 7. Flows and inventory details at Irún.

		Arrivals [TEU]			Máximum Inventory [TEU]							Departures [TEU]		
		Road	Railway	Water.	Sines	Entron.	Madrid	Bilbao	Irún	Le-Havre	Paris	Road	Railway	Water.
TMS 1	Scenario 1	0,00	3162,00	0,00	10,00	0,00	229,00	13,00	19,00	22,00	190,00	490,00	2672,00	0,00
	Scenario 2	0,00	3403,00	0,00	10,00	0,00	334,00	13,00	17,00	22,00	240,00	541,00	2862,00	0,00
	Scenario 3	0,00	3644,00	0,00	10,00	0,00	443,00	13,00	25,00	22,00	290,00	592,00	3052,00	0,00
TMS 2	Scenario 1	0,00	3162,00	0,00	10,00	0,00	266,00	23,00	19,00	22,00	140,00	500,00	2662,00	0,00
	Scenario 2	0,00	3403,00	0,00	10,00	0,00	384,00	13,00	17,00	22,00	165,00	556,00	2847,00	0,00
	Scenario 3	0,00	3644,00	0,00	10,00	0,00	503,00	13,00	25,00	22,00	190,00	612,00	3032,00	0,00
TMS 3	Scenario 1	0,00	3212,00	0,00	10,00	0,00	315,00	13,00	19,00	22,00	90,00	520,00	2692,00	0,00
	Scenario 2	0,00	3478,00	0,00	10,00	0,00	469,00	13,00	17,00	22,00	90,00	586,00	2892,00	0,00
	Scenario 3	0,00	3744,00	0,00	10,00	0,00	604,00	13,00	25,00	22,00	90,00	652,00	3092,00	0,00

Source: author

It is interesting to note that the increase in transport demand (set at other locations) leads to a peak in inventory at Irún, but the time taken to complete operations remains similar (see Graph 7). Taking Scenario 3 as a reference, the impact of the Sines and Le Havre Control Towers, which favour more sustainable modes, leads to a delay in inventory with a slightly lower peak and an increase in completion time for TMS 3 (see Graph 7).

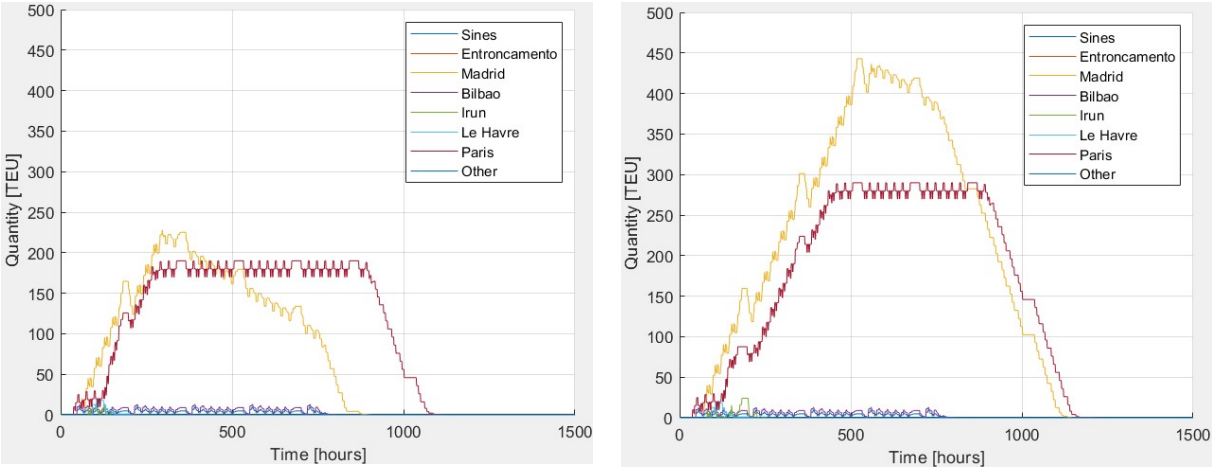
Graph 7. Inventory levels for TMS 3 (left) and Scenario 3 (right) at Irún.



Source: authors

Examining the inventory at Irún in more detail reveals that its evolution is due to cargo flows destined for Paris from Sines, Madrid and Bilbao, and destined for Madrid from Le Havre and Paris (see Graph 8). The numerical experiments conducted using the Digital Twin for the Atlantic Corridor demonstrate that decisions made locally by the Control Towers take time to take effect and can either increase or alleviate pressure on logistics operations. It is preferable to keep inventory levels low at locations in order to foster operational efficiency and reduce the need for additional handling. In order to maintain smooth cargo flows, coordination among the main players influencing the Atlantic Corridor performance (terminal managers, transport managers and regulators) is recommended. This coordination can be achieved in two ways: i) in terms of network design, impacting the routes and schedules; and ii) in terms of coordinating cargo allocation decisions to prevent operational congestion and achieve multimodal transportation.

Graph 8. Inventory levels at Irún for Scenario 3, TMS 1 (left) and TMS 3 (right).



Source: authors

5. CONCLUSIONS

In this paper, the authors propose a digital twin framework for building a container transport network twin composed of control towers. To illustrate this, the Atlantic Corridor is used as a practical example to demonstrate the typical dynamics of these systems and the types of decisions that the Control Towers must address. The constructed Digital Twin was able to track operations at seven locations and manage decisions for all Control Towers responsible for cargo allocation using the SACA approach. The digital twin allows the decision-making

process at the control towers to be easily parametrised by adjusting the transport modal splits used in the SACA approach. Modifying the decision-making process clearly impacts the transport performance of the network. As the transport network is highly interconnected, different decisions at a control tower spread throughout the system, impacting all locations. Cargo flows can be directed towards more sustainable transport modalities, such as railways and waterways, which require additional handling points. It is vital that, whenever decisions are taken, some degree of coordination is assured to avoid congestion and maintain smooth cargo flows. Future work will consider risk analysis in order to track operations, anticipate congestion and other situations, and develop cooperation strategies among the control towers towards multimodal transport.

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Prethodno priopćenje

OKVIR DIGITALNOG BLIZANCA ZA KONTEJNERSKI PRIJEVOZ KROZ MREŽU KONTROLNIH TORNJEVA: STUDIJA SLUČAJA ATLANTSKOG KORIDORA

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SAŽETAK

*Globalizacija je intenzivirala tokove kontejneriziranog tereta kroz globalne opskrbne lance, zbog čega su mreže kontejnerskog prijevoza postale složenije u operativnom i koordinacijskom smislu. Luke i kontejnerski terminali djeluju kao ključna logistička čvorišta unutar tih mreža te oblikuju ukupnu uspješnost opskrbnog lanca. Kao mjesta susreta više prometnih pravaca, luke okupljaju širok raspon dionika, pri čemu neki od njih mogu imati usklađene, a drugi međusobno suprotstavljene ciljeve. To izravno utječe na učinkovitost i pouzdanost tokova kontejnera. Sve veća složenost interakcija na lučkoj razini pokazuje da lokalno optimizirano i fragmentirano donošenje odluka postaje sve manje dostatno. Kako bi se osigurali kontinuitet i učinkovitost duž cijelog opskrbnog lanca, potreban je integriraniji pristup upravljanju. U logistici i upravljanju opskrbnim lancem ta se uloga često naziva kontrolni toranj (*Control Tower*), a omogućuje cjelovitu vidljivost procesa, koordinirano donošenje odluka i usklađivanje među dionicima u stvarnom vremenu. Kada se primjenjuje na lučkoj razini, kontrolni toranj podupire orkestraciju lokalnih kontejnerskih operacija, uz istodobno zadržavanje uvida u učinke odluka donesenih u drugim međusobno povezanim lukama. Kada je više lučkih kontrolnih tornjeva međusobno povezano, oni čine prilagodljiv i složen logistički sustav u kojem se lokalne odluke prenose kroz širu mrežu kontejnerskog prijevoza. Razumijevanje učinaka takvih prijenosa ključno je za predviđanje poremećaja, upravljanje premještanjem praznih kontejnera i unapređenje ukupne učinkovitosti mreže. Tehnologija digitalnog blizanca (*Digital Twin – *DT) prikladan je okvir za prikaz takvih sustava jer omogućuje dinamičko modeliranje fizičke imovine, informacijskih tokova i pravila odlučivanja unutar opskrbnih lanaca. U ovom radu predlaže se okvir digitalnog blizanca osmišljen za obuhvaćanje procesa donošenja odluka u kontrolnim tornjevima i procjenu njihova utjecaja na učinkovitost kontejnerskog prijevoza na razini mreže. Okvir je primijenjen na Atlantski koridor Transeuropske prometne mreže (TEN-T), uzimajući u obzir raznolikost tokova tereta kroz terminale, uključujući kontejnere s unaprijed definiranim odredištima i prazne kontejnere. Time se pokazuje njegov potencijal za potporu sinkromodalnom prijevozu i upravljanju opskrbnim lancem.*

Ključne riječi: *digitalni blizanac, kontrolni toranj, sinkromodalni prijevoz, Atlantski koridor, TEN-T.*

II. DIGITALIZATION, CIRCULAR ECONOMY AND SUPPLY CHAIN RESILIENCE
II. DIGITALIZACIJA, KRUŽNO GOSPODARSTVO I OTPORNOST OPSKRBNOG LANCA

Original scientific paper

SELECTION OF DIGITAL TECHNOLOGIES FOR DATA MANAGEMENT IN SUPPLY CHAINS BASED ON MCDM APPROACH

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ABSTRACT

Modern supply chains (SC) are undergoing significant structural changes driven by global disruptions, geopolitical risks, and increasing demands for resilience and flexibility, which have led many companies to adopt strategies focused on the regionalization of SCs. The purpose of this research is to examine data-related challenges in regional SCs and to assess the role of contemporary digital technologies in improving data exchange, processing efficiency, and overall SC resilience. The analysis addresses the complexity of cross-border flows of goods, information, and capital, as well as the interaction of heterogeneous information systems, which represent systemic challenges rather than isolated operational issues. Based on the identified challenges, the study considers three digital solutions: an artificial intelligence (AI) agent, blockchain technology, and the supply chain control tower concept. The methodology is based on a multi-criteria decision-making approach that integrates the Best–Worst Method for criteria weighting and the Fuzzy Technique for Order Preference by Similarity to the Ideal Solution for evaluating and ranking the alternatives. The solutions are assessed using nine criteria covering technical, organizational, and operational dimensions. The findings indicate notable differences in the performance of the analyzed technologies, with solutions based on AI demonstrating particularly strong potential for enhancing data management and operational responsiveness in regional SCs. The contribution of the research lies in the systematic consideration and comparative evaluation of contemporary digital technologies within the context of regional SCs, providing decision-makers with structured insights for selecting aproprirate data management solutions

Key words: *Supply chain; Resilience; Multi-criteria decision-making; Artificial intelligence agent; Blockchain technology*

1. INTRODUCTION

Supply chains (SC) are undergoing significant structural changes due to global disruptions, geopolitical risks, regulatory constraints, and increasing requirements for resilience and flexibility (Ageron et al., 2020). In response to these challenges, a growing number of companies are reassessing their global strategies and shifting toward the regionalization of SC. The objective is to reduce dependence on distant markets, increase operational control, and enhance system resilience (Božić & Poledica, 2024). Regional SC can contribute to greater stability and shorter logistics routes. However, they also introduce specific challenges, particularly in the area of data exchange and data management. The regional context implies the involvement of multiple countries, diverse regulatory regimes, heterogeneous information systems, and organizations with uneven levels of digital maturity (Cao et al., 2022). In such an environment, information flows tend to become fragmented,

misaligned, and prone to delays, which directly affects planning accuracy, delivery reliability, and the ability to respond to disruptions on time (Hannibal et al., 2022).

In this context, increasing attention is being paid to the application of advanced digital technologies as potential solutions for improving data exchange, interoperability, and transparency in SC (Haddud et al., 2017). Technologies such as artificial intelligence (AI), blockchain, and other digital data processing technologies offer different approaches to managing heterogeneous data sources, enhancing visibility, and supporting real-time decision-making (Ivanov et al., 2021). Nevertheless, selecting an appropriate digital solution for a regional SC represents a complex challenge, as it requires the simultaneous consideration of technical, organizational, and operational criteria (Govindan et al., 2021).

The aim of this paper is to identify and systematize the key challenges related to data exchange and data management in regional SC, as well as to assess the potential of advanced digital technologies in addressing these challenges. Based on the identified challenges, the study examines three alternative solutions: an AI agent, blockchain technology, and the Supply Chain Control Tower concept (SC Tower). These alternatives are then evaluated using a multi-criteria decision-making approach based on a combination of the Best–Worst Method (BWM) and the Fuzzy Technique for Order Preference by Similarity to Ideal Solution (FTOPSIS). This approach enables a structured and transparent evaluation of the alternatives, taking into account multiple aspects of the implementation and application of digital solutions in regional SC. The contribution of this paper lies in linking theoretical insights on data exchange challenges in SC with a practical evaluation of advanced digital technologies. The study provides a structured analytical framework for comparing different technological solutions, thereby supporting decision-makers in selecting appropriate digital tools to improve SC performance and resilience.

The paper is structured as follows. After the introduction, the second section presents a review of the relevant literature, focusing on challenges related to data exchange and data management in SC. The third section identifies and analyzes key challenges associated with data exchange in regional SC, which serve as the basis for defining the evaluation criteria. The fourth section proposes alternative solutions to the identified problem. Within this section, the evaluation criteria and the ranking of alternatives are defined. Finally, the conclusion discusses the results, provides overall conclusions of the study, and outlines directions for future research.

2. LITERATURE REVIEW

Data exchange and information integration are recognized as key elements for the effective functioning of SC. Existing research indicates that timely, accurate, and complete information sharing among SC participants enables better coordination, reduces uncertainty, and improves overall SC performance.

Chang et al. (2019) emphasize that regional SC face specific challenges related to transparency, traceability, and trust within logistics flows. The authors identify the lack of real-time data exchange and the fragmentation of information systems as major barriers to effective coordination, while considering blockchain technology as a potential, yet insufficient, solution if applied in isolation. Ageron et al. (2020) provide a broader overview of digital SC and systematize challenges across three dimensions: technological, organizational, and human. The authors stress that digitalization without prior process rationalization and standardization leads to increased complexity rather than performance improvement. Organizational and cultural barriers to data exchange are examined in detail in an empirical study by Hannibal et al. (2022). Based on interviews with industry professionals, the authors demonstrate that poor data quality and deeply embedded normative practices significantly constrain information sharing and increase risk in multi-tier and regional SC.

The regulatory dimension of data exchange in global SC is addressed by Cao et al. (2022), who point out that growing regulatory and customs barriers further complicate cross-border data flows. Their analysis shows that digital solutions can mitigate certain issues, but without institutional harmonization and shared standards, their effectiveness remains limited. Using a sector-specific example, Baldin et al. (2025) analyze the standardization of data collection and processing in the dairy industry and demonstrate that the absence of common procedures, heterogeneous data formats, and manual data entry leads to data fragmentation and interoperability problems. Although the study is sector-specific, the identified challenges have broader applicability to regional SC across different industries.

This brief review of the literature indicates that data exchange challenges in SC, particularly in regional contexts, are complex and multidimensional. They arise from a combination of misaligned procedures, fragmented IT systems, regulatory barriers, and organizational practices. Conference-based empirical studies further support the notion that regional supply chains represent a multifaceted domain of resilience and sustainability, especially in cross-border contexts (Božić & Poledica, 2024).

3. KEY CHALLENGES IN REGIONAL SUPPLY CHAINS

Regional SC often involves multiple countries, diverse types of companies, and heterogeneous information systems. Such an environment significantly complicates data exchange and data management. Information flows are frequently slow, misaligned, and associated with increased operational risk. Existing studies confirm that a lack of standardization and limited digital connectivity directly affect planning accuracy, delivery reliability, and the overall resilience of SC (Ageron et al., 2020). A review of the literature indicates that a wide range of challenges hinder effective data exchange in regional SC; however, this study focuses on a limited set of key challenges, which are described below.

The first challenge relates to misaligned procedures and the lack of standardization. In practice, there are no unified rules for data collection, processing, and exchange, which leads to different interpretations of the same information and frequent errors in planning and operational decision-making (Lotfi et al., 2013; Haddud et al., 2017; Baldin et al., 2025). The second challenge concerns the fragmentation of information systems and their limited compatibility. Legacy Enterprise Resource Planning (ERP), Warehouse Management System (WMS), and Transportation Management System (TMS) systems are often not designed for external data exchange, resulting in manual data entry, delays, and reduced visibility across the SC (Ageron et al., 2020; Haddud et al., 2017). The third challenge relates to the lack of real-time visibility. Due to longer transportation routes, cross-border movements, and a higher number of intermediaries, companies often lack timely insights into shipment status, which limits their ability to respond proactively and adjust plans accordingly (Chang et al., 2019; Ageron et al., 2020). The fourth challenge concerns limited access to reliable inventory data. Outdated and inaccurate information leads to excess inventory in certain parts of the region and simultaneous shortages in others, increasing uncertainty and risk in procurement and distribution planning (Lotfi et al., 2013; Hannibal et al., 2022).

The fifth challenge relates to regulatory and customs barriers. Misaligned regulations, differing documentation formats, and weak integration of digital systems cause delays, increase administrative costs, and reduce the efficiency of cross-border data exchange (Cao et al., 2022). The sixth challenge concerns the insufficient adoption of international data standards. The absence of standards such as the GS1 system, EDI messages, and API integrations hinders automated data exchange, the establishment of unique identifiers, and the rapid integration of new partners into the SC (Haddud et al., 2017; Ageron et al., 2020). The seventh challenge relates to low levels of trust among regional partners. Limited sharing of information on inventories, sales, and demand plans leads to closed information flows, less reliable forecasts, and inefficient planning processes (Hannibal et al., 2022). The eighth challenge concerns limited cybersecurity capabilities. Insufficient protection of information systems increases the risk of security incidents and reduces companies' willingness to share

data in real time, further undermining trust and transparency in regional SC (Ageron et al., 2020; Chang et al., 2019).

4. CASE STUDY

Regional SC encompasses multiple countries, diverse types of companies, and heterogeneous information systems. This complexity leads to data fragmentation, delays in information exchange, and an increased risk of disruptions in flows of goods and capital. A lack of standardization, limited digital connectivity, and regulatory barriers further hinder coordination and timely decision-making. These challenges reduce the agility, resilience, and reliability of SC, thereby creating a clear need for digital solutions. Such solutions can enhance data visibility, interoperability, and transparency. This study does not focus on a single empirical company case. Instead, the case study represents a conceptual decision-making scenario that reflects typical data management challenges observed in regional supply chains.

4.1 Alternative Solutions

One potential approach to addressing the identified challenges is the implementation of advanced digital technologies. Solutions based on artificial intelligence, digital data platforms, and modular architectures can significantly contribute to overcoming data-related limitations in regional SC. Accordingly, this study proposes three alternative solutions for improving data exchange and data processing in regional SC: an AI Agent, Blockchain Technology, and the SC Tower. From an economic perspective, the implementation of digital technologies in supply chains requires significant investments in infrastructure, integration, and organizational capabilities. AI-based systems often require high initial investments in data preparation, algorithm development, and system integration. SC Tower solutions involve substantial costs related to software platforms and integration with existing enterprise systems. Blockchain solutions may require additional investments in infrastructure, regulatory alignment, and partner adoption across the supply chain. Therefore, economic feasibility remains one of the key considerations when selecting an appropriate digital technology.

4.1.1 AI Agent

AI agents represent an advanced digital solution for addressing data management challenges in regional SC, as they enable intelligent processing, interpretation, and coordination of heterogeneous data sources. Unlike traditional rule-based systems, AI agents are capable of handling uncertainty, inconsistencies, and delays in data. Such delays typically arise from fragmented IT systems, misaligned procedures, and limited real-time visibility. By leveraging machine learning (ML) methods and large language models (LLMs), AI agents can analyze large volumes of operational and transactional data, identify patterns, predict disruptions, and support proactive decision-making. These capabilities are particularly valuable in regional SC, where cross-border operations, regulatory complexity, and low levels of transparency further complicate coordination. In this way, AI agents contribute to increased resilience, agility, and a higher level of data integration among SC partners (Abaku et al., 2024; Gaddala, 2023).

The advantages of AI agents include reduced decision-making time, improved interoperability through standardized integrations, and high scalability in processing large volumes of data. However, certain limitations must also be considered, including dependence on the quality of input data, cybersecurity requirements, and governance and transparency issues related to autonomous decision-making, which require careful organizational and regulatory alignment (Abaku et al., 2024; Gaddala, 2023).

4.1.2 SC Tower

SC Tower represents a centralized digital solution for the real-time collection, integration, and visualization of data from different segments of the SC. Its primary role is to provide end-to-end visibility of flows of goods, information, and finances. In doing so, it directly addresses

challenges related to fragmented IT systems, limited transparency, and insufficient coordination in regional SC. Control Tower platforms integrate data from ERP, WMS, TMS, and other operational systems into a unified information layer, enabling decision-makers to obtain a holistic view of SC performance. This approach supports the timely identification of deviations, delays, and disruptions, as well as faster responses to unforeseen events. In regional SC, where cross-border operations are particularly complex, Control Towers contribute to enhanced operational stability and resilience (Xu et al., 2024; Vlachos, 2023).

The key advantages of this solution include a relatively high level of technological maturity, easier integration with existing information systems, and clear organizational control over data. However, limitations include high implementation costs, dependence on the quality and availability of input data, and lower flexibility compared to autonomous AI agents (Xu et al., 2024; Vlachos, 2023).

4.1.3 Blockchain Technology

Blockchain technology represents a digital solution that can enhance data exchange, transparency, and trust in regional SC. As a decentralized database, blockchain enables permanent and immutable recording and sharing of data related to transactions, product movements, and accompanying documentation among multiple participants, without the need for a central authority. This feature is particularly relevant in environments characterized by low trust and misaligned procedures. In regional SC, different actors often rely on heterogeneous information systems and standards. By using a shared data ledger, blockchain can reduce the risk of data manipulation, duplication of information, and loss of documentation in cross-border flows. Consequently, the technology enhances traceability, transparency, and data reliability across regional SC (Vazquez et al., 2024; Tripathi et al., 2023).

Within the regional SC context, blockchain can support customs procedures, delivery confirmations, certificate exchanges, and payment settlements, thereby reducing administrative costs and border-related delays. The main advantages of blockchain solutions include improved data integrity, enhanced cybersecurity, and strengthened trust among partners. However, limitations include high implementation costs, limited scalability, energy consumption requirements, and dependence on regulatory harmonization across countries (Vazquez et al., 2024; Tripathi et al., 2023).

4.2 Criteria Evaluation

The criteria represent the key elements used for comparing and ranking the alternative solutions. In this study, nine criteria were applied to comprehensively assess the implementation and application of the proposed technologies across multiple dimensions (Abaku et al., 2024; Xu et al., 2024; Vazquez et al., 2024):

1. Interoperability with existing IT systems – The extent to which a solution can be easily integrated with existing ERP, WMS, TMS, and other information systems.
2. System scalability – The ability of the system to process large volumes of data and to scale in line with the evolving needs of the SC.
3. Cybersecurity and data protection – The level of protection against cyberattacks, data breaches, and unauthorized access.
4. Dependence on input data quality – The degree to which the effectiveness of the solution depends on the accuracy and timeliness of input data.
5. Ease of implementation and maintenance – The extent to which the solution can be implemented, employee training conducted, and ongoing system maintenance performed with relative simplicity.
6. Support for regulatory compliance – The extent to which the solution facilitates compliance with local and international regulations and standards.

7. Real-time visibility and tracking – The ability to monitor the status of shipments, inventories, and processes in real time.
8. Enhancement of SC agility and resilience – The contribution of the solution to the SC's ability to rapidly adapt to changes and disruptions.
9. Trust and transparency among partners – The extent to which the solution supports transparent data sharing and fosters trust among SC participants.

4.3 MCDM Model

In order to select the most appropriate alternative solution for data processing in regional SC, this study proposes a multi-criteria decision-making (MCDM) model that integrates the BWM and the FTOPSIS. The BWM is applied to determine the weights of the evaluation criteria, while FTOPSIS is used to rank the alternative solutions.

The BWM is employed for criteria weighting because it requires a relatively small number of pairwise comparisons compared to methods such as the Analytic Hierarchy Process (AHP), thereby reducing inconsistency in expert judgments and enabling more stable and reliable weighting results. The FTOPSIS method is applied because it allows for the modeling of uncertainty and linguistically expressed evaluations, ensuring a more robust ranking of alternatives based on their distances from the ideal and anti-ideal solutions.

The first step of the proposed model involves determining the weights of the criteria using the BWM. Initially, the most important criterion is identified, after which the remaining criteria are compared relative to this reference criterion. The application of the BWM results in the calculation of the criteria weights, which are presented in Table 1.

Table 2 Weights of the Criteria

Ci	*C1*	*C2*	*C3*	*C4*	*C5*	*C6*	*C7*	*C8*	*C9*
Wi	0.058	0.068	0.051	0.081	0.031	0.068	0.300	0.136	0.204

After calculating the criteria weights, an expert evaluation of the alternatives with respect to each criterion was conducted. The sample consisted of experts in logistics and supply chain management with at least five years of professional experience. The expert panel consisted of 15 professionals from the fields of logistics, supply chain management, and digital transformation. The experts were selected based on the following criteria: (1) a minimum of five years of professional experience in supply chain management, (2) experience with digital technologies or information systems in logistics operations, and (3) involvement in cross-organizational or regional supply chain coordination.

The experts represent professionals working in logistics companies, manufacturing firms, and consulting organizations dealing with supply chain digitalization. Each expert independently evaluated the alternatives using a standardized scale from 1 to 9. The resulting fuzzy assessments were then aggregated to obtain a composite score for each alternative under each criterion. The aggregated evaluation scores of the alternatives are presented in Table 2.

Table 2. Evaluation Scores of Alternatives by Criteria

Alternative	**AI Agent**	**SC Tower**	***Blockchain Technology***
C1	8	6	7
C2	9	5	7
C3	7	9	6
C4	7	6	5
C5	6	4	7
C6	6	7	5
C7	9	6	8
C8	9	5	7
C9	7	9	6

After applying the FTOPSIS method, the following ranking of the alternatives was obtained (Table 3). The AI Agent ranked first, achieving the highest overall closeness to the ideal solution across most criteria, particularly in intelligent processing of heterogeneous data, predictive analytics, and support for proactive decision-making under conditions of uncertainty. The SC Tower ranked second due to its high level of technological maturity and its ability to provide end-to-end visibility through the integration of existing systems (ERP/WMS/TMS). However, it received a lower ranking due to its greater reliance on input data quality, lower flexibility compared to autonomous AI agents, and potentially higher implementation costs. Blockchain Technology ranked third; although it significantly enhances data integrity, traceability, and trust through immutable records, it demonstrates a weaker contribution to operational agility and real-time decision-making, along with additional limitations related to cost, scalability, and the need for regulatory harmonization in a regional context.

Table 3. Ranking of Alternatives

	Ci	**Rang**
AI Agent	0.722	1
SC Tower	0.453	2
Blockchain Technology	0.378	3

5. CONCLUSION

Market dynamism, frequent disruptions in global flows, and growing demands for stability, sustainability, and predictability have led to the strengthening of regional SCs. This development represents part of a strategic response to the limitations of globally dispersed networks. Regional SC models enable shorter delivery times, improved inventory control, and reduced exposure to geopolitical and logistical risks. As a result, they are increasingly recognized as a sustainable compromise between efficiency and supply security (Božić & Poledica, 2024).

However, the functioning of regional SCs is accompanied by a number of challenges, particularly in the area of data exchange and data management. Cross-border flows of goods, information, and capital take place under conditions of misaligned procedures, diverse regulatory regimes, and fragmented information systems. Additional obstacles include limited IT system interoperability, a lack of standardization, weak real-time visibility of

flows, unreliable inventory data, and low levels of trust among partners. These challenges slow down planning processes and hinder timely decision-making. All of these factors directly affect the agility and resilience of regional supply chains, clearly indicating the need for the adoption of advanced digital solutions.

Based on the identified challenges in regional SCs, this study conducted an evaluation of alternative digital solutions using a multi-criteria decision-making framework that integrates the BWM and FTOPSIS methods. The analysis enabled a structured comparison of solutions from technical, organizational, and operational perspectives. Three alternative solutions were considered: an AI Agent, blockchain technology, and the SC Tower concept. The results of the model indicate that the AI agent–based solution represents the most favorable alternative for data management in regional SCs. The AI agent achieved the highest closeness to the ideal solution due to its ability to intelligently process heterogeneous data sources. A particular advantage lies in the use of predictive analytics and support for proactive decision-making under conditions of uncertainty. These capabilities enable faster responses to disruptions and contribute to improved overall supply chain agility and resilience.

The obtained results confirm that contemporary AI-based solutions have significant potential to enhance interoperability, visibility, and coordination in regional supply chains. At the same time, the findings highlight the need for careful management of input data quality, cybersecurity, and organizational aspects related to the implementation of AI systems.

From a managerial perspective, the results of this study provide practical guidance for supply chain managers and decision-makers involved in digital transformation initiatives. The proposed evaluation framework enables organizations to systematically compare different technological solutions and to select those that best align with their operational needs and strategic priorities. Managers should consider not only technological capabilities but also organizational readiness, implementation costs, and the maturity of existing information systems when selecting digital solutions for data management.

This study has several limitations. One limitation relates to the number and types of criteria considered in the selection of the most appropriate alternative solution. Different results might be obtained if the set of evaluation criteria were modified, for example, through the inclusion of additional criteria or changes in their relative importance. Another limitation concerns the geographical scope of the expert panel, which consisted of professionals from a single country. Although the experts possess relevant experience in international supply chain operations, the results may partially reflect regional perspectives.

An additional limitation relates to the rapid evolution of digital technologies. The relevance and performance of specific solutions may change as technological capabilities continue to develop. Future research could therefore incorporate dynamic analysis approaches to capture the evolution of digital technologies and their long-term implications for supply chain management. Future studies should also examine emerging digital technologies for data processing, which continue to expand rapidly year by year. In addition, alternative groups of evaluation criteria could be considered depending on the specific characteristics of the analyzed problem. Further research may explore the application of other decision-making methods or combinations of methods for the selection and evaluation of digital solutions. Finally, future research could apply additional multi-criteria decision-making techniques, such as MARCOS or WASPAS, to test the robustness and stability of the obtained results

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Izvorni znanstveni rad

ODABIR DIGITALNIH TEHNOLOGIJA ZA UPRAVLJANJE PODACIMA U OPSKRBNIM LANCIMA PRIMJENOM MCDM PRISTUPA

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SAŽETAK

Suvremeni lanci opskrbe (LO) prolaze kroz značajne strukturne promjene potaknute globalnim poremećajima, geopolitičkim rizicima te rastućim zahtjevima za otpornošću i fleksibilnošću, što je mnoge organizacije potaknulo na usvajanje strategija usmjerenih na regionalizaciju lanaca opskrbe. Cilj ovog istraživanja jest analizirati izazove povezane s podacima u regionalnim lancima opskrbe te procijeniti ulogu suvremenih digitalnih tehnologija u unaprjeđenju razmjene podataka, učinkovitosti njihove obrade i ukupne otpornosti lanaca opskrbe. Analiza obuhvaća složenost prekograničnih tokova robe, informacija i kapitala, kao i interakciju heterogenih informacijskih sustava, koji predstavljaju sustavne izazove, a ne izolirane operativne probleme. Na temelju identificiranih izazova, u radu se razmatraju tri digitalna rješenja: agent temeljen na umjetnoj inteligenciji (AI), blockchain tehnologija i koncept kontrolnog tornja lanca opskrbe (eng. Supply Chain Control Tower). Metodologija istraživanja temelji se na višekriterijskom pristupu odlučivanja koji integrira metodu Best–Worst za određivanje težina kriterija te metodu Fuzzy Technique for Order Preference by Similarity to Ideal Solution za vrednovanje i rangiranje alternativa. Rješenja se procjenjuju primjenom devet kriterija koji obuhvaćaju tehničke, organizacijske i operativne dimenzije. Rezultati ukazuju na značajne razlike u učinkovitosti analiziranih tehnologija, pri čemu rješenja temeljena na umjetnoj inteligenciji pokazuju osobito snažan potencijal za unaprjeđenje upravljanja podacima i operativne prilagodljivosti u regionalnim lancima opskrbe. Doprinos istraživanja ogleda se u sustavnom razmatranju i usporednoj evaluaciji suvremenih digitalnih tehnologija u kontekstu regionalnih lanaca opskrbe, čime se donositeljima odluka pružaju strukturirani uvidi za odabir odgovarajućih rješenja za upravljanje podacima.

Ključne riječi: *lanac opskrbe; otpornost; višekriterijsko odlučivanje; agent umjetne inteligencije; blockchain tehnologija*

Preliminary communication

CHOOSING A PROCUREMENT STRATEGY IN CONDITIONS OF SUPPLY DISRUPTIONS: A CONTINGENCY MATCHING FRAMEWORK

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ABSTRACT

Disruptions in supply chains have become a structural feature of the modern business environment. Still, the debate on resilience remains largely at the systemic level and is only loosely related to specific procurement decisions. The purpose of this article is to examine how the frequency, intensity, and predictability of disruptions affect the rationality of procurement strategy choices. The research is based on a conceptual approach to theory development and a structured synthesis of the literature on supply chain resilience, viability, and strategic procurement. A typology of disruptions is developed, which is linked to archetypal procurement strategies through a matching matrix based on the principle of proportionality. The key finding is that the rationality of structural adaptation in procurement is not linearly related to the degree of redundancy. The optimal level of resource diversification, flexibility, or capacity provision depends on the configuration of the disruption characteristics. The proposed matrix distinguishes between proportional and disproportionate procurement responses by comparing the expected loss from the disruption with the marginal cost of structural adjustment. The article's contribution is to conceptualise procurement resilience as a conditional property resulting from the match between the structure of the disruption and the degree of structural adjustment, thereby extending existing resilience theory toward a more differentiated and economically grounded procurement perspective.

Keywords: *supply chain disruptions, procurement strategies, risk management, resilience, viability.*

1. INTRODUCTION

The increased frequency and intensity of disruptions have revealed the vulnerability of highly optimized supply chains, which in recent decades have been designed primarily with a view to cost efficiency, lean operations, and global dispersion (Ivanov, 2022; Ivanov and Dolgui, 2021) Simultaneous pandemic, geopolitical, and energy disruptions have shown that systemic stability does not depend solely on operational optimization, but also on the ability to adapt to structural shocks that exceed normal variability in demand or delivery times.

In recent years, it has become increasingly clear that the current changes do not represent merely cyclical uncertainty but rather a more permanent transformation of the global trading system. Geopolitical fragmentation, strategic reorientation of trade flows, and the strengthening of protectionist policies are contributing to the fragmentation of world markets and the transformation of global value chains. Analyses by international institutions show that

such processes lead to structural adjustments in supply networks and increased long-term instability in trade flows (OECD, 2024; WTO, 2024). This also changes the nature of risk: disruptions are no longer just occasional events, but are becoming part of the broader structural environment.

In such circumstances, resilience is no longer simply the ability to recover from an exceptional event, but a condition for the long-term functioning and adaptation of the supply network. The debate is therefore shifting from how to restore the system after a disruption to how to design it to withstand more persistent geopolitical and trade uncertainty. The literature has responded to these changes by developing concepts of resilience and viability, but the focus has remained mainly at the system or supply network level (Lücker *et al.*, 2024; Sawik, 2024; Scholten *et al.*, 2019; Wieland, 2021).

More recent review studies also point to the tension between resilience and efficiency and the risk of sustained cost increases if adjustments are made without a clear assessment of their economic justification (Lücker et al., 2024). In practice, this relationship between benefits and costs is most evident at the procurement level, where adjustments are implemented through supplier selection, contract design, resource diversification, and capacity assurance.

Research in the field of strategic procurement shows that the effects of flexibility, digitalisation, and multi-supplier structures are not universal, but are conditioned by the characteristics of the disruption and the broader risk environment (Di Mauro et al., 2024; Harju et al., 2023; Pratono, 2024). Nevertheless, it is often implicitly assumed in the literature and in practice that more reserves and more suppliers always increase resilience. In a procurement context, this assumption does not necessarily hold, as the effectiveness of the chosen strategy depends on the type, intensity, and predictability of the disruption.

The article, therefore, starts with the following research question: how do the frequency, intensity, and predictability of disruptions affect the appropriateness of the procurement strategy? The main contribution of the article is the development of a conceptual matrix that enables a systematic assessment of when additional procurement adjustments are justified and when they represent a disproportionate cost relative to the type of disruption.

2. CONCEPTUAL FRAMEWORK AND ANALYTICAL DIMENSIONS

The proposed framework defines the type of disruption using three basic characteristics: frequency, impact intensity, and predictability. These three characteristics are derived from research on the spread of supply chain disruptions, their vulnerability, and procurement response methods (Hosseini *et al.*, 2019; Ivanov and Dolgui, 2021; Lücker *et al.*, 2024). Rather than treating disruptions as uniform events, the framework assumes that the appropriateness of a procurement adjustment varies depending on the type and characteristics of the disruption. Similar thinking can be found in more recent studies that treat disruptions as a process of propagation through a network and distinguish between phases of response (absorption, adjustment, recovery), showing that different situations require different responses (Habibi *et al.*, 2023). This confirms that frequency, intensity, and predictability should be considered as separate but interrelated dimensions.

Frequency distinguishes between recurring operational disruptions and rare but disruptive events. Repetitive disruptions cause constant uncertainty and require adaptive mechanisms, while rare events pose occasional but potentially very significant risks. Intensity describes the magnitude of the loss or the degree of service interruption. This characteristic is key to assessing whether the system can still cope with the disruption using existing capacities or whether it exceeds its operational limits (Ivanov, 2022). Predictability determines the extent to which a disruption can be predicted and prepared for. Higher predictability enables planned, cost-effective adjustments, while lower predictability increases the need for safety reserves and more stable solutions (Harju et al., 2023; Pratono, 2024).

These three characteristics are not entirely independent of each other. The same intensity has different consequences depending on whether the disturbance occurs frequently or only exceptionally. Similarly, high intensity with good predictability allows for planned restructuring, while an equally intense but unpredictable disruption requires more reserve capacity. The combination of frequency, intensity, and predictability, therefore, determines not only the level of risk but also the type of appropriate response.

The three dimensions selected represent a basic set for assessing the choice of procurement strategy. Each dimension contributes its own perspective: frequency captures the repeatability of events, intensity captures the magnitude of impact, and predictability captures the possibility of timely preparation. Their combination helps answer whether a structural adjustment—such as adding more suppliers or additional capacity—is justified or represents a disproportionate increase in costs.

This approach complements established procurement theory, in particular the Kraljič matrix, which classifies procurement items according to their impact on business and supply risk (Kraljič, 1983). The Kraljič matrix primarily treats risk as a relatively stable market characteristic. The proposed framework, however, views risk as a function of the type of disruption. This means that the same procurement item can find itself in different risk situations depending on the kind of disruption. The model, therefore, does not replace existing procurement category classifications, but adds a time and intensity dimension that explains why the appropriateness of a particular strategy may change even without a change in the market structure of suppliers.

This shifts procurement decision-making from static item classification to dynamic assessment of circumstances. The decision is no longer based solely on the procurement item's category, but on the characteristics of the disruption that determine whether a deviation from cost optimisation is economically justified.

3. TYPOLOGY OF DISRUPTIONS AND THEIR IMPACT ON PROCUREMENT DECISIONS

The combination of frequency and intensity allows us to distinguish four basic types of disruptions, which differ in risk level and consequences for procurement decisions. Predictability is an additional factor that influences whether a company responds with minor adjustments or significant structural changes. The proposed typology is not intended to classify events in themselves, but to link the type of disruption to the choice of a sensible procurement strategy.

Type T1: Frequent and low-intensity disruption

This type covers minor operational deviations, such as short delays, fluctuations in delivery times, or temporary quality issues. An individual event does not threaten the continuity of supply, but its frequency creates constant uncertainty. In such circumstances, it makes sense to manage variability with limited adjustments, without permanently increasing reserves or complexity. Additional capacity or a broader supplier base would mean a permanent increase in costs that would not proportionally reduce the risk. The key issue, therefore, is not to eliminate the risk but to find a balance between coordination costs and operational stability.

Type T2: Rare and low-intensity disruption

In rare events with limited consequences, the risk is intermittent and does not threaten the system as a whole. Since both frequency and intensity are low, permanent protective measures are rarely economically justified. In this case, procurement faces a choice between preventive investments and accepting limited losses in the event of a disruption. Excessive diversification of suppliers or long-term provision of additional capacity would be a disproportionate response to the actual level of risk in such circumstances.

Type T3: Frequent and highly intense disruption

This type represents more persistent instability. A single event can cause a significant loss or disrupt the supply chain, and such events occur frequently. In this case, minor adjustments are no longer sufficient. It makes sense to introduce structural solutions such as multiple suppliers, secured capacity, or greater standardisation. The cost of additional reserves may be justified because the total loss from recurring disruptions exceeds the price of the extra complexity. The substitutability of resources also becomes important here, as without it, a broader supplier base does not actually reduce risk.

Type T4: Rare and highly intense disruption

This type covers rare but very extensive shocks that can threaten the continuity of supply. Although they are infrequent, they can have serious consequences for businesses. In such situations, decision-making goes beyond short-term cost optimisation. The key question is no longer whether additional reserves are adequate, but whether the lack of reserves jeopardises the company's long-term operations. Research on the spread of disruptions shows that an initial failure can trigger a chain reaction throughout the supply network and increase total losses (Ivanov and Dolgui, 2021). In this context, minimum guaranteed capacities or resource diversification serve as a form of protection against major systemic failure.

3.1 The role of predictability

Predictability determines whether it is possible to identify the transition between different types of disruptions promptly and plan a response. If high-intensity events are sufficiently predictable, a company can gradually adjust its supply structure, standardise resources, or phase in an expansion of its supplier base. However, when events are unpredictable, the importance of pre-secured reserves and more stable solutions increases. Predictability, therefore, primarily affects the timing and manner of adaptation, rather than the basic logic of proportionality between risk and cost.

The proposed typology of disruptions does not assess events by their "severity," but rather by the appropriate response given their characteristics. The same intensity may require different solutions if the frequency differs, while the same frequency may lead to other decisions if the degree of predictability differs. Risk is therefore not an absolute category, but a combination of characteristics that determines the economic justification of individual procurement mechanisms.

4. PURCHASING STRATEGIES BASED ON THE TYPE OF DISRUPTION

If the type of disruption determines the level of risk, then procurement strategies represent different ways of adjusting to that risk. Research in risk management and strategic procurement highlights several common approaches: close cooperation with suppliers, contractual flexibility, diversification of sources, capacity assurance, and standardisation of specifications (Di Mauro *et al.*, 2024; El Baz and Ruel, 2021). However, the appropriateness of a particular strategy is not universal, but depends on the characteristics of the disruption.

Relational partnership

Closer cooperation with suppliers reduces operational fluctuations through information exchange, better coordination, and mutual adaptation. Empirical research shows that this approach improves responsiveness to low-intensity and recurring disruptions, aiming to stabilise supply without permanently increasing reserves El Baz and Ruel, 2021). However, cooperation alone cannot compensate for missing capacities or eliminate structural constraints on the supplier. In highly intensive disruptions, its effect is limited, as better communication cannot create additional physical capacity. Such an approach is therefore particularly appropriate where disruptions remain within the system's capacity to manage them.

Contractual flexibility

Contractual flexibility allows changes in quantities, prices, or delivery times without altering the structure of the supply network. It is beneficial in environments with low-intensity or predictable disruptions, where adjustments can be made without long-term capacity commitments (Harju *et al.*, 2023). It serves as a way to adapt to uncertainty rather than as protection against substantial disruptions. When disruptions are highly intense and unpredictable, contractual flexibility alone does not ensure continuity of supply unless it is supported by alternative sources or additional capacity.

Diversification of sources

It is often assumed that more reserves and more suppliers always increase resilience. In procurement practice, this is not always the case. Research shows that having too many suppliers or reserves can reduce efficiency, especially during less severe disruptions (Yang *et al.*, 2024). Greater diversification also means more coordination, quality control, and relationship management, which increases costs (Pratono, 2024). Therefore, diversification makes sense primarily when the expected loss due to disruptions exceeds the costs of additional complexity. It is not a universal solution, but a decision that must be proportionate to the risk. Research warns that when supplier risks are systemically linked or correlated, diversification does not yield the expected risk reduction (Shan *et al.*, 2023).

Capacity provision

Capacity provision means long-term capacity reservations, minimum guaranteed quantities, or other forms of permanent commitments. This is the strongest form of adjustment and makes sense primarily in the case of rare but very extensive disruptions, where the potential loss exceeds the costs of additional reserves (Ivanov, 2022). In other circumstances, such a decision may result in a permanent increase in costs and reduce flexibility. Its justification, therefore, depends on the relationship between the probability of a significant supply disruption and the cost of tied-up assets.

Standardisation of specifications

Standardisation increases substitutability between suppliers and reduces dependence on individual sources. It thus supports other strategies by enabling diversification or contractual flexibility to actually work. In the event of frequent disruptions, it allows orders to be redirected without a complete increase in reserves. However, it does not in itself create additional capacity and therefore cannot replace reserves in the event of substantial disruptions.

In general, none of the strategies mentioned is the best in all circumstances. The appropriateness of the choice depends on the match between the type of disruption and the strategy's degree of flexibility. Therefore, procurement mechanisms should be selected based on the frequency, intensity, and predictability of the disruption. This match is systematically presented in the conceptual matrix in the next chapter.

5. MATRIX OF MATCHING BETWEEN THE TYPE OF DISRUPTION AND THE CHOICE OF PROCUREMENT STRATEGY

The typology of disruptions and individual procurement strategies becomes meaningful only when combined. Table 1 shows that the appropriateness of choosing a particular approach depends on the combination of the disruption's frequency, intensity, and predictability. The matrix thus answers the article's research question: under what circumstances is a certain degree of adaptation justified, and when does it represent a disproportionate use of resources?

Table 1. Matrix of correspondence between the type of disruption and the choice of procurement strategy

Dimensions: Frequency × Intensity
Additional characteristic: Predictability

Frequency / Intensity	Low intensity	High intensity
High frequency	**T1 Operational variability** Basic logic: Adjustment without permanent reserves Meaningful strategies: Cooperation with suppliers, contractual flexibility Disproportionate: Securing capacity	**T3 Recurring interruptions** Basic logic: Structural protection against recurring losses Sensible strategies: Diversification of sources, standardisation With low predictability: Partial capacity assurance
Low frequency	**T2 Occasional deviations** Basic logic: Cost discipline Sensible strategies: Limited flexibility, standardisation Disproportionate: Complex multi-supplier structure	**T4 Systemic shock** Basic logic: Ensuring continuity of supply Meaningful strategies: Ensuring capacity Complementary: Diversification of sources

Predictability primarily affects the timing and manner of adjustment. If disruptions are sufficiently predictable, changes can be planned gradually and without permanent reserves. However, when events are unpredictable, pre-secured capacities and more stable solutions become more critical.

In economic terms, the matrix is based on the relationship between expected loss and adjustment costs. The expected loss depends on how often the disruption occurs and how strong its impact is. The cost of adaptation, on the other hand, stems from the degree of permanent commitment that the chosen strategy entails. The choice makes sense when the reduction in expected loss justifies the additional costs of adaptation. If this relationship does not exist, the strategy is disproportionate.

For frequent and low-intensity disruptions (T1), it makes sense to use adjustment mechanisms without permanent reserves. Cooperation with suppliers and contractual flexibility reduces operational fluctuations at minimal cost. Securing capacity or extensive diversification of resources would, in this case, entail permanent costs disproportionate to the risk.

In the case of rare and low-intensity disruptions (T2), the justification for additional investment is even weaker. As both frequency and impact are limited, the system generally remains within its capacity. Limited flexibility and standardisation are sufficient to manage deviations. Extensive multi-supplier structures or secured capacities would result in higher coordination costs without a corresponding reduction in risk.

However, in the case of frequent and highly intensive disruptions (T3), the matrix shows a shift towards structural solutions. Repeated major outages cause cumulative losses that can exceed the costs of additional complexity. Diversification of sources and standardisation reduces concentration risk and facilitates order redirection. Research shows that in such situations, additional complexity may be justified because it reduces the spread of disruption through the supply network (Ivanov and Dolgui, 2021; Pratono, 2024). If such events are also unpredictable, partial capacity provision also becomes sensible.

Rare but very severe shocks (T4) pose a serious threat to supply continuity. Although they occur infrequently, they can cause very high losses. In such circumstances, securing capacity or long-term supply commitments is justified as a form of protection against major

business interruptions (Ivanov, 2022). Diversification of sources can serve as a supplement, but does not, in itself, guarantee supply if multiple sources or regions fail simultaneously.

The matrix thus shows that more reserves do not always mean greater rationality. Increasing reserves is only worthwhile when the characteristics of the disruption justify the cost—over-adjustment at T1 or T2 results in permanent coordination and capital commitment costs without commensurate benefits. Conversely, under-adjustment at T3 or T4 can lead to significant losses and the spread of disruption throughout the supply network.

The use of the matrix can be illustrated by the example of a pharmaceutical active ingredient produced in a single geographic region. If an export restriction occurs due to a geopolitical event, this is a rare but pervasive disruption (T4). In this case, it makes sense to secure alternative sources or capacities, even if this means higher costs. However, if the identical item faces occasional minor logistical delays, this is a T1 situation in which permanent reserves are not justified, and contractual flexibility or closer cooperation with the supplier is more appropriate. The example shows that the appropriateness of the strategy is not a permanent feature of the procurement item, but depends on the characteristics of the disruption.

A similar logic can be illustrated in the automotive electronics sector. A semiconductor component sourced from a geographically concentrated supplier base may face repeated delivery instability due to congestion or short-term logistics bottlenecks. In such a case, the disruption is closer to T1, and the more appropriate response may involve contractual flexibility, closer supplier coordination, and selective standardisation rather than costly structural redesign. However, if access to the same component becomes restricted by export controls or geopolitical escalation, the situation shifts toward T4. Under those conditions, dual sourcing, regional diversification, or secured allocation agreements become more economically justified. This example further shows that the appropriate procurement strategy is not determined solely by the item itself, but by the surrounding disruption profile.

6. DISCUSSION

The proposed matrix shifts the discussion of resilience from general system characteristics to specific procurement decisions. In the existing literature, reserves, resource diversification, and flexibility are often treated as fundamentally positive characteristics of supply chains (Ivanov, 2022; Wieland, 2021). This view usually assumes that greater flexibility automatically means greater resilience. The analysis in this article shows that in a procurement context, this relationship is not always valid.

The main theoretical contribution of the model is that it understands resilience in procurement as the result of a match between the type of disruption and the degree of adaptation. Resilience is not a permanent characteristic of an organisation; instead, it results from the appropriate allocation of resources in relation to risk characteristics. The appropriateness of a particular strategy, therefore, varies depending on the frequency, severity, and predictability of disruptions.

The model builds on research on the propagation of disruptions (Ivanov and Dolgui, 2021) by transferring these insights to the level of the procurement function. It thus ties in with recent discussions on the long-term adaptability of supply networks in the face of geopolitical and systemic shocks (Dubey et al., 2023). While contagion studies analyse how shocks spread through a network, the proposed matrix explains why a certain level of reserves makes sense in one context but causes unnecessary costs in another. In this way, it goes beyond a simple division between efficiency and resilience and introduces a logic of proportionality between risk and expense (Lücker *et al.*, 2024).

An essential emphasis of the model is that the procurement category itself does not always determine the best strategy. The Queen's Matrix treats risk as a relatively stable market characteristic. Still, the proposed framework shows that the appropriateness of a strategy can change even without a change in the supplier environment if the type of disruption

changes. This means that even strategic or leverage items are not tied to a single permanent optimal solution, but require adjustment depending on the circumstances.

The model also allows us to understand the consequences of misalignment. Over-adjustment causes permanent costs of coordination, relationship management, and capital commitment without adequately reducing risk. Under-adjustment, on the other hand, can lead to significant losses and the spread of disruption throughout the supply network. The matrix thus helps to distinguish between justified and excessive use of reserves.

In practice, this means that the type of disruption must be systematically assessed before choosing a strategy. First, the frequency of the disruption must be evaluated, then its severity in terms of potential loss or supply interruption, and finally, its predictability. Only a combination of these three assessments allows for an assessment of whether additional adjustment is appropriate. The matrix, therefore, acts as a tool for more informed decision-making and reduces the risk of intuitive or generic solutions.

In practical procurement settings, the matrix can be used as a simple decision-support heuristic. Managers first assess whether the disruption is recurring or rare, then estimate whether its impact remains operationally manageable or threatens supply continuity, and finally evaluate its predictability. On this basis, they compare the expected loss from disruption with the cost of structural adjustment, such as supplier diversification, specification standardisation, or capacity reservation. The value of the matrix is not that it prescribes a single universal best practice, but that it helps decision-makers distinguish between proportional and disproportionate responses across different disruption profiles.

The model also has limitations. It is a conceptual framework that has not yet been empirically tested in specific industries or sourcing settings. First, it simplifies the procurement reality by focusing on three disruption characteristics. At the same time, other factors, such as switching costs, supplier power, regulatory constraints, and technical substitutability, may also materially affect strategy choice. Second, the boundaries between disruption types are not always sharp in practice, since repeated low-intensity events may accumulate into a structurally significant risk over time. Third, the framework does not yet define measurable threshold values at which frequency or intensity justify a shift from flexible adjustment to structural protection. Future research should therefore examine the relationship between disruption type and procurement performance empirically, and assess how sectoral and supply-network characteristics influence the relevance of particular strategies.

Despite these limitations, the model contributes to a clearer understanding of procurement resilience by matching the type of disruption to the degree of adaptation. This opens up opportunities for further empirical testing and for developing tools to measure the economic effects of different procurement approaches.

7. CONCLUSION

The article develops a conceptual framework that links the type of disruption to the choice of procurement strategy. The central finding is that the degree of adaptation of the procurement function is not generally the best solution; rather, it depends on the combination of the frequency, intensity, and predictability of the disruption. The rationality of the decision stems from the relationship between expected loss and the cost of adaptation, not from a general belief that more reserves always mean greater resilience.

The model makes three contributions. First, it brings the discussion of resilience down to the level of concrete procurement decisions. Second, it complements existing procurement theory with a dynamic view of risk that goes beyond static item classification. Third, it introduces a clear logic of matching between the type of disturbance and the chosen strategy, allowing a distinction between justified and excessive adjustment.

The proposed framework provides a starting point for empirical testing and the development of quantitative tools to measure the economic effects of different procurement decisions under conditions of disruption. In this way, the article contributes to a more accurate

understanding of procurement resilience as a question of risk-cost trade-offs. As a preliminary communication, the article does not aim to provide empirical verification but rather to offer a theoretically grounded framework to guide future testing in specific procurement contexts.

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Prethodno priopćenje

ODABIR STRATEGIJE NABAVE U UVJETIMA POREMEĆAJA U OPSKRBI: KONTINGENCIJSKI OKVIR USKLAĐIVANJA

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SAŽETAK

Poremećaji u opskrbnim lancima postali su strukturno obilježje suvremenog poslovnog okruženja. Unatoč tomu, rasprava o otpornosti i dalje se uglavnom vodi na sustavnoj razini te je samo labavo povezana s konkretnim odlukama u nabavi. Svrha je ovoga rada ispitati kako učestalost, intenzitet i predvidljivost poremećaja utječu na racionalnost izbora strategija nabave. Istraživanje se temelji na konceptualnom pristupu razvoju teorije i strukturiranoj sintezi literature o otpornosti, održivosti i strateškoj nabavi u opskrbnim lancima. Razvijena je tipologija poremećaja, koja je povezana s arhetipskim strategijama nabave pomoću matrice usklađivanja temeljene na načelu proporcionalnosti. Ključni nalaz rada jest da racionalnost strukturne prilagodbe u nabavi nije linearno povezana sa stupnjem redundancije. Optimalna razina diverzifikacije resursa, fleksibilnosti ili osiguranja kapaciteta ovisi o konfiguraciji obilježja poremećaja. Predložena matrica razlikuje proporcionalne i neproporcionalne odgovore nabave usporedbom očekivanog gubitka uzrokovanog poremećajem i graničnog troška strukturne prilagodbe. Doprinos rada sastoji se u konceptualizaciji otpornosti nabave kao uvjetovanog svojstva koje proizlazi iz podudarnosti između strukture poremećaja i stupnja strukturne prilagodbe, čime se postojeća teorija otpornosti proširuje prema diferenciranijoj i ekonomski utemeljenoj perspektivi nabave.

Ključne riječi: *poremećaji u opskrbnim lancima, strategije nabave, upravljanje rizicima, otpornost, održivost.*

Prethodno priopćenje

ULOGA LOGISTIKE U KRUŽNOJ EKONOMIJI: KVANTITATIVNI PRISTUP UČINKOVITOSTI POVRATNIH TOKOVA

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SAŽETAK

Predmet analize od značaja za ovaj rad jest mjesto i uloga logistike u kružnoj ekonomiji s posebnim naglaskom na kvantitativno vrednovanje učinkovitosti povratnih materijalnih tokova. Polazeći od konceptualnih načela kružne ekonomije, razvijen je integrirani kvantitativni metodološki okvir koji omogućuje analizu odnosa između logističkih ulaza (transportni rad, energija i emisije) i korisnih izlaza u obliku sekundarnih sirovina. Metodologija se temelji na scenarijskoj analizi referentnog stanja te alternativnih varijanti operativne optimizacije i strukturnih promjena logističkog sustava, uključujući modalni pomak i elektrifikaciju transporta. Rezultati upućuju na to da operativne optimizacije generiraju ograničene, ali statistički relevantne dobitke u resursnoj učinkovitosti i smanjenju ugljične intenzivnosti povratnih tokova, dok strukturne logističke intervencije ostvaruju znatno veće dugoročne učinke. Rad potvrđuje da logistika predstavlja ključni operativni mehanizam provedbe kružne ekonomije te naglašava važnost primjene kvantitativnih modela u evaluaciji i oblikovanju održivih logističkih strategija.

Ključne riječi: *kružna ekonomija, logistika, povratna logistika, kvantitativno modeliranje, resursna efikasnost*

1. UVOD

U posljednjim desetljećima sve izraženiji pritisci na prirodne resurse, rast količine otpada te negativni učinci industrijskih i logističkih aktivnosti na okoliš potaknuli su razvoj novih modela gospodarskog djelovanja usmjerenih prema održivosti (Pupavac, 2016). Tradicionalni linearni model gospodarstva, temeljen na načelu „*uzmi–proizvedi–odbaci*“, pokazao se dugoročno neodrživim zbog intenzivne potrošnje resursa i ograničenih mogućnosti zbrinjavanja otpada (Ghisellini et al., 2016). Kao odgovor na navedene izazove razvija se koncept kružne ekonomije, koji naglašava smanjenje otpada, produljenje životnog vijeka proizvoda, ponovnu uporabu materijala te njihovo vraćanje u proizvodne procese (Geissdoerfer et al., 2017). Kružna ekonomija ne predstavlja isključivo tehnološku ili ekološku promjenu, već zahtijeva cjelovitu transformaciju gospodarskih sustava, uključujući organizaciju proizvodnje, potrošnje i distribucije (Kirchherr et al., 2017). U tom kontekstu logistika zauzima posebno važno mjesto jer omogućuje fizičko kretanje materijala, proizvoda i otpada unutar kružnih tokova. Bez učinkovito organiziranih logističkih procesa, poput transporta, skladištenja, razvrstavanja i povrata proizvoda, nije moguće ostvariti temeljna načela kružne ekonomije u praksi (Stahel, 2016).

Posebna važnost logistike u kružnoj ekonomiji očituje se u upravljanju materijalnim tokovima kroz cijeli životni ciklus proizvoda – od sirovina i poluproizvoda, preko distribucije gotovih proizvoda, do povratnih tokova koji uključuju reciklažu, ponovnu uporabu ili ekološki prihvatljivo zbrinjavanje (Ellen MacArthur Foundation, 2019). Pritom povratna logistika postaje ključni element sustava, jer omogućuje prikupljanje iskorištenih proizvoda i materijala te njihovo ponovno uključivanje u proizvodne ili energetske procese (Govindan et al., 2015).

Učinkovitost tih procesa izravno utječe na smanjenje količine otpada, optimizaciju troškova i smanjenje negativnog utjecaja na okoliš.

Cilj ovoga rada jest istražiti mjesto i ulogu logistike u kružnoj ekonomiji s naglaskom na transport, skladištenje i upravljanje materijalnim tokovima. Rad analizira kako logistički sustavi doprinose učinkovitom funkcioniranju kružnih modela gospodarstva te identificira ključne izazove i mogućnosti za njihovo unaprjeđenje. U skladu s tim, rad razmatra teorijski okvir kružne ekonomije, analizira ulogu logistike u različitim vrstama materijalnih tokova te kroz primjere iz prakse prikazuje potencijalne učinke kružne logistike na održivost i gospodarsku učinkovitost.

U skladu s definiranim ciljem, rad nastoji odgovoriti na sljedeća istraživačka pitanja:

1. Koja je uloga logistike u ostvarivanju temeljnih načela kružne ekonomije?
2. Na koji način logistički procesi transporta, skladištenja i upravljanja materijalnim tokovima doprinose učinkovitosti kružnih sustava?
3. Koje su specifičnosti logističkog upravljanja sirovinama, proizvodima i materijalima koji se (ne)mogu reciklirati u okviru kružne ekonomije?
4. S kojim se izazovima suočava povratna logistika u implementaciji kružnih modela gospodarstva?

2. TEORIJSKI OKVIR I PROBLEM ISTRAŽIVANJA

Kružna ekonomija predstavlja koncept gospodarskog razvoja usmjeren na učinkovito korištenje resursa, smanjenje otpada i produljenje životnog vijeka proizvoda kroz zatvorene materijalne tokove (Kirchherr et al., 2017). Za razliku od linearnog modela gospodarstva, u kojem se resursi nakon uporabe odbacuju, kružna ekonomija teži ponovnoj uporabi, obnovi, reciklaži i energetskoj oporabi materijala (Ghisellini et al., 2016). Temeljna ideja kružne ekonomije jest zadržavanje vrijednosti proizvoda, materijala i resursa u gospodarstvu što je dulje moguće, uz istodobno smanjenje negativnih utjecaja na okoliš (Ellen MacArthur Foundation, 2013). U teorijskom smislu, kružna ekonomija obuhvaća skup načela koja uključuju dizajn proizvoda prilagođen reciklaži, optimizaciju resursne učinkovitosti, smanjenje gubitaka u proizvodnim i logističkim procesima te razvoj sustava povrata i ponovne uporabe (Bocken et al., 2016). Ta načela zahtijevaju koordinirano djelovanje različitih dionika unutar opskrbnih lanaca, pri čemu logistika ima ključnu ulogu u osiguravanju funkcionalnosti kružnih tokova.

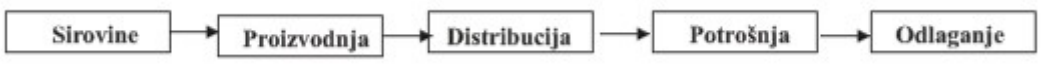
Linearni model gospodarstva temelji se na slijedu aktivnosti koji započinje eksploatacijom sirovina, nastavlja se proizvodnjom i distribucijom, a završava odlaganjem otpada (Stahel, 2016). U takvom sustavu logistika ima primarno jednosmjernu ulogu, usmjerenu na optimizaciju transporta i skladištenja gotovih proizvoda prema krajnjim korisnicima, dok su povratni tokovi slabo razvijeni ili potpuno izostaju.

Tok resursa u linearnoj ekonomiji može se predstaviti na sljedeći način:

$$\text{Resursi}_{\text{ulaz}} \rightarrow \text{Proizvod} \rightarrow \text{Otpad}$$

ili grafički

Slika 1. Linearni tok resursa



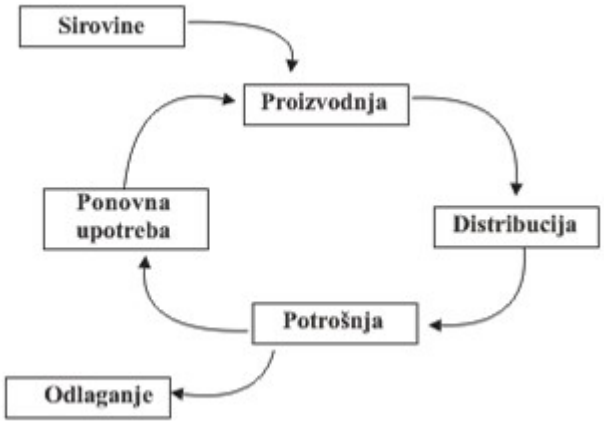
Nasuprot tome, kružni model gospodarstva zahtijeva višesmjerne materijalne tokove i znatno složenije logističke strukture. Osim klasičnih distribucijskih tokova, uključeni su i povratni tokovi proizvoda, ambalaže i otpada, koji se vraćaju u proizvodne ili reciklažne procese (Guide, 2000).

Tok resursa u kružnoj ekonomiji može se predstaviti na sljedeći način:

$$\text{Resursi}_{\text{ulaz}} \rightarrow \text{Proizvod} \rightarrow \text{Recikliranje} \rightarrow \text{Resursi}_{\text{ulaz}}$$

Ili grafički

Slika 2. Kružni tok resursa



Izvor: Priredio autor prema: Crane, A., Matten, D. (2010): Busines Ethics, Oxford University Press Inc, New York, p.379

Linearna ekonomija temelji se na kontinuiranoj potrošnji resursa i stvaranju otpada, dok kružna ekonomija nastoji zatvoriti materijalne tokove ponovnom uporabom, reciklažom i produljenjem životnog vijeka proizvoda.

Logistika u kružnom modelu prerasta u integrirani sustav upravljanja materijalima kroz cijeli životni ciklus proizvoda, a ne samo funkciju podrške distribuciji. Temeljna razlika uloge logistike u linearnoj i kružnoj ekonomiji očituje se u potrebi za fleksibilnim mrežama, razvijenim sustavima prikupljanja i razvrstavanja te povećanoj ulozi informacijskih sustava koji omogućuju praćenje materijalnih tokova (Govindan et al., 2015).

Održivost predstavlja jedno od temeljnih obilježja kružne ekonomije te se očituje kroz ekološku, ekonomsku i društvenu dimenziju (Geissdoerfer et al., 2017). Logistika izravno doprinosi resursnoj učinkovitosti kroz optimizaciju transportnih ruta, smanjenje praznih vožnji, racionalno korištenje skladišnih kapaciteta te primjenu ekološki prihvatljivih transportnih rješenja (McKinnon, 2018).

U kružnoj ekonomiji logistički sustavi omogućuju učinkovitu distribuciju sekundarnih sirovina i recikliranih materijala, čime se smanjuje potreba za primarnim resursima. Razvoj održivih logističkih sustava dodatno je potaknut primjenom digitalnih tehnologija koje omogućuju praćenje tokova materijala, planiranje kapaciteta i koordinaciju povratnih procesa (ISO 14040, 2006).

3. METODOLOGIJA ISTRAŽIVANJA

Istraživanje je koncipirano kao konceptualno-analitička studija uz primjenu kvantitativnog scenarijskog modeliranja logističkih procesa u kontekstu kružne ekonomije. Metodološki

pristup kombinira analizu relevantne znanstvene i stručne literature s razvojem kvantitativnog okvira za vrednovanje učinkovitosti kružne logistike te ilustrativnim numeričkim primjerom temeljenim na realističnim logističkim pretpostavkama. U radu se ne provodi klasično empirijsko istraživanje na stvarnim operativnim podacima, već se koristi analiza slučaja kao metoda za kvantitativnu ilustraciju odnosa između logističkih ulaza (energija, transportni rad, emisije) i korisnih izlaza (sekundarne sirovine) u sustavima kružne ekonomije.

Razvijeni metodološki okvir polazi od pretpostavke da se učinkovitost logistike u kružnoj ekonomiji može analizirati kroz odnos logističkih resursa uloženih u povratne tokove i količine materijala koji se uspješno vraćaju u kružni sustav. Promatrani logistički sustav obuhvaća procese prikupljanja proizvoda na kraju životnog vijeka, njihova transporta, skladištenja, razvrstavanja te upućivanja u reciklažne ili druge oblike oporabe.

Model se temelji na sljedećim ključnim pretpostavkama:

- promatra se agregirana razina logističkog sustava bez prostorne diferencijacije,
- energetski i emisijski učinci logistike aproksimiraju se prosječnim intenzitetima izraženim po jedinici transportnog rada i energije procesa,
- kvantitativni primjer ima ilustrativni karakter, ali se oslanja na vrijednosti uobičajene u praksi i znanstvenoj i stručnoj literaturi,
- masa materijala vraćena u kružni tok zadržava se konstantnom u scenarijskoj analizi kako bi se izolirao učinak logističkih intervencija.

Navedene pretpostavke omogućuju transparentnu i dimenzijski konzistentnu analizu, uz zadržavanje dovoljne općenitosti rezultata.

Za kvantitativnu analizu razvijen je skup pokazatelja podijeljenih u tri funkcionalne skupine.

Pokazatelji kružnosti materijalnih tokova obuhvaćaju stopu povrata proizvoda, definiranu kao omjer broja prikupljenih proizvoda i ukupnog broja proizvoda stavljenih na tržište, te stupanj materijalnog iskorištenja povratnog toka, izražen kao omjer sekundarnih sirovina i ukupne mase vraćenog materijala.

Energetski pokazatelji logistike temelje se na objedinjavanju energije utrošene u procesima skladištenja i razvrstavanja s energijskim ekvivalentom transportnog rada. Budući da su transportni rad i energija različitih dimenzija, transportni rad izražen u tonskim kilometrima prevodi se u energijski ekvivalent primjenom prosječnih energetskih intenziteta pojedinih vrsta prijevoza i prijevoznih sredstava.

Integrirani pokazatelji učinkovitosti uključuju resursnu učinkovitost logistike, definiranu kao količina sekundarnih sirovina po jedinici ukupne logističke energije, te ugljičnu intenzivnost povratnih tokova, izraženu kao emisije CO_2 po toni materijala vraćenog u kružni sustav. Ovi pokazatelji omogućuju istodobno vrednovanje materijalnih, energetskih i okolišnih aspekata logistike.

Kako bi se procijenio učinak različitih logističkih intervencija, provedena je scenarijska analiza koja obuhvaća tri varijante: referentni scenarij, scenarij operativne optimizacije i scenarij strukturnih promjena. Referentni scenarij opisuje postojeću organizaciju logističkih povratnih tokova. Scenarij operativne optimizacije uključuje smanjenje transportnog rada i energetske potrošnje procesa uz poboljšanje učinkovitosti razvrstavanja. Scenarij strukturnih promjena temelji se na modalnom pomaku dijela transporta prema željeznici te elektrifikaciji lokalnog prikupljanja.

Scenariji su definirani tako da omogućuju izravnu usporedbu ključnih pokazatelja učinkovitosti, pri čemu se pretpostavlja ista količina materijala vraćenog u kružni tok, čime se osigurava metodološka konzistentnost analize.

4. KVANTITATIVNI POKAZATELJI UČINKOVITOSTI LOGISTIKE U KRUŽNOJ EKONOMIJI

Kako bi se uloga logistike u kružnoj ekonomiji analizirala ne samo deskriptivno, već i kvantitativno, u literaturi se koriste različiti pokazatelji učinkovitosti koji omogućuju mjerenje uspješnosti logističkih sustava u zatvaranju materijalnih tokova (Govindan et al., 2015). Jedan od temeljnih pokazatelja jest stopa povrata materijala, koja se može izraziti omjerom količine vraćenog materijala i ukupne količine proizvoda stavljenih na tržište:

$$R = Q_p / Qt \quad (1)$$

pri čemu R označava stopu povrata materijala, Q_p količinu prikupljenih povratnih materijala, a Q_t ukupnu količinu proizvoda distribuiranih na tržište u promatranom razdoblju. Viša vrijednost pokazatelja R upućuje na učinkovitije funkcioniranje povratne logistike i veći stupanj zatvaranja materijalnih tokova.

Drugi važan pokazatelj odnosi se na resursnu učinkovitost logističkog sustava, koja se u kontekstu kružne ekonomije često definira kao omjer korisnog izlaza (sekundarne sirovine ili obnovljeni proizvodi) i ukupnih logističkih ulaza (energija, transportni rad, skladišni kapaciteti):

$$E_r = Q_s / (E + T) \quad 2)$$

pri čemu E_r označava resursnu učinkovitost logistike, Q_s količinu sekundarnih sirovina vraćenih u proizvodni proces, E utrošenu energiju, a T transportni rad izražen, primjerice, u neto tonskim kilometrima (McKinnon, 2018).

U analizi okolišnih učinaka logistike u kružnoj ekonomiji često se koristi i pokazatelj emisija po jedinici materijalnog toka, koji se može zapisati kao:

$$C_e = CO_2 / Q_m \quad (3)$$

pri čemu C_e predstavlja specifične emisije ugljikova dioksida, CO_2 ukupne emisije nastale u logističkim procesima, a Q_m količinu materijala koja je uspješno vraćena u kružni tok. Smanjenje vrijednosti ovog pokazatelja upućuje na ekološki učinkovitiji logistički sustav.

Uvođenje kvantitativnih pokazatelja u analizu kružne logistike omogućuje objektivniju procjenu uspješnosti različitih logističkih rješenja te predstavlja važan korak prema empirijskom vrednovanju kružnih modela gospodarstva.

5. PRAKTIČNI PRIMJER

Distributer elektroničke opreme tijekom jedne godine stavlja na tržište ukupno Q_t = 50.000 uređaja. Kroz sustav povrata na kraju životnog vijeka prikupljeno je Q_p = 12.000 uređaja. Nakon razvrstavanja i obrade prikupljenih proizvoda dobiva se Q_s = 350 t sekundarnih sirovina koje se vraćaju u proizvodne procese. Ukupna masa materijala vraćenog u kružni tok iznosi Q_m=550 t. Pretpostavlja se prosječna masa povratnog uređaja

$$m = \frac{Qm}{Qp} \approx 45{,}8\ kg,$$

što odgovara mješavini male i srednje elektroničke opreme.

Logistički sustav u promatranom razdoblju troši E = 120.000 kWh energije u skladištima, sortirnicama i manipulacijskim procesima te ostvaruje ukupno T = 1.500.000 tkm transportnog rada u okviru prikupljanja i prijevoza do sortirnica i reciklažnih postrojenja. U lokalnom prikupljanju dominiraju mali kamioni, dok se u međugradskom prikupljanju koriste teški kamioni. Lokalno prikupljanje čini 40 % ukupnog transportnog rada. Prosječni energetski intenzitet iznosi e_L = 0,35kWh/tkm za male kamione (više stajanja, niža popunjenost, gradski režim vožnje), te e_M = 0,20 kWh/tkm za teške kamione (stabilnija vožnja, veća popunjenost). Vrijednosti e_L i e_M predstavljaju pretpostavljene prosjeke energetskog intenziteta te se u empirijskoj primjeni kalibriraju prema stvarnoj potrošnji

goriva/telemetrijskim podacima ili standardiziranim faktorima. Ukupne emisije logistike povezane s povratnim tokovima iznose CO_2 = 150 t te obuhvaćaju emisije iz transporta i potrošnje energije u skladišnim i sortirnim procesima.

6. REZULTATI ISTRAŽIVANJA

Učinkovitost sustava povratne logistike u početnoj fazi može se procijeniti analizom stope povrata proizvoda, definirane kao omjer broja prikupljenih proizvoda i ukupnog broja proizvoda stavljenih na tržište (v. formulu 1).

$R=Qp/Qt$

$R=12\,000/50\,000=0,24=24\%$

U promatranom primjeru stopa povrata iznosi 24 %, što znači da je gotovo četvrtina proizvoda nakon završetka životnog vijeka vraćena u sustav povratnih tokova. Dobivena vrijednost upućuje na umjerenu do relativno dobru učinkovitost sustava povrata, osobito u usporedbi s brojnim stvarnim sustavima u kojima su stope povrata često niže zbog ograničene dostupnosti infrastrukture, nedostatnih poticaja za korisnike ili nedovoljne informiranosti. Time se potvrđuje da organizacijski i logistički aspekti imaju presudnu ulogu u ostvarenju kružnih materijalnih tokova već u njihovoj početnoj fazi.

Učinkovitost procesa razvrstavanja i obrade povratnih tokova može se procijeniti analizom stupnja materijalnog iskorištenja, odnosno omjera količine sekundarnih sirovina i ukupne mase prikupljenog materijala.

$\eta=Qs/Qm=350/550=0,636\approx63,6\%$

U analiziranom slučaju materijalno iskorištenje iznosi približno 63,6 %. Dobiveni rezultat upućuje na to da se više od polovice vraćenog materijala uspješno reintegrira u proizvodne procese, dok preostali dio obuhvaća gubitke, onečišćene ili tehnički neiskoristive frakcije te tokove usmjerene prema drugim oblicima oporabe. Ovakva razina iskorištenja u skladu je s vrijednostima zabilježenima u praksi te potvrđuje da kvaliteta razvrstavanja predstavlja ključni čimbenik ukupne učinkovitosti kružne logistike.

Kako bi se omogućila integrirana analiza energetskih učinaka logistike, transportni rad izražen u tonskim kilometrima potrebno je prevesti u energijski ekvivalent. U promatranom sustavu lokalni transport čini 40 % ukupnog transportnog rada, dok se preostalih 60 % odnosi na međugradski transport.

$T_L=0,40\ T, \quad T_M=0,60\ T$

$T_L=0,40\cdot1\,500\,000=600\,000$ tkm

$T_M=0,60\cdot1\,500\,000=900\,000$ tkm

Energetski ekvivalent transporta:

$E_T=T_L\,e_L+T_M\,e_M=600\,000\cdot0,35+900\,000\cdot0,20=210\,000+180\,000=390\,000$ kWh

Primjenom prosječnih energetskih intenziteta za pojedine vrste vozila dobiven je ukupni energijski ekvivalent transporta od 390 000 kWh. Ovoj vrijednosti potrebno je dodati energiju utrošenu u skladišnim i sortirnim procesima te tada ukupni energetski ulaz logističkog sustava iznosi

$E_{tot}=E+E_T=120\,000+390\,000=510\,000$ kWh.

Na temelju ukupnog energetskog ulaza i količine proizvedenih sekundarnih sirovina definira se pokazatelj resursne učinkovitosti logistike (v. formulu 2).

$Er=Qs/E_{tot}=350/510\,000=0,000686$ t/kWh$\approx0,686$ kg/kWh

Dobivena vrijednost od približno 0,686 kg sekundarne sirovine po kWh logističke energije ukazuje na sposobnost sustava da relativno učinkovito pretvara energetske ulaze u korisne materijalne izlaze. Ovaj pokazatelj posebno je prikladan za usporedbu alternativnih

logističkih scenarija, jer omogućuje izravno vrednovanje učinaka operativnih optimizacija, promjena u organizaciji transporta ili uvođenja novih tehnologija na ukupnu učinkovitost kružnog sustava.

Okolišni učinci logistike povratnih tokova dodatno se procjenjuju analizom ugljične intenzivnosti, definirane kao emisije ugljikova dioksida po toni materijala vraćenog u kružni tok (v.formulu 3).

$C_e=CO_2/Q_m$

Ce=150/550=0,2727 t CO_2/t≈273 kg CO_2/t

U analiziranom primjeru taj pokazatelj iznosi približno 273 kg CO_2 po toni materijala. Dobivena vrijednost ukazuje na značajan doprinos logističkih aktivnosti ukupnim emisijama, čime se potvrđuje potreba za sustavnim dekarbonizacijskim mjerama. Pokazatelj ugljične intenzivnosti osobito je koristan za evaluaciju mjera poput povećanja popunjenosti vozila, smanjenja praznih vožnji, optimizacije ruta ili prelaska na niskougljične i elektrificirane oblike transporta.

U nastavku rasprave, u odnosu na referentni scenarij, razmatraju se dva alternativna scenarija unaprjeđenja logističkog sustava s ciljem procjene učinaka operativnih i strukturnih intervencija na učinkovitost kružne logistike.

Prvi scenarij usmjeren je na operativnu optimizaciju postojećih logističkih procesa bez promjene temeljne strukture logističke mreže ili korištenih prijevoznih sredstava. U okviru ovog scenarija pretpostavlja se smanjenje ukupnog transportnog rada za 15 %, što proizlazi iz optimizacije ruta, konsolidacije pošiljaka i smanjenja praznih vožnji. Istodobno se pretpostavlja smanjenje energetske potrošnje skladišnih i sortirnih procesa za 10 % kao rezultat učinkovitijeg upravljanja kapacitetima i operativnih poboljšanja procesa. Dodatno, pretpostavlja se povećanje sekundarnog izlaza za 5 %, koje se pripisuje smanjenju kontaminacije materijalnih frakcija i poboljšanoj separaciji tijekom razvrstavanja. Ukupne emisije povezane s logističkim procesima smanjuju se za 12,5 %, dok masa materijala vraćena u kružni tok ostaje nepromijenjena, čime se osigurava izravna usporedivost rezultata s referentnim stanjem. U ovom scenariju pretpostavlja se da omjer lokalnog i međugradskog transporta ostaje približno nepromijenjen (40 % : 60 %), kao i da se energetski intenziteti pojedinih vrsta vozila ne mijenjaju, iako u praksi mogu dodatno pasti uslijed veće popunjenosti vozila i boljeg planiranja.

Drugi scenarij razmatra strukturne promjene logističkog sustava kroz promjenu prijevoznih sredstava i uvođenje niskougljičnih tehnologija. Polazi se od pretpostavke da se 50 % međugradskog transporta preusmjerava na željeznicu, dok se 50 % lokalnog prikupljanja obavlja električnim vozilima. Za razliku od prvog scenarija, ukupni transportni rad u ovom slučaju ostaje nepromijenjen, a poboljšanja učinkovitosti ostvaruju se isključivo kroz smanjenje energetskog ekvivalenta transporta, koje proizlazi iz nižih energetskih intenziteta željezničkog prijevoza (e_R = 0,06 kWh/tkm) i električnih vozila ($e_{L,ev}$ = 0,20 kWh/tkm) u usporedbi s konvencionalnim dizelskim kamionima. Analiza se temelji na prosječnim energetskim intenzitetima pojedinih vrsta prijevoza, odnosno prijevoznih sredstava, pri čemu se jasno diferenciraju lokalni i međugradski tokovi.

U Tablici 1 prikazana je usporedba ključnih pokazatelja učinkovitosti logistike za referentni scenarij te alternativne scenarije operativne optimizacije i strukturnih promjena, čime se omogućuje izravna kvantitativna analiza učinaka različitih logističkih intervencija.

7.1 Tablica 1. Pokazatelji učinkovitosti logistike u referentnom i alternativnim scenarijima

Pokazatelj	Referentno stanje	Prvi scenarij - Optimizacija (T−15%, E−10%, Qs+5%, CO_2−12,5%)	Drugi scenarij - Modal shift + EV (50% željeznica, 50% EV lokalno)
T (tkm)	1 500 000	1 275 000	1 500 000
E (kWh)	120 000	108 000	120 000
E_T (kWh)	390 000	331 500	282 000
E_tot = E+E_T (kWh)	510 000	439 500	402 000
Qs (t)	350	367,5	350
Er = Qs/E_tot (kg/kWh)	0,686	0,836	0,871
CO_2 (t CO_2)	150	131,25	111,75
Ce = CO_2/Qm (kg CO_2/t)	273	239	203
Qm (t)	550	550	550
R = Qp/Qt	24%	24%	24%

Izvor: Vlastiti izračuni

7. DISKUSIJA

Dobiveni rezultati potvrđuju da logistika predstavlja jedan od ključnih operativnih mehanizama provedbe kružne ekonomije, što je u skladu s nalazima brojnih autora koji logistiku prepoznaju kao poveznicu između konceptualnih načela kružnih sustava i njihove praktične implementacije (Geissdoerfer et al., 2017; Kirchherr et al., 2017). Posebno se ističe uloga povratne logistike u zatvaranju materijalnih tokova, što je u literaturi prepoznato kao temeljni preduvjet funkcioniranja kružne ekonomije (Govindan et al., 2015).

Rezultati scenarija operativne optimizacije pokazuju da relativno ograničene intervencije u organizaciji povratnih tokova mogu rezultirati mjerljivim poboljšanjima učinkovitosti, osobito kroz smanjenje logističkih ulaza i povećanje korisnog materijalnog izlaza. Ovakvi nalazi u skladu su s istraživanjima koja ukazuju da optimizacija ruta, konsolidacija pošiljaka i poboljšanje procesa razvrstavanja predstavljaju najčešće i troškovno najučinkovitije mjere u ranim fazama razvoja povratne logistike (Govindan et al., 2015; Srivastava, 2007). Porast resursne učinkovitosti logistike od približno 22 % potvrđuje tezu da se znatan dio potencijala kružne logistike može ostvariti unutar postojećih infrastrukturnih i organizacijskih okvira, bez potrebe za značajnim kapitalnim ulaganjima.

Istodobno, smanjenje ugljične intenzivnosti povratnih tokova za oko 12,5 % ukazuje na to da operativne mjere mogu ostvariti istodobne ekonomske i okolišne dobitke, što je u skladu s konceptom ekološke učinkovitosti kako ga definiraju Geissdoerfer i suradnici (2017). Međutim, literatura također upozorava na ograničenja takvog pristupa. Stahel (2016) naglašava da se kružna ekonomija ne može temeljiti isključivo na inkrementalnim poboljšanjima postojećih sustava, već zahtijeva dublje strukturne promjene u organizaciji proizvodnje, distribucije i logističkih mreža.

Ova se tvrdnja jasno potvrđuje rezultatima drugog scenarija, koji uključuje modalni pomak dijela međugradskog transporta na željeznicu i elektrifikaciju lokalnog prikupljanja. Smanjenje ukupne logističke potrošnje energije za više od 20 % te pad ugljične intenzivnosti povratnih tokova za približno 25 % u skladu su s nalazima McKinnona (2018), koji ističe da

dekarbonizacija logistike u najvećoj mjeri ovisi o promjeni vrsta prijevoza i tehnologija, a ne samo o optimizaciji postojećih operativnih procesa. Slično tome, izvještaji Ellen MacArthur Foundation (2013, 2019) naglašavaju da se puni klimatski i resursni učinci kružne ekonomije ostvaruju tek kombinacijom operativnih mjera i dugoročnih infrastrukturnih ulaganja.

Usporedba operativnog i strukturnog scenarija ukazuje na jasnu komplementarnost različitih razina intervencija. Operativna optimizacija omogućuje brze i relativno niskobudžetne dobitke te predstavlja nužan prvi korak u tranziciji prema kružnijim logističkim sustavima, dok strukturne promjene omogućuju kvalitativni iskorak prema dugoročno održivim rješenjima. Ovakav hijerarhijski pristup tranziciji u skladu je s konceptualnim okvirom kružne ekonomije koji predlažu Kirchherr et al. (2017), prema kojem su operativne, taktičke i strateške mjere međusobno uvjetovane i komplementarne.

Dobiveni rezultati potvrđuju da se logistika ne može promatrati kao pomoćna funkcija kružne ekonomije, već kao njezin središnji operativni stup. Kvantitativni pristup primijenjen u ovom radu nadopunjuje postojeću literaturu pružajući dimenzijski konzistentan analitički okvir za usporedbu različitih logističkih strategija te empirijski podupire tvrdnje da integracija operativnih poboljšanja s dugoročnim strukturnim promjenama predstavlja ključni preduvjet ostvarivanja punog potencijala kružne ekonomije (Govindan et al., 2015; McKinnon, 2018).

8. ZAKLJUČAK

Glavni nalazi ovoga rada upućuju na zaključak da se uloga logistike u kružnoj ekonomiji značajno razlikuje od njezine tradicionalne funkcije u linearnom modelu gospodarstva. Umjesto jednostavne distribucije proizvoda, logistika u kružnom gospodarstvu obuhvaća upravljanje složenim, višesmjernim tokovima sirovina, proizvoda i otpada. Posebno se ističe važnost povratne logistike, koja omogućuje prikupljanje, razvrstavanje i ponovno uključivanje materijala u procese proizvodnje i/ili reciklaže. Istodobno, upravljanje tokovima proizvoda koji ne mogu biti predmetom reciklaže zahtijeva posebnu pažnju u pogledu sigurnosti, usklađenosti s propisima i ekološki prihvatljivog zbrinjavanja. Ove spoznaje potvrđuju da logistička rješenja u kružnoj ekonomiji moraju biti prilagođena specifičnostima različitih vrsta materijalnih tokova. Stoga se daljnji razvoj kružne ekonomije ne može promatrati bez sustavnog unaprjeđenja logističkih sustava, uključujući primjenu digitalnih tehnologija i odgovarajućih regulatornih poticaja.

Predloženi metodološki pristup povezuje teorijski koncept kružne ekonomije s mjerljivim logističkim ishodima te pruža analitičku podlogu za donošenje operativnih i strateških odluka u području kružne logistike. Ograničenja predloženog pristupa proizlaze iz činjenice da korišteni energetski i emisijski intenziteti predstavljaju prosječne vrijednosti te da model ne uključuje dinamičke promjene ponašanja korisnika, kao ni prostornu strukturu logističkih mreža. Buduća istraživanja trebala bi se usmjeriti na kvantitativnu analizu učinaka kružne logistike, kao i na razvoj inovativnih logističkih modela koji će dodatno unaprijediti učinkovitost i održivost kružnih gospodarskih sustava.

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Preliminary Communication

THE ROLE OF LOGISTICS IN THE CIRCULAR ECONOMY: A QUANTITATIVE APPROACH TO REVERSE FLOW EFFICIENCY

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ABSTRACT

This paper examines the place and role of logistics in the circular economy with a specific focus on the quantitative evaluation of reverse material flow efficiency. Building on the conceptual foundations of the circular economy, an integrated quantitative methodological framework is developed to analyse the relationship between logistical inputs—namely transport work, energy consumption, and emissions—and useful outputs in the form of secondary raw materials. The methodology is based on scenario analysis comparing a reference state with alternative configurations involving operational optimisation and structural changes in the logistics system, including modal shift and transport electrification. The results indicate that operational improvements yield limited but measurable gains in resource efficiency and reductions in the carbon intensity of reverse flows, whereas structural logistics interventions generate substantially larger long-term effects. The findings confirm that logistics constitutes a critical operational mechanism for the implementation of circular economy principles and underscore the importance of quantitative modelling in the evaluation and design of sustainable logistics strategies.

Keywords: *circular economy, logistics, reverse logistics, recycling, sustainability, quantitative modelling, resource efficiency*

Stručni rad

DIGITALNA TRANSFORMACIJA LOGISTIČKIH SUSTAVA KAO ČIMBENIK POSLOVNE USPJEŠNOSTI PODUZEĆA

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SAŽETAK

Digitalna transformacija postaje ključni razvojni mehanizam povećanja konkurentnosti poduzeća te ima snažan utjecaj na strukturu troškova, produktivnost i logističku učinkovitost. U radu se analizira uloga digitalnih tehnologija (ERP, WMS, TMS, IoT, AI i automatizacija) u optimizaciji logističkih sustava te njihov doprinos poboljšanju poslovne uspješnosti Temeljem teorijskog okvira i konceptualnog modela provodi se preliminarno istraživanje na uzorku od 42 poduzeća iz Republike Hrvatske. Rezultati potvrđuju pozitivnu povezanost između razine digitalne zrelosti i ekonomskih pokazatelja uspješnosti, uz naglašene učinke na smanjenje troškova (–9,8 %) i povećanje produktivnosti (+14 %).Rad ukazuje na potrebu jačeg ulaganja u digitalnu transformaciju logistike, osobito u malim i srednjim poduzećima, te predstavlja teorijski i empirijski doprinos razumijevanju ekonomskih učinaka digitalizacije logističkih sustava u hrvatskom gospodarstvu.

Ključne riječi: *digitalna transformacija; Industrija 4.0; ekonomija poduzeća; logistika; poslovna uspješnost*

1. UVOD

Digitalna transformacija predstavlja temeljni čimbenik razvoja suvremenog gospodarstva i jedan je od ključnih izvora povećanja produktivnosti u poslovnom sektoru. U uvjetima globalizacije, volatilnosti tržišta i rastućih zahtjeva kupaca, sposobnost poduzeća da učinkovito integriraju digitalne tehnologije u logističke sustave postaje strateški uvjet konkurentnosti (Porter i Heppelmann, 2015). Logistika se pritom više ne promatra isključivo kao operativna funkcija, već kao ekonomski podsustav poduzeća s izravnim učinkom na troškovnu strukturu, profitabilnost i stvaranje dodane vrijednosti (Christopher, 2016).

Primjenom ERP (Planiranje resursa poduzeća), WMS (Sustav za upravljanje skladištem), TMS (Sustav za upravljanje transportom) i IoT sustava (Internet stvari) postiže se smanjenje transakcijskih i operativnih troškova, povećanje točnosti isporuke i ubrzanje protoka informacija, što dovodi do rasta ekonomskih performansi poduzeća (Bowersox, Closs i Cooper, 2019). U tom se kontekstu digitalna transformacija logistike promatra kao investicija s pozitivnim povratom (ROI) te kao izvor dugoročne tržišne održivosti i otpornosti.

Cilj rada je analizirati ekonomske učinke digitalne transformacije logističkih sustava poduzeća u Republici Hrvatskoj te istražiti u kojoj mjeri razina digitalne zrelosti logističkih

procesa utječe na ključne pokazatelje poslovne uspješnosti. U radu se polaze sljedeća istraživačka pitanja:

RQ1: Kako digitalna transformacija logistike utječe na strukturu troškova i profitabilnost poduzeća?
RQ2: Koje tehnologije imaju najveći ekonomski učinak u procesu optimizacije logističkih aktivnosti?
RQ3: Može li se razina digitalne zrelosti logističkog sustava smatrati prediktorom ukupne poslovne uspješnosti poduzeća?

Metodološki pristup temelji se na teorijskoj analizi te izradi konceptualnog modela koji prikazuje odnose između digitalne transformacije logistike i poslovnih performansi poduzeća. Rezultati rada predstavljaju podlogu za buduća empirijska istraživanja, kao i smjernice za menadžere i donositelje odluka u poslovnoj praksi.

2. TEORIJSKI OKVIR

2.1. Logistički sustavi kao ekonomski podsustav

Logistički sustavi predstavljaju temeljni dio poslovnog sustava poduzeća, a odnose se na integrirano upravljanje tokovima materijala, informacija i financija između dobavnih izvora, proizvodnje i isporuke krajnjem kupcu (Christopher, 2016). Logistika doprinosi poslovnoj uspješnosti kroz:

- smanjenje transakcijskih i operativnih troškova,
- povećanje brzine protoka informacija,
- optimizaciju zaliha te
- povećanje kvalitete usluge i točnosti isporuke.

Udio logističkih troškova u ukupnim troškovima poslovanja iznosi 10 % do 25 %, ovisno o djelatnosti (Ballou, 2004), dok suvremene studije potvrđuju da digitalna transformacija može smanjiti logističke troškove za 8–15 % godišnje (Ivanov, 2022; Deloitte, 2023).

2.2. Industrija 4.0 i logistika 4.0

Koncept Industrije 4.0 podrazumijeva integraciju fizičkih, informacijskih i komunikacijskih sustava u jedinstveni digitalni ekosustav koji omogućuje automatizaciju, razmjenu podataka u stvarnom vremenu i inteligentno upravljanje poslovnim procesima. Riječ je o razvojnoj paradigmi koja se temelji na primjeni cyber-fizičkih sustava, Interneta stvari, umjetne inteligencije, napredne analitike i autonomnih tehnologija u cilju povećanja učinkovitosti i prilagodljivosti poslovanja (Kagermann, 2013).

U kontekstu logistike i upravljanja opskrbnim lancem navedeni koncept razvija se u okviru pojma Logistika 4.0, koji označava primjenu digitalnih tehnologija radi optimizacije tokova robe, informacija i resursa. Takav pristup omogućuje veću transparentnost procesa, preciznije planiranje, bolju koordinaciju između sudionika opskrbnog lanca te smanjenje troškova poslovanja. Logistika 4.0 stoga ne predstavlja samo tehnološko unaprjeđenje logističkih aktivnosti, nego i strateški okvir za povećanje konkurentnosti i poslovne uspješnosti poduzeća.

Najvažnije tehnološke komponente Logistike 4.0 prikazane su u Tablici 1. Njihova primjena omogućuje unaprjeđenje različitih segmenata logističkog sustava, od planiranja resursa i upravljanja skladištem do optimizacije prijevoza, praćenja pošiljki i automatizacije operativnih procesa. Pritom se njihov doprinos ne očituje samo u tehnološkoj modernizaciji, nego i u mjerljivim ekonomskim učincima, kao što su smanjenje administrativnih i logističkih troškova, povećanje produktivnosti, racionalnije upravljanje zalihama i veća točnost izvršenja logističkih aktivnosti.

Tablica 1. Tehnološke komponente Logistike 4.0 i njihov ekonomski učinak

Tehnologija	Puni naziv	Ključna funkcija	Ekonomski učinak
ERP	Enterprise Resource Planning (Planiranje resursa poduzeća)	Integracija planiranja resursa i podataka	Smanjenje administrativnih troškova
WMS	Warehouse Management System (Sustav za upravljanje skladištem)	Upravljanje zalihama, lokacijama i procesima	Smanjenje nepotrebnih zaliha i gubitaka
TMS	Transport Management System (Sustav za upravljanje transportom)	Planiranje ruta, praćenje pošiljki i optimizacija prijevoza	Smanjenje troškova prijevoza
IoT	Internet of Things (Internet stvari)	Senzori, GPS nadzor i povezani uređaji	Učinkovitija kontrola procesa u realnom vremenu
AI	Artificial Intelligence (Umjetna inteligencija)	Prediktivna analitika i donošenje odluka na temelju podataka	Povećanje produktivnosti
Automatizacija	AGV/AMR robotika i automatske linije	Automatizacija skladišnih i operativnih procesa	Operativna učinkovitost i veća točnost

Izvor: Autorova obrada prema: Kagermann (2013), Deloitte (2023), Ivanov (2022).

Na temelju prikazanih obilježja može se zaključiti da digitalna transformacija logističkih procesa ne treba biti promatrana isključivo kao tehničko-tehnološko pitanje, nego kao investicijski i upravljački model s mogućnošću ostvarivanja pozitivnog povrata na ulaganje. U tom smislu, Logistika 4.0 predstavlja važan instrument ekonomske racionalizacije, povećanja operativne učinkovitosti i dugoročnog jačanja tržišne otpornosti poduzeća.

2.3. Hrvatski kontekst

Prema DESI indeksu (2024.), Hrvatska bilježi rast digitalne zrelosti, ali sektor logistike zaostaje u usporedbi s financijskim i telekomunikacijskim sektorom (Eurostat, 2024).

Prepreke digitalizaciji logistike u RH uključuju:

- nedostatak stručnog kadra za napredne digitalne alate,
- ograničene investicijske kapacitete MSP sektora,
- nisku implementaciju IoT i AI rješenja te
- manjak integracije među sustavima (Dujak, 2023; Deloitte, 2023).

Time se potvrđuje da logistika u Hrvatskoj zaostaje u odnosu na sektore s većom dodanom vrijednošću, ali istodobno posjeduje značajan potencijal za ubrzani rast produktivnosti.

2.4. EU kontekst i strateški okvir

Europska unija digitalnu transformaciju logistike jasno povezuje s ekonomskom strategijom rasta (EC, 2022). Kroz programe *Digital Europe*, *Horizon Europe* i *CEF Transport* dostupna su sredstva za financiranje ulaganja u digitalne tehnologije u logistici.

Za hrvatska poduzeća, to posebno znači mogućnosti investicija u:

- ERP/WMS/TMS implementacije
- automatizaciju skladišta
- senzorska rješenja u transportu te
- pametno planiranje ruta.

2.5. Konceptualni model

Konceptualni model istraživanja:

Digitalna zrelost → Operativna učinkovitost → Troškovna racionalizacija → Poslovna uspješnost

Model predviđa da poduzeća s većom digitalnom zrelošću imaju bolji ROI**,** manje logističke troškove **i** veću profitabilnost**.**

Ovaj konceptualni model istraživanja temelji se na teorijskoj pretpostavci da digitalna zrelost djeluje kao inicijalna varijabla koja potiče operativne i financijske mehanizme unaprjeđenja logističkog sustava. Time se operacionalizira logički slijed: (1) implementacija tehnologije → (2) smanjenje transakcijskih i operativnih troškova → (3) optimizacija resursnih tokova → (4) rast poslovne uspješnosti. Model je u skladu s pristupom upravljanja opskrbnim lancima koji digitalnu transformaciju promatra kao strategiju ekonomske valorizacije logističkih procesa, a ne samo kao tehnološko unapređenje (Porter i Heppelmann, 2015; Kagermann, 2013). Na taj način stvara se teorijska osnova za postavljene hipoteze i interpretaciju empirijskih rezultata.

3. METODOLOGIJA ISTRAŽIVANJA

Istraživanje je eksplanatornog karaktera jer nastoji utvrditi odnose među varijablama. Podaci su analizirani metodama deskriptivne statistike i Pearsonove korelacije za testiranje hipoteza i provedeno je tijekom 2025. godine korištenjem online anketnog upitnika. Istraživanje ima karakter pilot empirijskog istraživanja kojim se preliminarno ispituju odnosi između digitalne zrelosti logističkih sustava i poslovne uspješnosti poduzeća. Rezultati imaju indikativni karakter i služe kao temelj za daljnja empirijska istraživanja na većem i reprezentativnijem uzorku poduzeća.

Osim korelacijske analize, provedena je i deskriptivna statistička analiza (prosjek i standardna devijacija) kako bi se dobio uvid u distribuciju ključnih varijabli istraživanja.

Veličina uzorka: 42 poduzeća.

Djelatnosti: proizvodnja 31 %, trgovina 43 %, logističke usluge 21 %, ostalo 5 %. Ciljana skupina: voditelji logistike, menadžeri nabave, direktor/član uprave.

Anketni upitnik sastojao se od 12 pitanja raspoređenih u tri tematske cjeline:

(1) razina digitalne zrelosti logističkih sustava,

(2) implementacija digitalnih tehnologija (ERP, WMS, TMS, IoT i AI),

(3) percepcija ekonomskih učinaka digitalne transformacije. Primjer tvrdnje korištene u mjerenju digitalne zrelosti bio je:

„Digitalni logistički sustavi u našem poduzeću integrirani su s ključnim poslovnim procesima.“

Mjerni instrument koristi Likert skale (1–5), nominalne i otvorene varijable. Testirane hipoteze:

H1: Poduzeća s višom razinom digitalne zrelosti ostvaruju veće smanjenje logističkih troškova.
H2: Implementacija ERP/WMS/TMS sustava pozitivno utječe na ROI i produktivnost.
H3: Digitalna transformacija logistike pozitivno korelira s povećanjem profitabilnosti poduzeća.

Validacija instrumenta provedena je kroz početnu testnu fazu pouzdanosti (Cronbach α = 0,81), što upućuje na zadovoljavajuću pouzdanost upitnika (Hair et al., 2021).

Kako bi se osigurala dodatna metodološka transparentnost, istraživanje je koncipirano kao pilot empirijsko istraživanje koje služi za preliminarno testiranje konceptualnog modela digitalne zrelosti logističkih sustava. Pilot pristup omogućuje identifikaciju osnovnih odnosa među varijablama prije provedbe opsežnijeg empirijskog istraživanja na većem uzorku

poduzeća. U skladu s tim, rezultati istraživanja imaju indikativni karakter te služe kao analitička osnova za buduća istraživanja u području digitalne transformacije logistike u hrvatskom gospodarstvu. Naime, pilotni empirijski dizajn omogućuje preliminarno testiranje konceptualnih odnosa između digitalizacije i pokazatelja ekonomske uspješnosti, pružajući temelj za buduća istraživanja na većem i statistički reprezentativnom uzorku.

Procjene ekonomskih učinaka (npr. –9,8 % smanjenja troškova i +14 % povećanja produktivnosti) temelje se na subjektivnim procjenama ispitanika prikupljenima putem Likertove skale. Ispitanici su procjenjivali očekivani raspon promjena logističkih troškova i produktivnosti nakon implementacije digitalnih sustava, a prosječne vrijednosti transformirane su u indikativne postotne promjene radi lakše interpretacije rezultata.

4. REZULTATI I RASPRAVA

Prije analize odnosa među varijablama provedena je deskriptivna statistička analiza kako bi se dobio osnovni uvid u distribuciju ključnih konstrukata istraživanja. Deskriptivna statistika omogućuje preliminarnu procjenu razine digitalne zrelosti logističkih sustava te percepcije ekonomskih učinaka digitalne transformacije među promatranim poduzećima. Prosječne vrijednosti (M) i standardne devijacije (SD) korištene su kao indikatori centralne tendencije i disperzije podataka, čime se omogućuje bolja interpretacija rezultata pilot istraživanja.

Tablica 2. Deskriptivna statistika ključnih varijabli istraživanja

Varijabla	Prosjek (M)	Standardna devijacija (SD)
Digitalna zrelost logističkog sustava	3,72	0,81
Implementacija ERP/WMS/TMS sustava	3,54	0,87
Procjena smanjenja logističkih troškova	3,61	0,76
Procjena povećanja produktivnosti	3,84	0,69
Procjena utjecaja na profitabilnost	3,42	0,74

Izvor: autorova obrada

Deskriptivna statistika ukazuje na umjereno visoku razinu digitalne zrelosti logističkih sustava u promatranom uzorku poduzeća (M = 3,72). Najvišu prosječnu vrijednost bilježi procjena povećanja produktivnosti (M = 3,84), dok je najniža vrijednost zabilježena kod procjene utjecaja digitalne transformacije na profitabilnost (M = 3,42). Dobiveni rezultati potvrđuju da ispitanici percipiraju digitalizaciju logistike prvenstveno kao instrument povećanja operativne učinkovitosti.

4.1. Digitalna zrelost

Promatrano po djelatnostima, najvišu razinu digitalne zrelosti iskazuju poduzeća iz sektora trgovine (61 %) **i** proizvodnje (57 %), što je u skladu s činjenicom da se ta poduzeća češće susreću s kompleksnijim operativnim sustavima i potražnjom za većom procesnom automatizacijom.

Najnižu digitalnu zrelost iskazuju MSP poduzeća iz sektora logističkih usluga (29 **%**), koja se dominantno oslanjaju na manualne procese i tradicionalne modele upravljanja.

Dodatno, procjena digitalne zrelosti ukazuje da postoji jaz između tehničke implementacije i organizacijske prilagodbe, odnosno da poduzeća koja uvode digitalna rješenja ne ostvaruju automatski puni ekonomski učinak ako ne razvijaju interne kompetencije i analitičke procese

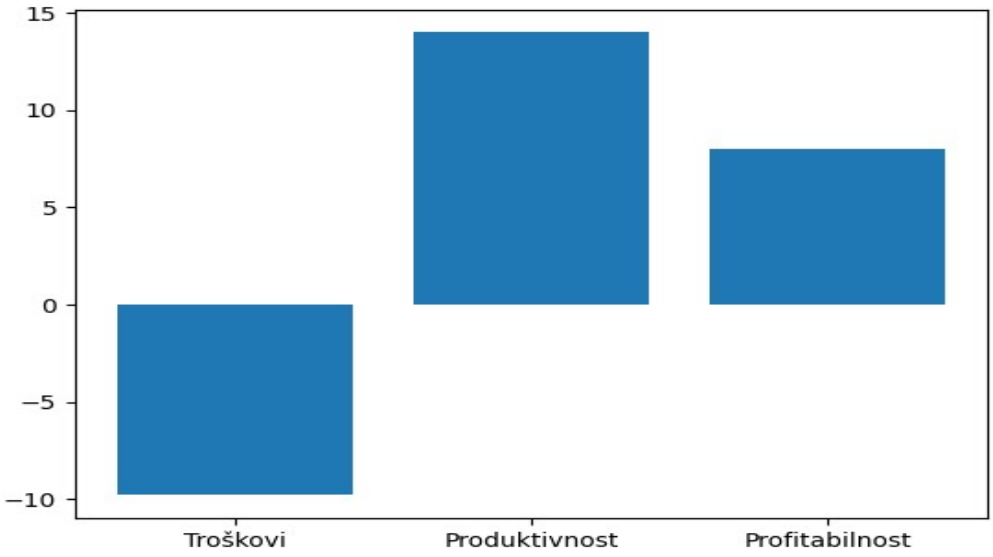
odlučivanja. Ovaj nalaz je važan jer potvrđuje da je digitalizacija logistike organizacijski, a ne samo tehnološki proces, što je u skladu sa suvremenim teorijskim modelima poslovne transformacije (Kagermann, 2013; Deloitte, 2023).

Ovi nalazi potvrđuju da je digitalna zrelost presudan preduvjet za ostvarivanje ekonomskih učinaka, što se u nastavku detaljnije prikazuje kroz kvantitativne pokazatelje poslovne uspješnosti.

4.2. Ekonomski učinci

Procijenjeni ekonomski učinci digitalne transformacije potvrđuju statistički značajne pomake u ključnim pokazateljima poslovne uspješnosti, i to: (a) prosječno smanjenje logističkih troškova za –9,8 %, (b) prosječno povećanje produktivnosti za +14 %, te (c) pozitivan neto doprinos profitabilnosti od 3,9 na Likertovoj skali (1–5).

Grafikon 1. Procijenjeni prosječni ekonomski učinci digitalne transformacije logistike na uzorku od 42 poduzeća



Izvor: Autorova obrada

Podaci upućuju na to da digitalna transformacija ima materijalno mjerljiv utjecaj na financijsku strukturu poslovanja. U prosjeku, smanjenje logističkih troškova od 9,8 **%** predstavlja snažan indikativni pokazatelj potencijalnog **rasta neto profitne marže**, osobito u sektorima s visokim udjelom logističkih troškova u strukturi rashoda (trgovina, distribucija i proizvodnja).

Produktivnost rada povećava se 14 **%**, što upućuje na pozitivne učinke automatizacije i digitalne koordinacije tokova informacija, dok se učinak profitabilnosti (Likert prosjek 3,9) može smatrati srednje jakim zbog neujednačenog ulaganja i različite faze implementacije među poduzećima.

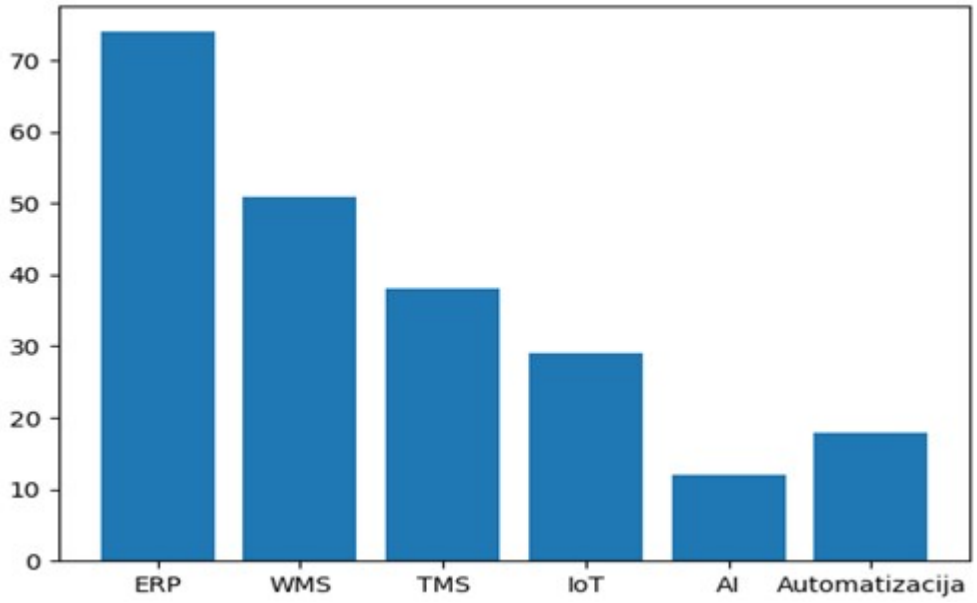
Ovaj nalaz potvrđuje tezu da će se financijski učinci jačati proporcionalno stupnju integracije tehnologije u cjelokupan logistički proces.

Stoga se učinci mogu smatrati ekonomski značajnima, iako u pojedinim slučajevima ograničenima zbog parcijalne implementacije i niske digitalne zrelosti.

4.3. Implementirane tehnologije

Promotrimo li učestalost implementacije po tehnologijama (Tablica 1), vidljivo je da ERP sustavi imaju najvišu stopu primjene (74 **%**) što potvrđuje da je integrirano planiranje resursa temelj za daljnji razvoj digitalnih poslovnih modela.

Grafikon 2. Učestalost primjene digitalnih tehnologija u logistici na uzorku od 42 poduzeć (%)



Izvor: Autorova obrada (2025).

Međutim, iako su ERP sustavi široko rasprostranjeni, ne ostvaruju sva poduzeća u potpunosti analitički potencijal ERP-a, što se najčešće pripisuje nedostatku kadrova i ograničenom korištenju naprednih modula.

Tablica 3. Učestalost implementacije digitalnih tehnologija i njihovi ekonomski učinci u uzorku poduzeća

Tehnologija	**Učestalost u uzorku**	**Primarni ekonomski učinak**	**Prepreke implementaciji**
ERP – Planiranje resursa poduzeća	74 %	smanjenje administrativnih troškova i vremena obrade narudžbi	trošak inicijalne implementacije
WMS – Sustav za upravljanje skladištem	51 %	smanjenje pogrešaka, bolja kontrola zaliha	potreba za edukacijom zaposlenika
TMS – Sustav upravljanja transportom	38 %	optimizacija ruta i goriva	nedostatak kadrova za rad sustava
IoT – Internet stvari	29 %	praćenje pošiljki u realnom vremenu	tehnološka infrastruktura
AI – Umjetna inteligencija	12 %	prediktivno planiranje opskrbe	nedostatak kompetencija
Automatizacija (AGV/AMR robotika)	18 %	skraćenje ciklusa obrade i povećanje kapaciteta	investicijski trošak

Izvor: Autorova obrada prema: Kagermann (2013), Deloitte (2023), Ivanov (2022).

WMS sustavi postižu značajan učinak u kontekstu smanjenja grešaka i optimizacije zaliha (51 % implementacije), čime izravno doprinose povećanju obrtaja zaliha i smanjenju neaktivne imovine.

TMS sustavi bilježe nižu razinu primjene (38 **%**), ali imaju izrazito pozitivan učinak na troškovnu strukturu prijevoza — u prosjeku smanjuju troškove goriva i rute između **6 %** i 11 **%**, ovisno o složenosti mreže distribucije.

Za razliku od navedenog, primjena IoT sustava (29 **%**) i umjetne inteligencije (12 **%**) još je u fazi rane difuzije, što se može pripisati višim početnim ulaganjima i tehnološkim zahtjevima. Ipak, upravo su IoT i AI najsnažniji potencijalni nositelji budućih konkurentskih prednosti, posebice u prediktivnom upravljanju zalihama, praćenju pošiljki u realnom vremenu i optimizaciji prijevoznih kapaciteta (Tiwari, 2023; Zhu, 2024).

4.4. Statistička provjera hipoteza

Dobiveni koeficijenti korelacije ukazuju kako je najjači odnos vidljiv kod H2 (r = 0,61), što potvrđuje hipotezu da tehnologije usmjerene na planiranje, skladištenje i transport imaju najkonkretniji i najbrži financijski učinak.

Hipoteza H1 također je potvrđena (r = 0,52), pri čemu je utjecaj digitalne zrelosti na smanjenje troškova najizraženiji u poduzećima s visokim udjelom logističkih aktivnosti u ukupnom procesu poslovanja.

Hipoteza H3 (r = 0,47) ukazuje na umjerenu, ali statistički značajnu povezanost između digitalne logistike i profitabilnosti.

Razlog niže korelacije jest što profitabilnost ovisi o širem skupu varijabli (tržišne cijene, potražnja, konkurencija). Zbog toga je za buduća istraživanja preporučljivo koristiti višestruku regresijsku analizu kako bi se preciznije kvantificirao utjecaj logističkih pokazatelja na profitabilnost.

Tablica 4. Sažetak statističke provjere hipoteza

Hipoteza	Povezanost varijabli	Koeficijent	p vrijednost	Status
H1	Digitalna zrelost → smanjenje troškova	r = 0,52	p < 0,05	prihvaćena
H2	Implementacija ERP/WMS/TMS → ROI i produktivnost	r = 0,61	p < 0,01	prihvaćena
H3	Digitalna logistika → profitabilnost poduzeća	r = 0,47	p < 0,05	prihvaćena

Izvor: Autorova obrada, 2025.

Pearsonova korelacijska analiza potvrđuje statistički značajnu povezanost između digitalne zrelosti logističkih sustava i ključnih pokazatelja poslovne uspješnosti.

4.5. Rasprava

Rezultati potvrđuju da digitalna transformacija logistike generira ekonomske koristi u vidu optimizacije troškova, povećanja produktivnosti i rasta profitabilnosti. Poduzeća s višom digitalnom zrelosti postižu bolje poslovne pokazatelje. Najveći utjecaj imaju ERP i WMS sustavi, dok IoT i AI predstavljaju razvojni potencijal, ali s nižom razinom implementacije. Ovaj proces nije homogen, već se odvija diferencirano prema veličini poduzeća i djelatnosti.

Rezultati dobiveni pilot istraživanjem ukazuju da je najveći stupanj implementacije prisutan u velikim poduzećima iz sektora trgovine i proizvodnje, dok se MSP sektor suočava s ograničenjima kapitala, nedostatkom kadrova i percepcijom rizika ulaganja. Ovakvi rezultati podudaraju se s recentnim europskim pokazateljima prema kojima se razina digitalne zrelosti MSP-a kreće oko 30–40 **%** prosjeka EU-a (Eurostat, 2024; DESI, 2024), što potvrđuje potrebnu ulogu državnih potpora i EU fondova. U kontekstu Republike Hrvatske, posebno je

važna koordinacija Ministarstva gospodarstva, HGK i razvojnih agencija s ciljem ubrzanja investicijskog ciklusa u području digitalne logistike. Rezultati ukazuju na postojanje gospodarskih koristi od digitalne transformacije logistike, ali i na strukturne izazove specifične za hrvatsko gospodarstvo (npr. nedostatak kvalificiranih kadrova, ograničeni investicijski kapacitet MSP-a).

Dobiveni rezultati mogu se dodatno interpretirati u kontekstu europskih pokazatelja digitalne transformacije gospodarstva. Prema DESI indeksu (Digital Economy and Society Index), razina digitalne zrelosti poduzeća u Hrvatskoj još uvijek zaostaje za prosjekom Europske unije, osobito u segmentu integracije digitalnih tehnologija u poslovne procese. Upravo zato rezultati ovog istraživanja potvrđuju važnost ulaganja u digitalne logističke sustave kao jednog od ključnih mehanizama povećanja produktivnosti i konkurentnosti poduzeća u tranzicijskim gospodarstvima. Slične zaključke donose i recentna europska istraživanja koja naglašavaju da digitalna transformacija logistike predstavlja jedan od glavnih pokretača učinkovitosti opskrbnih lanaca u okviru Industrije 4.0 (Ivanov, 2022; Kache i Seuring, 2022). Ovakvi nalazi potvrđuju da digitalna transformacija logističkih sustava predstavlja ne samo tehnološki, već i strateški ekonomski proces koji izravno utječe na strukturu troškova i operativnu učinkovitost poduzeća.

Ovdje se otvara prostor za javne politike i financijske instrumente EU-a, čime logistika postaje strateška točka nacionalne konkurentnosti (Deloitte, 2023; EC, 2022).

4.5.1. Ograničenja istraživanja

Istraživanje ima nekoliko metodoloških ograničenja. Prije svega, uzorak od 42 poduzeća nije reprezentativan za cjelokupno gospodarstvo Republike Hrvatske. Nadalje, dio pokazatelja temelji se na percepciji ispitanika o ekonomskim učincima digitalne transformacije, što može uključivati određeni stupanj subjektivnosti u procjeni.

Rezultati pilot istraživanja imaju indikativni karakter i zahtijevaju dodatnu provjeru na većem i statistički reprezentativnom uzorku.

Buduća istraživanja trebala bi uključivati naprednije metode analize, poput regresijske analize ili strukturnog modeliranja, kako bi se preciznije utvrdili uzročno-posljedični odnosi između digitalne transformacije logistike i poslovnih performansi poduzeća. Osim toga, buduća istraživanja planiraju se proširiti na veći uzorak poduzeća korištenjem kombinacije primarnih i sekundarnih podataka (npr. financijski izvještaji FINA-e, HGK ankete i Eurostat baze), čime bi se omogućila primjena naprednijih statističkih metoda poput višestruke regresijske analize ili strukturnog modeliranja.

4.5.2. Implikacije za poslovnu praksu

Rezultati istraživanja ukazuju na potrebu intenzivnijeg ulaganja u digitalnu transformaciju logistike, osobito u malim i srednjim poduzećima. Ulaganja u sustave ERP, WMS i TMS pokazuju najveći povrat na investiciju te su preporučeni kao početni korak. Nadalje, korištenje EU fondova predstavlja ključni mehanizam financiranja za poduzeća s ograničenim investicijskim kapacitetima.

4.5.3. Studija slučaja: učinci implementacije WMS/TMS sustava u MSP sektoru

Poduzeće X, srednje trgovačko poduzeće iz Slavonije, implementiralo je sustav za upravljanje skladištem i transportom (WMS i TMS) uz djelomičnu primjenu Interneta stvari za praćenje pošiljki. U razdoblju od šest mjeseci zabilježeno je smanjenje zaliha za 11 %, skraćenje prosječnog vremena isporuke za 18 % i povećanje produktivnosti zaposlenika za 13 %. Ukupni logistički troškovi smanjeni su za 8,6 %, što potvrđuje nalaze ovog rada.

Navedeni primjer ukazuje da prelazak s tradicionalnih skladišnih praksi na digitalno potpomognute logističke sustave ima multiplikativne učinke na cjelokupan operativni proces — ne samo na troškove i produktivnost, već i na kvalitetu korisničke usluge, pouzdanost

isporuke i reputaciju poduzeća. U tom smislu, digitalna transformacija postaje izravni instrument unapređenja tržišne pozicije poduzeća, što odgovara literaturi koja logistiku definira kao generatora konkurentske prednosti (Christopher, 2016; Porter i Heppelmann, 2015).

5. ZAKLJUČAK

Digitalna transformacija logistike predstavlja strateški smjer razvoja poduzeća u Hrvatskoj. Empirijski rezultati potvrđuju povezanost između primjene digitalnih tehnologija i poboljšanja poslovne uspješnosti, osobito kroz smanjenje troškova i povećanje produktivnosti. Preporučuje se veća integracija digitalnih rješenja u MSP sektor te korištenje dostupnih EU fondova.

Rad predstavlja doprinos razumijevanju ekonomskih učinaka digitalne transformacije logističkih sustava u hrvatskom gospodarstvu te pruža teorijski i analitički okvir za buduća empirijska istraživanja u području logistike i upravljanja opskrbnim lancima. Rad je praktično i znanstveno značajan jer potvrđuje da digitalizacija logistike nije samo tehnološka modernizacija, već ekonomska nužnost za rast poduzeća i nacionalne konkurentnosti.

Rezultati rada potvrđuju da digitalna transformacija logističkih sustava ima mjerljiv i održiv ekonomski učinak te predstavlja ključan čimbenik povećanja konkurentnosti hrvatskih poduzeća. Uočljivo je da je najveći napredak ostvaren u segmentima planiranja resursa i upravljanja skladištem (ERP i WMS), dok je primjena IoT i AI tehnologija još uvijek u ranoj fazi i predstavlja razvojni potencijal za budućnost.

S teorijskog aspekta, rad potvrđuje valjanost konceptualnog modela prema kojem digitalna zrelost djeluje kao prediktor operativne učinkovitosti i poslovne uspješnosti poduzeća. S praktičnog aspekta, dobiveni nalazi ukazuju na potrebu strateškog planiranja digitalnih ulaganja, jačanja kadrovskih kompetencija i korištenja dostupnih EU fondova kao mehanizma poticanja investicija.

U konačnici, digitalizacija logistike treba se promatrati ne kao opcija, nego kao ekonomska nužnost, osobito u MSP sektoru koji je najosjetljiviji na tržišne promjene i ograničenja resursa. Ovaj rad pruža doprinos nacionalnoj znanstvenoj i stručnoj literaturi te može poslužiti kao temelj za buduća empirijska istraživanja, izradu javnih politika i daljnje unapređenje logističke prakse u Republici Hrvatskoj.

U svrhu ubrzavanja digitalne transformacije logističkih sustava u Republici Hrvatskoj, preporučuju se sljedeće mjere javnih politika i regulatornih intervencija za kreatore politika:

- ciljana alokacija EU fondova (Digital Europe, CEF Transport, Horizon Europe) za financiranje uvođenja ERP/WMS/TMS sustava i senzorskih tehnologija u MSP sektor, uz pojednostavljenje administrativnih procedura;
- programi stručnog usavršavanja i certifikacija kadrova u području digitalne logistike (AI, IoT, podatkovna analitika), u suradnji s visokoškolskim ustanovama, komorama i centrima kompetencija;
- smanjenje regulatornih i administrativnih barijera kroz digitalizaciju logističke dokumentacije, ubrzavanje procesnih procedura (eCMR, e-dokumenti) i poticanje interoperabilnosti informacijskih sustava u nacionalnom logističkom lancu.

Predložene mjere upućuju na potrebu strateškog pristupa razvoju logistike kao ključnog infrastrukturnog i gospodarskog podsustava, čime se stvara institucionalni okvir za održiv rast produktivnosti i konkurentnosti hrvatskih poduzeća.

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Professional paper

DIGITAL TRANSFORMATION OF LOGISTICS SYSTEMS AS A FACTOR OF BUSINESS PERFORMANCE

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ABSTRACT

Digital transformation has become a key strategic mechanism for improving business competitiveness, with a strong impact on cost structure, productivity, and logistics efficiency. This paper analyses the role of digital technologies, including ERP, WMS, TMS, IoT, AI and automation, in optimising logistics systems and improving overall business performance. Based on a theoretical framework and a proposed conceptual model, the study presents a preliminary pilot investigation conducted on a sample of 42 companies in the Republic of Croatia. The findings confirm a positive relationship between the level of digital maturity and economic performance indicators, with notable effects on cost reduction (–9.8%) and productivity growth (+14%).The results highlight the need for stronger investment in the digital transformation of logistics, particularly in small and medium-sized enterprises, and provide a theoretical and empirical contribution to understanding the economic effects of logistics digitalisation in the Croatian economy.

Keywords: *digital transformation; Industry 4.0; enterprise economics; logistics; business performance*

Review

AN APPLICATION OF DIGITALIZATION AND TECHNOLOGY USE IN THE CONTEXT OF LOGİSTICS PROCESS OPTIMIZATION IN MANUFACTURING ENTERPRISES

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ABSTRACT

Today, the optimization of logistics processes in manufacturing enterprises has become a strategic issue of growing importance. The intensification of global competition, the diversification of customer expectations, and uncertainties in supply chains compel manufacturing enterprises to manage their logistics activities in a more effective, flexible, and efficient manner. The recognition of logistics process optimization as a fundamental concept has necessitated the restructuring of business processes related to digitalization and technology use in manufacturing enterprises. In this context, digital technologies such as information and communication technologies, artificial intelligence, big data analytics, the Internet of Things, and automation systems play a critical role in the planning, monitoring, and control of logistics processes. The effective utilization of these technologies provides manufacturing enterprises with significant competitive advantages by reducing costs, shortening delivery times, increasing operational efficiency, and ensuring sustainable logistics performance. Consequently, the factors influencing digitalization and technology use in the context of logistics process optimization are gaining increasing importance and stand out as key components that warrant thorough examination. Within this framework, focusing on the identification of factors affecting digitalization and technology use in the context of logistics process optimization in manufacturing enterprises is of great importance for the effectiveness of business processes. Accordingly, to address the identified research gap, this study employs the SIWEC method to identify and rank the factors influencing digitalization and technology use in the context of logistics process optimization according to their relative importance levels.

Key words: *Logistics Process Optimization, Factors Influencing Digitalization and Technology Use, SIWEC Method.*

1. INTRODUCTION

One of the most critical issues that contemporary businesses must focus on is the effective, economical, and efficient use of resources, as well as ensuring customer satisfaction. The continuous intensification of competition driven by globalization, the diversification of customer expectations, and the transformation of cost considerations into a strategic objective for businesses compel firms to adopt more systematic and holistic management approaches (Nguyen et al. 2025). In this context, various management techniques, elements, and components that enable enterprises to plan, monitor, and control their activities more effectively have gained prominence. Among these techniques, process management particularly logistics process management practices occupies a significant position. Process and logistics process management facilitate the coordinated management of material, information, and financial flows, thereby increasing operational efficiency, contributing to cost reduction, and enabling faster and more flexible responses to customer demands. Moreover,

the implementation of process and logistics process management supports enterprises in gaining a competitive advantage, improving service quality, and achieving a sustainable level of performance. Therefore, from the perspective of contemporary enterprises, process and logistics process management are regarded as strategic management tools (Korucuk, Küçük, 2018). Thus, supply chain and logistics processes constitute an essential part of modern business operations and play a significant role in global development (Min et al. 2019). Accordingly, it can be argued that logistics processes have a decisive impact on outcomes of success or failure, such as customer satisfaction or customer complaints. Optimization in the field of logistics is vital for ensuring the rapid flow of goods and services and plays an important role in achieving competitive advantage and enhancing customer satisfaction. The efficient and effective optimization of logistics processes contributes to reducing company costs and increasing delivery speed, thereby playing a crucial role in ensuring customer satisfaction. Moreover, the proper management of elements such as warehousing, transportation, and supply chain activities directly affects the success of logistics operations. Conversely, disruptions in these processes may result in time losses and increased costs (Göktürk, 2025).

In this respect, process optimization has become more important than ever across the entire supply chain in general, and particularly in the field of logistics. Process optimization involves the detailed analysis and improvement of logistics and supply chain activities to achieve higher efficiency, lower costs, improved service quality, and greater responsiveness. The implementation of these processes ensures the seamless movement of goods from the point of origin to the point of destination in a manner that meets customer needs and aligns with strategic business objectives (Zijm et al. 2018). Moreover, beyond these aspects, enterprises that implement effective process optimization in logistics and supply chain activities even during periods of uncertainty and unprecedented crises can enhance their competitiveness, respond more effectively to market fluctuations, and develop more resilient system structures (Korucuk et al. 2023). In other words, the optimization of an enterprise's business processes is fundamentally grounded in logistics tools and principles. The key determining factors in modern logistics include digitalization, the efficiency of business processes and operations, service quality, and the promotion of technical modernization (Zengwen et al. 2019).

In light of the issues discussed above, identifying the criteria related to digitalization and technology use in the context of logistics process optimization, and systematically ranking these criteria according to their levels of importance, are considered significant from both theoretical and practical perspectives. Accurately defining and prioritizing these criteria enable enterprises to plan their digital transformation processes more effectively, allocate resources more rationally, and develop more precise solutions to the complex problems encountered in logistics activities. Furthermore, analyzing these criteria provides substantial contributions to enterprises by increasing efficiency in logistics processes, reducing costs, improving service quality, and supporting the achievement of sustainable performance objectives. In this context, the identification and evaluation of digitalization and technology related criteria based on their relative importance play a critical role in the success of logistics process optimization.

Identifying and prioritizing these criteria not only provides various value-added benefits for manufacturing enterprises but also significantly enhances their ability to effectively meet efficiency, effectiveness and cost oriented requirements. Through this process, enterprises can ground their strategic decisions regarding digitalization and technology use in the context of logistics process optimization on a more informed basis, allocate limited resources to the most critical areas, and address structural and operational challenges in logistics processes through a systematic approach. Accordingly, this study presents a guiding framework for evaluating digitalization and technology-related criteria in logistics process optimization from a holistic perspective, aiming to help bridge the gaps identified in the literature and to make meaningful contributions to both academic research and industry practice.

Finally, the decision-making framework proposed in this study to address the relevant decision problem enables a systematic analysis of the criteria related to digitalization and technology use in the context of logistics process optimization in manufacturing enterprises. The application of this framework contributes to filling existing theoretical and methodological gaps in the literature and offers novel and valuable perspectives for researchers in the field. From this perspective, the study has the potential to serve as an important reference point, particularly for researchers focusing on decision making problems in the areas of production and supply chain management. In this context, the primary objective of the study is to propose solutions regarding criteria related to digitalization and technology use in the context of logistics process optimization in manufacturing enterprises operating in the province of İzmir by employing the SIWEC method. In this respect, the study aims to contribute to the academic literature while also providing practitioners with a guiding framework for decision-making processes.

2. LITERATURE REVIEW

In this section, national and international studies addressing criteria related to digitalization and technology use in the context of logistics process optimization are systematically reviewed, and the relevant studies are presented in Table 1.

Table 3. Literature Revıew

Author(s)	Year	Objective	Method(s)
Liberko, et al.	2015	They examined the possibilities and approaches for optimizing the logistics chain in manufacturing enterprises.	Statistical Analysis
Dobránsky, et al.	2016	They addressed the use of computer simulation in the process of optimizing material flow through the appropriate spatial layout of production facilities.	Triangular Method
Aksyonov, et al.	2017	The optimization of logistics processes related to the production of metallurgical products was examined.	Evolutionary-Simulation Algorithm
Volodina, et al.	2018	They studied the optimization of logistics business processes based on the implementation of cognitive information technologies.	Literature Review
Sorkun	2019	They examined the relationship between digitalization in logistics operations and Industry 4.0.	Statistical Analysis
Volodina, et al.	2020	Within the context of the development of the digital economy, the theoretical and methodological foundations for creating an export-oriented environment are addressed, and the relationships among logistics business processes in the field of export are analyzed.	Literature Review
Herold, et al.	2021	They evaluated the emergence and adoption of digitalization in the logistics and supply chain industry from an institutional perspective..	Longitudinal Analysis
Gritsenko, et al.	2022	They examined the digitalization of business processes in logistics enterprises under Industry 4.0 conditions.	SWOT Analysis
Kajba, Jereb.	2022	They assessed logistics process optimization through digitalization.	Process Approach
Lagodiienko, et al.	2023	They analyzed the role of digital technologies in optimizing the functioning of the enterprise's marketing and logistics system.	Systematic Approach
Jeong.	2023	They investigated digitalization in production logistics.	Real-Time Data and Machine Learning
Smerichevska, et al.	2024	They examined the digitalization of logistics and supply chain management.	Literature Review
Chen, et al.	2024	They provided an overview of various artificial intelligence models and algorithms used in logistics optimization, with a focus on sustainable practices.	Literature Review
Hongsakul, et al.	2025	They examined logistics activities related to digital transformation in the logistics sector..	Literature Review
Čamaj, et al.	2025	They investigated material flow optimization as a tool for improving logistics processes in companies.	Checkerboard Table Analysis

According to the table presented above, studies addressing criteria related to digitalization and technology use in the context of logistics process optimization are limited. The limited number of systematic and comprehensive studies on the adoption of digital technologies and the digitalization of logistics processes clearly reveals a significant theoretical and practical knowledge gap in the field. This deficiency not only hinders the full development of the theoretical framework in the literature but also restricts managers in the logistics sector from prioritizing criteria related to digitalization and technology use in strategic decision-making processes and from developing effective implementation strategies based on these criteria. In particular, the absence of a systematic approach regarding the interaction of digital technologies with organizational barriers and their impact on process optimization results in a lack of evidence based guidance for decision-makers.

The primary aim of this study is to address this research gap and to examine criteria related to digitalization and technology use in a more systematic manner, considering both theoretical and practical dimensions. The MCDM methods employed in this study enable the prioritization of organizational barriers in logistics enterprises, directly supporting managerial decision making processes. Moreover, the findings go beyond the limited existing studies in the literature, providing a more holistic understanding of digitalization and technology adoption processes. This framework not only contributes to the existing theoretical knowledge but also establishes a methodological foundation for future research, helping to address the systematic knowledge deficiency in the field. In this way, the study contributes both to the deepening of academic literature and to enabling managers in practical applications to plan digitalization strategies more consciously and effectively. This situation indicates a significant gap in the literature, particularly reflecting the lack of systematic studies on the adoption of digital technologies and the digitalization of processes within the logistics sector. This deficiency limits managers' ability to prioritize criteria related to digitalization and technology use in strategic decision making processes and to develop effective implementation practices. The aim of this study is to contribute to filling this gap in the literature by providing new and comprehensive perspectives on criteria related to digitalization and technology use. Additionally, the study seeks to establish a foundation for future research in this field.

3. SIMPLE WEIGHT CALCULATION METHOD

SIWEC was developed to determine the subjective weighting coefficients of criteria in the context of decision-maker or expert evaluations. It is a particularly easy and effective method to apply, especially for experts and decision-makers unfamiliar with MCDA methods. SIWEC is applied by following these steps (Puška et al., 2024).

Phase 1. Experts (E_k) and criteria (C_j) are determined, where $k = 1, \dots, r; j = 1, \dots, n$.

Phase 2**.** Experts evaluate the importance of each criterion on a 9-point scale from 1 (lowest) to 9 (highest).

Phase 3. An initial evaluation matrix $A = [a_{jk}]$ is created. Here, the columns represent the criteria, the rows represent the experts, and the cells correspond to the evaluations.

Phase 4. Normalization is performed using Eq. (1). This creates the normalized evaluation matrix $Z = [z_{jk}]$.

$$z_{jk} = \frac{a_{jk}}{\max(a_{jk})} \tag{1}$$

Phase 5. The standard deviation for each expert (σ_k) is calculated from the normalized evaluation matrix values.

Phase 6. The elements of the normalized evaluation matrix are multiplied by the standard deviation values corresponding to the relevant expert. As a result, the revised normalized evalution matrix $V = [v_{jk}]$ is constructed via Eq. (2).

$$v_{jk} = \sigma_k \times z_{jk} \quad (2)$$

Phase 7. The non-normalized criterion weights are calculated using Eq. (3).

$$\eth_j = \sum_{k=1}^{r} v_{jk} \quad (3)$$

Phase 8. The weighting coefficients of the criteria are calculated using Eq. (4).

$$w_j = \frac{\eth_j}{\sum_{j=1}^{n} \eth_j} \quad (4)$$

where $\sum_{j=1}^{n} w_j = 1$, and $0 \leq w_j \leq 1$.

4. RESULTS

This study examines the criteria related to digitalization and technology use in the context of logistics process optimization in manufacturing enterprises. For this purpose, the SIWEC method was employed. During the process of determining the criteria, opinions were obtained from a total of five experts, including four manufacturing enterprise managers and one academic. The selected experts possess extensive and long-standing experience in both innovation and logistics processes. Their evaluations support the accuracy and reliability of the core findings of our study and also enhance the practical applicability of the results. The experts' deep knowledge in their fields strengthens the methodological consistency of the study and plays a critical role in the interpretation of the collected data. Additionally, the diverse perspectives and experiences of the experts have helped reduce potential biases during the analysis process and ensured a comprehensive consideration of the findings. Future studies involving a larger and more diverse group of experts are expected to increase the generalizability of the results, enabling more robust inferences across different sectors and application contexts. In this way, the outcomes of the study not only contribute to the academic literature but also serve as valuable guidance for practical applications.

The process of defining the criteria was carried out carefully using a combination of literature review and expert opinions. In the first stage, existing theoretical frameworks and previous empirical studies in the field of logistics process optimization and digitalization were examined; then, the potential criteria derived from this literature were evaluated by the expert panel included in the study. The experts discussed the relevance and prioritization of the criteria, ensuring that only those most aligned with the field were selected. This process strengthened both the theoretical grounding of the criteria and the practical validity of the study. In addition, based on a review of the relevant literature and drawing on the studies of Sorkun (2019), Korucuk et al. (2022), Jeong (2023), Görçün et al. (2024) and Aytekin et al. (2025) Table 2 was constructed.

Table 2. The List of Criteria

Codes	Criteria
C1	Organizational Culture (Innovativeness and Openness to Change)
C2	Adequacy of Technological Infrastructure and Capability for Integration with Existing Systems
C3	Employees' Level of Digital Competence and Opportunities for Training and Continuous Learning
C4	Attitudes and Perceptions Toward Technology
C5	Level of Resistance to Change and Employee Engagement and Motivation
C6	Cybersecurity and Data Privacy
C7	Digital Technology Investment Costs
C8	Expected Return on Digital Investments

C9	Suitability of Processes for Digital Transformation and Operational Flexibility
C10	Regulations and Standards, and Government Incentives and Support Policies

The assessments provided by experts are given in Table 3.

Table 3. The Assessments Provided by Experts

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
E1	7	7	6	5	8	9	8	7	5	3
E2	5	5	3	7	7	6	7	5	7	5
E3	5	7	5	7	7	7	7	7	5	5
E4	7	6	7	3	3	7	5	5	3	3
E5	5	5	7	5	7	7	5	7	3	5

The results of the SIWEC are presented in Table 4.

Table 4. The Results of SIWEC

The normalized evaluation matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
E1	0.7778	0.7778	0.6667	0.5556	0.8889	1.0000	0.8889	0.7778	0.5556	0.3333
E2	0.5556	0.5556	0.3333	0.7778	0.7778	0.6667	0.7778	0.5556	0.7778	0.5556
E3	0.5556	0.7778	0.5556	0.7778	0.7778	0.7778	0.7778	0.7778	0.5556	0.5556
E4	0.7778	0.6667	0.7778	0.3333	0.3333	0.7778	0.5556	0.5556	0.3333	0.3333
E5	0.5556	0.5556	0.7778	0.5556	0.7778	0.7778	0.5556	0.7778	0.3333	0.5556

The revised normalized evaluation matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
E1	0.1459	0.1459	0.1251	0.1042	0.1667	0.1876	0.1667	0.1459	0.1042	0.0625
E2	0.0783	0.0783	0.0470	0.1097	0.1097	0.0940	0.1097	0.0783	0.1097	0.0783
E3	0.0605	0.0847	0.0605	0.0847	0.0847	0.0847	0.0847	0.0847	0.0605	0.0605
E4	0.1469	0.1259	0.1469	0.0630	0.0630	0.1469	0.1049	0.1049	0.0630	0.0630
E5	0.0791	0.0791	0.1107	0.0791	0.1107	0.1107	0.0791	0.1107	0.0474	0.0791
ϑ_j	0.5107	0.5139	0.4901	0.4406	0.5347	0.6238	0.5451	0.5245	0.3847	0.3433
w_j	0.1040	0.1046	0.0998	0.0897	0.1089	0.1270	0.1110	0.1068	0.0783	0.0699
Rank	6	5	7	8	3	1	2	4	9	10

As seen in Table 4, the most important criterion is “C6- Cybersecurity and Data Privacy”. The obtained results are consistent with the studies of Moakley (2021), Odimarha et al. (2024), and Reddy and Narayana (2025). The findings on cybersecurity and data privacy emerging from the study can be linked to existing theoretical frameworks and previous empirical research in the context of digitalization and logistics process optimization. In particular, the impact of digital tools and data-driven technologies on operational efficiency, cost-effectiveness, and service quality aligns with the information security and data privacy requirements emphasized in the literature (e.g., Moakley, 2021; Odimarha et al., 2024; Reddy and Narayana, 2025). In this context, the findings of our study support the strategic importance of cybersecurity and data management in digital logistics systems, both theoretically and practically. The findings related to digitalization and technology use in the context of logistics process optimization highlight the decisive role of digital tools and

technologies in enhancing operational efficiency, cost-effectiveness and service quality. In particular, technologies such as data analytics, AI-supported planning systems, sensor technologies and digital twins enable more effective management of material flows and operational activities. The results also indicate that cybersecurity and data privacy are critical criteria in process optimization, as secure data management is a fundamental requirement for uninterrupted operations, accurate decision-making, and sustainable management in digitalized logistics systems. In this context, as logistics enterprises implement their digital transformation strategies, strengthening technological infrastructure, enhancing employees' digital competencies, and integrating secure data management measures are of critical importance for both optimizing operations and enhancing competitive advantage. In conclusion, digitalization and technology use emerge as both a strategic opportunity and a risk area that must be managed in the optimization of logistics processes and the achievement of sustainable efficiency.

5. CONCLUSION

In modern enterprises, digitalization and technological transformation have become key driving forces of the global economy. Digital technological transformation has significantly enhanced business performance in the context of logistics process optimization, contributed to the efficient use of resources and enabled improvements in product and service quality. Beyond these operational benefits, it has facilitated the effective planning and management of supply chain processes using real-time data, smart devices and intelligent systems thereby contributing to greater transparency, flexibility and responsiveness in operations. Moreover, digital technologies reinforce data driven decision making mechanisms, enabling more effective execution of critical logistics activities, including demand forecasting, inventory management and transportation planning. In this context, digitalization emerges as a strategic factor that not only enhances the operational efficiency of logistics enterprises but also facilitates the attainment of competitive advantage and sustainable growth.

In this context, the present study analyzed the criteria related to digitalization and technology use for logistics process optimization in manufacturing enterprises operating in the province of İzmir. The findings indicate that the most important criterion in digitalization and technology use for logistics process optimization is "Cybersecurity and Data Privacy. Vulnerabilities in these areas pose serious threats not only to operational continuity but also to an enterprise's competitive advantage and corporate reputation. Furthermore, the adoption of a robust cybersecurity infrastructure and effective data privacy policies is considered a fundamental requirement for the secure and sustainable utilization of digital technologies in logistics process optimization.

Conversely, "Regulations and Standards, and Government Incentives and Support Policies" were identified as the lowest priority criteria. This suggests that, in logistics enterprises, the legal framework and public support are not perceived as direct determining factors in the adoption of digital technologies. Nevertheless, in the long term, the establishment of clear and directive regulations, along with effective incentive mechanisms, could substantially contribute to accelerating the digital transformation process and ensuring a sustainable framework.

Overall, this study can be regarded as a guiding effort that addresses a significant gap in the literature on digitalization and technology use in the context of logistics process optimization in the examined manufacturing enterprises. The findings offer valuable insights for enterprises in developing policies and strategies concerning digitalization and technology use within the scope of logistics process optimization. These findings provide decision makers with a clearer understanding of which areas should be prioritized during the technological transformation process, enabling digital investments to be guided in a more planned, effective, and sustainable manner. Additionally, the results offer strategic insights for enterprises to enhance operational efficiency, strengthen competitive advantage and align digital transformation processes with long term corporate objectives.

In future research, this topic could be examined more comprehensively and in greater depth using various Multi Criteria Decision Making (MCDM) methods. Such an approach would allow for comparisons across different analytical techniques, enabling the assessment of the consistency and reliability of the findings. Furthermore, methodological diversity would facilitate the generation of more robust and generalizable results concerning decision-making processes.

Furthermore, existing analyses could be extended and restructured more comprehensively using alternative fuzzy logic based methods or hybrid multi criteria decision-making models. Such approaches would allow for a multidimensional evaluation of digitalization and technology use in the context of logistics process optimization in manufacturing enterprises, enabling a comparative assessment of the robustness and consistency of the findings. Studies conducted along these lines would provide significant theoretical and practical contributions to the literature on sustainable technology management, while also guiding enterprises in shaping their digital transformation strategies more effectively and holistically.

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Pregledni rad

PRIMJENA DIGITALIZACIJE I UPORABA TEHNOLOGIJE U OPTIMIZACIJI LOGISTIČKIH PROCESA U PROIZVODNIM PODUZEĆIMA

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SAŽETAK

Danas je optimizacija logističkih procesa u proizvodnim poduzećima postala strateško pitanje od sve veće važnosti. Jačanje globalne konkurencije, sve raznolikija očekivanja kupaca i neizvjesnosti u opskrbnim lancima prisiljavaju proizvodna poduzeća da svojim logističkim aktivnostima upravljaju na učinkovitiji, fleksibilniji i djelotvorniji način. Prepoznavanje optimizacije logističkih procesa kao temeljnog koncepta nametnulo je potrebu za restrukturiranjem poslovnih procesa povezanih s digitalizacijom i uporabom tehnologije u proizvodnim poduzećima. U tom kontekstu digitalne tehnologije, kao što su informacijsko-komunikacijske tehnologije, umjetna inteligencija, analitika velikih podataka, internet stvari i automatizacijski sustavi, imaju ključnu ulogu u planiranju, praćenju i kontroli logističkih procesa. Učinkovita primjena tih tehnologija proizvodnim poduzećima osigurava značajne konkurentske prednosti kroz smanjenje troškova, skraćivanje vremena isporuke, povećanje operativne učinkovitosti i osiguravanje održive logističke uspješnosti. Slijedom toga, čimbenici koji utječu na digitalizaciju i uporabu tehnologije u kontekstu optimizacije logističkih procesa dobivaju sve veću važnost te se ističu kao ključne sastavnice koje zahtijevaju temeljito istraživanje. U tom je okviru usmjerenost na utvrđivanje čimbenika koji utječu na digitalizaciju i uporabu tehnologije u kontekstu optimizacije logističkih procesa u proizvodnim poduzećima od velike važnosti za učinkovitost poslovnih procesa. Sukladno tome, kako bi se odgovorilo na utvrđeni istraživački jaz, u ovom se radu primjenjuje metoda SIWEC radi identifikacije i rangiranja čimbenika koji utječu na digitalizaciju i uporabu tehnologije u kontekstu optimizacije logističkih procesa prema njihovoj relativnoj razini važnosti.

Ključne riječi: *optimizacija, logistički procesi, čimbenici digitalizacije i uporabe tehnologije, metoda SIWEC*

Preliminary Communication

THE IMPACT OF DIGITAL TRANSFORMATION OF LOGISTICS AND DISTRIBUTION ON CUSTOMER EXPERIENCE

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ABSTRACT

Based on the growing presence of online shopping and the increasing adoption of digital logistics and distribution activities related to goods delivery, this paper theoretically and empirically examines customer satisfaction with delivery services for ordered goods and possible improvements. The aim of the research is to investigate the level of customer satisfaction with delivery services in online shopping. Furthermore, specific elements of distribution services are examined: delivery speed and accuracy, customer information and digital shipment tracking, and overall customer satisfaction. The research sample consists of users who have used online shopping services with home delivery or delivery to a specific location (parcel lockers). The sample included students of higher education institutions who had experience with online shopping and delivery services. The research instrument was a structured questionnaire consisting of 10 questions, divided into four thematic sections (online shopping habits, satisfaction with delivery, tracking and information about shipments, and overall satisfaction and perceptions of possible improvements in delivery services). The questionnaire was distributed via a Google Form, which was available to respondents from December 10 to December 23, 2025. Statistical data analysis was conducted using the JASP software. The obtained research results indicate a significant relationship between the quality of digital logistics services and overall customer satisfaction. Given the accelerated growth of online shopping and the increasing frequency of goods delivery, the development of digital logistics and distribution aimed at improving customer experience represents a strong foundation for building competitiveness in the logistics and distribution sector, as well as in e-commerce. Therefore, the research results provide a valuable basis for further improvement of distribution and logistics services.

Keywords: *Logistics, distribution, online shopping, customer satisfaction with delivery services*

1. INTRODUCTION

The digital transformation of logistics and distribution is an extremely topical topic when it comes to improving the quality of work and, consequently, all the changes that have occurred in modern supply chains.

The supply chain was evaluated from a simple structure to a complex one with a dynamic connection of all logistics elements (Choi, Ivanov, & Pesch, 2022); (Sawik, 2023).

Technology is constantly evolving, and it is impossible to imagine a competitive business without investing and applying it. The development of technologies such as the Internet is

used every day in both business and private life. In terms of logistics and distribution, the use of artificial intelligence, blockchain and warehouse systems that are automated, greatly affect the new way of management related to planning, organizing, leadership, human resources and controlling applications.

Logistics processes are managed consciously, nothing is left to chance, which has made a big positive step forward in business. Logistics is no longer an operational function but has become a strategic instrument of competitive advantage, especially in the context of customer experience management. Furthermore, digitalisation contributes to increased efficiency, reduced costs and greater transparency of the supply chain, but at the same time poses new challenges related to data management, cybersecurity and system integration. In its beginnings, the supply chain was a simple process, but over the years it has evolved into a complex process in which it is possible to make significant improvements in savings, as well as the application of new IT knowledge and technologies. Traditional supply chain management systems, while effective in improving short-term results, show limitations in anticipating future requirements and applying effective responses as well as providing holistic visibility. Customer experience is becoming a key determinant of a company's competitiveness. Customer satisfaction becomes the primary goal of every service company. It is shaped through all phases of ordering/buying goods until their delivery to the customer. Digitalization makes this process easier and makes shopping easier. Delivery delays or its complexity can significantly impair the overall perception of online shopping and delivery. The delivery time is also an important element. Lack of transparency or lack of information in the distribution process disrupts the entire process, while efficient and technologically supported logistics can create a differentiating advantage (Ivanov, Tsipoulanidis, & Schonberger, 2019); (Burgos & Ivanov, 2021); (Lemon & Verhoef, 2016).

The challenge of the research arises from the need for a systematic understanding of how the digital transformation of logistics and distribution affects the customer experience, and to what extent technological innovations contribute or do not contribute to increasing customer satisfaction, trust and loyalty. Although there is a lot of research on digital transformation and supply chains, a smaller number of papers integrate analyse their impact on the perception and experience of end users.

The subject of this paper is the analysis of the connection between the digital transformation of logistics and distribution processes and customer experience, with special emphasis on the speed of delivery, transparency of information, flexibility of delivery and personalization of service. In accordance with the above, the following hypotheses have been set:

H1: The digital elements of logistics and distribution are positively correlated with overall customer satisfaction

H2: Transparency and ability to track your shipment in real-time have a significant impact on the quality of service.

2. DIGITALIZATION OF DISTRIBUTION PROCESSES IN E-COMMERCE

According to Christopher (2016), the digitalization of distribution processes represents one of the key transformations of modern logistics, especially in the context of the rapid development of e-commerce. The growth of online shopping has led to increased demands for speed, transparency and flexibility of delivery, making distribution a strategic element of a company's competitiveness.

Traditional distribution systems are based on physical infrastructure and operational efficiency, while digitized systems integrate information and communication technologies to optimize processes and improve user experience, thus affecting the level of customer satisfaction. On the other hand, the digital transformation of logistics implies the application of advanced information systems, automation, data analytics and digital platforms in the management of goods and information flows. The application of modern technologies makes

every company more competitive and fast in a turbulent market (Ivanov, Tsipoulanidis, & Schonberger, 2019).

When distributing processes are observed, warehouse management systems (WMS) are involved, transport management systems (TMS), automated shipment sorting, real-time digital shipment tracking, and integration with e-commerce platforms. Considering the reach of information technology, it is almost impossible to imagine business without it.

Such technologies enable proactive management of goods flows, predictive route planning and improved transparency of the entire distribution system – from order to delivery to the end user (Quynh & Buics, 2024).

One of the most significant aspects of digitalization in e-commerce is the transparency of the delivery process. The ability to track your shipment in real-time reduces customer uncertainty and increases the perception of service reliability. Digital notifications, automated communication and precise information about the status of the shipment are becoming a standard in business. Now, customers who buy products through e-commerce can track the delivery status of goods through stages, from the exact time of packaging to the time of transport on the road, all the way to the time of delivery of the goods to a specific location. The development of technologies such as artificial intelligence, the Internet further improves route planning, optimization of delivery networks and predictive demand analytics. Furthermore, logistics companies are turning to innovative delivery methods as personalized delivery models and distribution processes are increasingly viewed in the context of customer satisfaction, and such a way of thinking leads, or becomes a key factor in long-term competitiveness. The authors Tabim, Franco & Hoerede (2024) indicate that the digitalization of distribution processes has become one of the fundamental factors in the transformation of logistics and supply chain management, especially in the context of strong growth of e-commerce and customer expectations for fast and transparent delivery.

The integration of information and communication technologies enables real-time shipment tracking, automation of operations and optimization of resources, which contributes to increasing the efficiency and competitiveness of logistics systems. This allows users to plan their private time while at the same time informing when the goods will be delivered, e.g. to your home address (it is possible to plan to stay at home and pick up the shipment), (Hubner et al,. 2016); (Winkelhaus, Grosse, 2020).

When looking at the background of companies and industries, managers of large manufacturers, small and medium-sized enterprises want to understand digitalization. Managers find the implications of management particularly interesting, as digitalization gives them insights that help solve problems in collaboration with industry. This helps in decision-making and policy-making in the supply chain. In logistics processes, when the decision is based on quantitative indicators, then there is a high probability that the goals resulting from that decision will be met with minor deviations. Otherwise, decisions and goals may be in discrepancy and the possibility of deviating from the set goal is far greater because there is no foundation. The result of such business may be increased costs (Kazantsev et al., 2022).

In the context of e-commerce, the digitalization of distribution represents not only a technological improvement, but also a strategic resource for the sustainability and effectiveness of services. Companies that successfully integrate digital tools into logistics processes can significantly reduce operating costs, increase customer satisfaction, and build a more flexible business model focused on growth in demand and competitive pressures. The lack of practical decision-making tools within the supply chain and the lack of digital supply networks are hampering the industry's ability to cope with disruptions (Yanginlar et al., 2024); (Padovano, Ivanov, 2025).
It is quite certain that digitalization is clearly emphasized as a tool in all logistics processes and is actually becoming a competitive tool for the entire company. An important link is between digital tools, cost reduction and increased satisfaction in the distribution channel, which implies an increase in the satisfaction of service users. This positions digitalization in

the context of e-commerce as a key factor for long-term sustainability in the dynamic e-commerce environment.

3. RESEARCH METHODOLOGY

Quantitative research using the survey method was applied in this paper. The aim of the research was to examine the impact of digital transformation of logistics and distribution with an emphasis on the elements of delivery and customer satisfaction with e-commerce delivery services. Students of higher education institutions who had previously used online shopping services participated in the research.
Participation was voluntary and anonymous. The data was collected through an online questionnaire created in *the Google Forms* tool and was available in the period from 10 to 23 December 2025.
The research instrument was a structured survey questionnaire consisting of 13 questions. Most of the questions were measured on a Likert scale from 1 to 5 (1 – completely dissatisfied, 5 – completely satisfied). The dependent variable was: overall satisfaction with the delivery service, and the independent variables included: delivery speed, delivery accuracy, quality of online shipment tracking, usefulness of shipment status notifications.

Additional questions related to the type of delivery service most used by respondents. Statistical data processing was carried out using the JASP statistical program. The paper used descriptive statistics (arithmetic mean and standard deviation), Pearson correlation to examine the correlation between digital elements of logistics and overall satisfaction, then synthesis and analysis methods to determine the impact of independent variables on satisfaction. Pearson analysis was used because we wanted to examine the relationship between different variables, which are interval data and assume a linear relationship.

4. RESULTS AND DISCUSSION

110 respondents participated in the study. The age group ranged from 18 to 40+ years old. The descriptive analysis shows that the respondents expressed a high level of satisfaction with almost all observed aspects of the logistics and distribution service.

Table 1 shows that the highest rated condition of the shipment at pick-up (M=4.609; SD=0.592), which indicates a very positive perception of the preservation and quality of the delivered goods. A relatively high standard deviation indicates a high level of agreement between respondents. High marks were also recorded for: professionalism and friendliness of the courier (M = 4.473; SD = 0.821; the usefulness of the consignment status notification (M = 4.464; SD = 0.820), delivery accuracy (M = 4.345; SD = 0.818).

Overall satisfaction with the delivery service in online shopping was (M = 4,491; SD = 0.6469), which shows a high level of satisfaction of respondents with logistics and distribution services. A slightly lower, but still positive average score was given to the speed of delivery (M = 4.073; SD = 0.809) and the quality of online tracking of the shipment (M = 4.027; SD = 1.018). The table shows that a slightly lower, but still positive average score was given to the speed of delivery (M = 4.073; SD = 0.820) and the quality of online shipment tracking (M = 4.027; SD = 1.018).

The largest standard deviation was recorded in the shipment tracking variable (SD = 1.018), which indicates a greater dispersion of responses and different experiences of respondents regarding the digital elements of the logistics service. These data indicate that there is room for further digital transformation and improvement of the shipment tracking system.

Array 4. Descriptive analysis

Descriptive Statistics

	Evaluate the speed of delivery of the ordered goods	Rate the accuracy of the delivery	Assess the status of the shipment at pick-up	Rate the professionalism and friendliness of the courier	Evaluate the quality of online shipment tracking (accuracy and clarity of information)	How useful were the notifications about the status of the shipment (SMS/e-mail)?	How satisfied are you with the delivery service when shopping online?
Valid	110	110	110	110	110	110	110
Mean	4.073	4.345	4.609	4.473	4.027	4.464	4.491
Std. Deviatic	0.809	0.818	0.592	0.821	1.018	0.820	0.646
Minimu m	2.000	2.000	3.000	2.000	1.000	1.000	3.000
Maximu	5.000	5.000	5.000	5.000	5.000	5.000	5.000

Source: Authors

Table 2 shows the correlation analysis. The correlation between individual elements of the logistics distribution service and the overall satisfaction conducted by Pearson's correlation analysis was examined. The results showed statistically significant positive correlations between all observed variables ($p < 0.001$). The most pronounced correlation is visible between the speed of delivery and overall satisfaction ($r = 0.528$), which indicates a large impact of operational efficiency of logistics on the perception of service quality.
A moderately strong correlation was found between the status of the shipment at pick-up and overall satisfaction ($r = 0.434$). The quality of online shipment tracking also shows a statistically significant positive correlation with overall satisfaction ($r = 0.342$).
Although the connectivity is moderate, the result confirms the importance of digital transformation of logistics processes in shaping the customer experience. The findings confirm that both operational and digital aspects of logistics are relevant factors in customer satisfaction in e-commerce.

Array 5. Pearson's correlation

Pearson's Correlations

Variable		Evaluate the speed of delivery of the ordered goods	Assess the status of the shipment at pick-up	Evaluate the quality of online shipment tracking (accuracy and clarity of information)	How satisfied are you with the delivery service when shopping online?
Evaluate the speed of delivery of the ordered goods	Pearson's r	—			
	p-value	—			
	Lower 95% CI	—			
	Upper 95% CI	—			
Assess the status of the shipment at pick-	Pearson's r	0.405***	—		

Pearson's Correlations

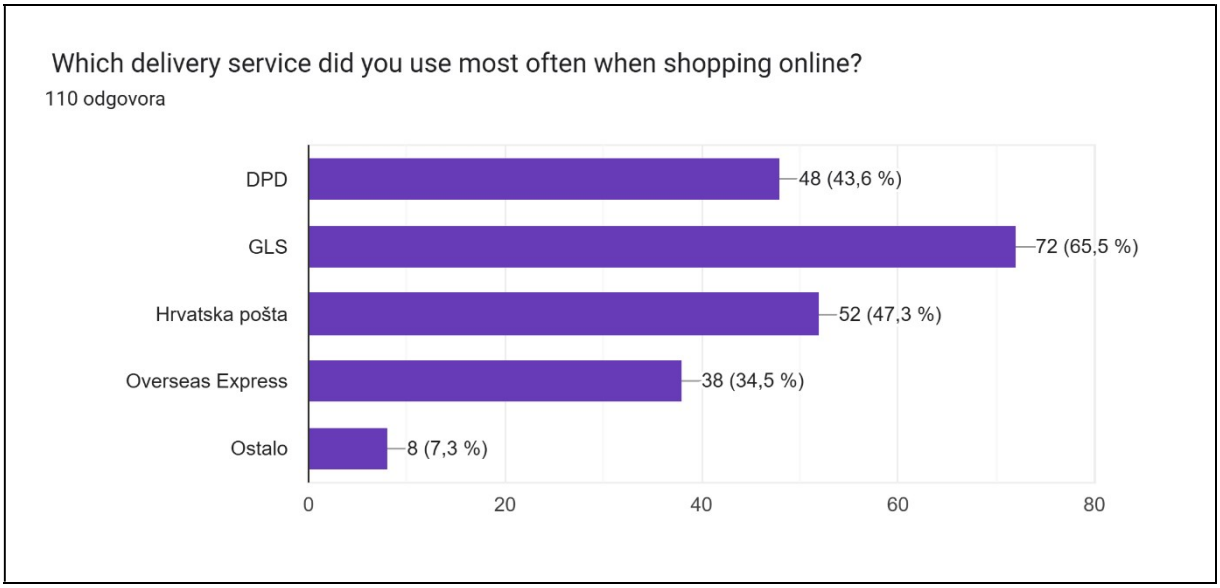
Variable		Evaluate the speed of delivery of the ordered goods	Assess the status of the shipment at pick-up	Evaluate the quality of online shipment tracking (accuracy and clarity of information)	How satisfied are you with the delivery service when shopping online?
up					
	p-value	< .001	—		
	Lower 95% CI	0.235	—		
	Upper 95% CI	0.550	—		
Evaluate the quality of online shipment tracking (accuracy and clarity of information)	Pearson's r	0.376***	0.383***	—	
	p-value	< .001	< .001	—	
	Lower 95% CI	0.203	0.211	—	
	Upper 95% CI	0.526	0.532	—	
How satisfied are you with the delivery service when shopping online?	Pearson's r	0.528***	0.434***	0.342***	—
	p-value	< .001	< .001	< .001	—
	Lower 95% CI	0.378	0.269	0.166	—
	Upper 95% CI	0.651	0.575	0.498	—

* p < .05, ** p < .01, *** p < .001

Source: Authors

Figure 1 shows which delivery services were most often used by respondents when shopping online (N = 110). The largest part of respondents cited *GLS* (65.5% of respondents), which indicates that this service is the most represented among users. It is followed by *Croatian Post* (47.3%), followed by *DPD* (43.6%). A smaller share of respondents use *Overseas Express* (34.5%), while the other category was chosen by 7.3% of respondents. The results indicate *GLS's* dominance in the delivery market in the context of online shopping among the surveyed users, while other services are more represented to a lesser but still significant extent.

Figure 1. Delivery services



Source: Authors

5. CONCLUSION

The research aimed to examine the impact of digital transformation of logistics and distribution on customer experience and satisfaction in the context of online shopping. The results of descriptive and Pearson's correlation analysis showed that there is a statistically significant positive correlation between digital elements of logistics and overall customer satisfaction. The results obtained confirm the hypotheses H1: The digital elements of logistics and distribution are positively correlated with overall customer satisfaction, H2: Transparency and ability to track your shipment in real-time have a significant impact on the quality of service.

The results of Pearson's correlation analysis showed a statistically significant positive correlation between the digital elements of logistics (online shipment tracking) and overall customer satisfaction ($r = 0.342$; $p < 0.001$), so the H1 hypothesis is accepted.

By testing Hypothesis 2, a statistically significant positive correlation was found between the transparency of the delivery process, operationalized through the quality of online shipment tracking, and overall customer satisfaction ($r = 0.342$; $p < 0.001$), therefore Hypothesis H2 is accepted.

The results obtained confirm the hypotheses and indicate that the digital transformation of logistics does not operate in isolation but upgrades traditional distribution processes. In the conditions of e-commerce development, the integration of operational efficiency and digital transparency is becoming a key factor in the competitiveness of logistics systems.

Despite the results obtained, the research has certain limitations, such as the size and structure of the sample, which may affect the possibility of generalizing the results. Future research should include more diverse groups of participants and more advanced statistical methods. Regardless of the limitations the research contributes to the understanding of the role of digital transformation in logistics and distribution and confirms its significant impact on shaping a positive user experience in the online environment.

The paper contributes to the field of logistics and distribution economics because it integrates the operational aspects of delivery (speed, shipment status) with digital components, looking at them through the prism of user experience.

The practical contribution of the paper is reflected in the possibility of applying the results in the business practice of logistics operators and e-retailers, which can improve the user experience.

The special value of the work is in connecting the operational and communication aspects of delivery into a unique model of customer satisfaction.

A recommendation for future research is reflected in the possibility of extending existing models by including additional variables and a comparative analysis between different logistics operators or national markets could be carried out. This would further deepen the understanding of the competitiveness and level of digital maturity of distribution system.

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Prethodno priopćenje

UTJECAJ DIGITALNE TRANSFORMACIJE LOGISTIKE I DISTRIBUCIJE NA ISKUSTVO KORISNIKA

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SAŽETAK

Na temelju rastuće prisutnosti online kupovine i sve većeg prihvaćanja digitalnih logističkih i distribucijskih aktivnosti vezanih uz dostavu robe, ovaj rad teoretski i empirijski ispituje zadovoljstvo kupaca uslugama dostave naručene robe i moguće poboljšanja. Cilj istraživanja je ispitati razinu zadovoljstva kupaca uslugama dostave u online kupovini. Nadalje, ispituju se specifični elementi distribucijskih usluga: brzina i točnost dostave, informacije o kupcima i digitalno praćenje pošiljki te opće zadovoljstvo kupaca. Istraživački uzorak čine korisnici koji su koristili usluge online kupovine s dostavom na kućnu adresu ili dostavom na određenu lokaciju (paketni ormarići). Uzorak je uključivao studente visokoškolskih ustanova koji su imali iskustva s online kupovinom i uslugama dostave. Istraživački instrument bio je strukturirani upitnik koji se sastojao od 10 pitanja, podijeljenih u četiri tematska dijela (navike online kupovine, zadovoljstvo dostavom, praćenje i informacije o pošiljkama te opće zadovoljstvo i percepcije mogućih poboljšanja u dostavnim uslugama). Upitnik je distribuiran putem Google obrasca, koji je bio dostupan ispitanicima od 10. do 23. prosinca 2025. Statistička analiza podataka provedena je pomoću JASP softvera. Dobiveni rezultati istraživanja ukazuju na značajnu povezanost između kvalitete digitalnih logističkih usluga i ukupnog zadovoljstva kupaca. S obzirom na ubrzani rast online kupovine i sve češću dostavu robe, razvoj digitalne logistike i distribucije usmjerene na poboljšanje korisničkog iskustva predstavlja snažan temelj za izgradnju konkurentnosti u sektoru logistike i distribucije, kao i u e-trgovini. Stoga rezultati istraživanja pružaju vrijednu osnovu za daljnje unapređenje distribucijskih i logističkih usluga

Ključne riječi: *Logistika, distribucija, online kupnja, zadovoljstvo korisnika uslugom dostave*

Preliminary Communication

THE ROLE OF DIGITALIZATION IN THE OPTIMIZATION OF THE PROCUREMENT PROCESS IN A TRADING COMPANY

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ABSTRACT

Procurement is a function of a company that directly affects the cost of doing business, product quality, sales volumes and customer satisfaction. Digitalization of procurement is one of the key factors in increasing the efficiency and competitiveness of trading companies in the modern business environment. Digitalization of procurement includes the use of digital technologies to optimize business processes. By introducing digital tools and systems into procurement processes, e.g. ERP systems, e-Procurement platforms for digitizing procurement processes, SRM tools for supplier relationship management, AI and predictive analytics, Blockchain solutions for tracking the origin of materials and goods, companies strive to increase efficiency, transparency and reduce operating costs. The benefits of digitalization of procurement are: cost reduction, shortening order times, better inventory control, predictive planning, increased transparency, and improved supplier relationships. With the digitalization of procurement, it is transformed from an administrative function to a strategic function of the company.
The aim of this paper is to analyze the impact of digital technologies on procurement processes, challenges in introduction and benefits for business. The research includes a review of the relevant literature of previous research in the field of digitalization of procurement and a qualitative approach to the research through a personal interview with purchasing managers in trading companies. The results of the research indicate that the introduction of digital tools in procurement has positive effects; the impact of digital transformation of procurement on faster decision-making, easier communication with other departments, cost reduction, better inventory control and a higher level of cooperation with suppliers.

***Keywords**: digitalization of procurement, digital tools and systems, advantages of digitalization of procurement, research*

1. INTRODUCTION

Traditional procurement, as it is known, focuses on reducing prices, speed and facilitating administrative processing of orders. On the other hand, digitalization is not just a mere implementation of software, but has been shown to transform traditional procurement into procurement 4.0 thanks to its capabilities. Thus, procurement becomes a strategic function, a paradigm shift is taking place in the company, but the main barriers to this move forward are rigid (obsolete) processes and a lack of digital skills of employees (Bienhaus, Haddud (2018). In this sense, management support and internal resource readiness are becoming critical for the adoption of Industry 4.0 (Srivastava et al., 2022). Srai and Lorentz develop a framework of seven value drivers that connect advanced technologies with strategic procurement goals (Srai, Lorentz, 2019). Sjödin et al. propose a 4.0 procurement model in 4

phases: opportunity mapping, partner selection, new design of digital contracts, and continuous innovation (Sjödin et al., 2023). Bag et al. suggest the importance of the actions of the main management, which must prioritize investment support and the design of a system that can ensure the convergence of technology, new employment models and the formation of plans for continuous improvements in the system. These authors point out the importance of developing a monitoring and management system for all actions in supply chain networks (S Bag et al., 2021). Govindan et al. suggest that there is a need to improve the understanding of the supply chain benefits achieved through various Industry 4.0 technologies.Govindan et al., 2022). Jain et al. make a systematic review of the literature on the topic of procurement 4.0 and suggest the need for additional empirical analyses of the proposed concepts and new substantiation of the findings, which is the intention of this research. They also emphasize the need to explore the so-called dark side of the technological implementation of Procurement 4.0 (Jain et al., 2024). In their research, Tetteh et al. prove the moderating role of digital transformation on business model innovation. Through digital transformation, companies need to identify, reshape resources and remain competitive (Tetteh et al., 2025).

For the purposes of this paper, research was conducted through personal interviews with procurement managers in trading companies with the aim of analyzing how digital tools in procurement affect the success and optimization of the procurement process. In the data analysis, a thematic analysis according to Braun and Clark was used, on the basis of which the topics of the research results were identified. The thematic analysis shows that the digitalization of procurement brings significant operational and strategic advantages, primarily in the form of efficiency, control and reduction of errors. The process of digital transformation is not devoid of challenges that are technologically conditioned, but are primarily organizational and human in nature.

2. RESEARCH METHODOLOGY

For the purposes of this paper, a qualitative research approach was used with the aim of understanding the potential and role of digitalization in the procurement process. The applied research method is a semi-structured personal interview method that allows for a combination of pre-prepared questions and open-ended answers. The research instrument is an interview guide made on the basis of the goals and hypotheses of the work. The guide includes 20 questions related to: the type and size of the company, the use of digital tools, the advantages of their use, the challenges of introducing digitalization and future activities in the digitalization of procurement. The interview was conducted with ten purchasing managers employed in trading companies who actively participate in the management and procurement process. The persons were selected on the basis of their functions in trading companies. The collected data were analyzed by qualitative content analysis, identifying key topics and patterns in responses. The results of the interview were used as a basis for interpretation and discussion.

In the research and analysis of the data, thematic analysis according to Braun and Clarke (2006) was used as a flexible method for interpretation and analysis of topics within the obtained qualitative data, and the topics resulted from the data themselves. The phases of thematic analysis are: getting acquainted with the data obtained from the research, identifying repetitive concepts (codes), grouping related codes, and forming and defining topics that include the advantages and challenges of digitalization of procurement. The aim of this paper is to explore how digital tools affect the procurement business in trading companies and to analyze the benefits and challenges of introducing digital tools in procurement. For the purposes of this paper, the basic terms and theoretical framework of digitalization of procurement and digital tools used in procurement business are defined.

In accordance with the theoretical-methodological approach, the hypothesis is put forward:

H1 – Digitalization of procurement contributes to the successful procurement business of a trading company.

3. DIGITALIZATION OF PROCUREMENT OPERATIONS

In the field of implementation of specific technologies that are the subject of an in-depth semi-structured interview, in this research we should mention the research that explains how these tools change operational processes. Govindan et al. identify blockchain technology as a key driver of procurement 4.0 and suggest the need for future research on the topic, which is also the goal of this study (Govindan et al., 2024). Gunasekara et al. point out that traditional procurement has problems with data security, efficiency, communication and transparency. On the other hand, e-procurement also has problems related to data security, poor transparency and integration. In this sense, the blockchain imposes itself as a solution to the identified problems (Gunasekara et al., 2022). Spreitzenbarth et al. analyse the existing research literature and, based on the assessment of the experts in the sample, identify a discrepancy between their estimates and published research. They suggest that cost analysis and supplier sustainability deserve a greater research focus (Spreitzenbarth et al., 2024). Hallikas et al. (2021) identify analytical abilities (data analytics) as a mediator because the digital skills of employees alone are not enough for the success of a company that must be able to transform data from procurement into operational performance (Hallikas et al., 2021).

Maheshwari et al. (2023) apply Digital Twins in food chains. The model uses the industrial symbiosis of suppliers, customers and manufacturers, gives the opportunity to optimize production times, delivery times, which has a positive effect on accelerating the productivity of the supply chain, improve production times, scheduling, overall efficiency, equipment efficiency, capacity. These simulations are suitable for managers who can more accurately forecast delivery times, inventory levels (Maheshwari et al., 2023).

In the analyzed set of papers, part of the papers deals with digitalization, which is not only seen as a tool for profit, but also as the key to environmental goals. Bag et al. (2021) identify 13 drivers of sustainability through Industry 4.0 and warn that research often neglects the social aspect of sustainability (jobs, ethics) in favor of environmental (S. Bag et al., 2021). Sharma et al. link Industry 4.0 to the UN Sustainable Development Goal 12 (SDG12) and find that digital technologies facilitate the adoption of circular economy practices in procurement, but only under pressure from institutions and markets (Sharma et al., 2024). Corbos et al. identify findings that companies with a high level of digital procurement and openness to the circular economy have the greatest competitive advantage and that the procurement strategy must be directly aligned with environmental goals (Corbos et al., 2023). Digitalization requires new roles and a change in work culture. New procurement roles are defined: data analyst, system innovation scout, process automation manager. It is pointed out that talent development is a critical point because technology itself without trained personnel leads to failure (Delke et al., 2023) (Tkác et al., 2020).

Colombo et al. distinguish between automation (replacing people) and augmentation (expanding human capabilities). They find that the digitalization of procurement increases the autonomy and scope of employees' work, which requires a socio-technical approach to management (Colombo et al., 2023). Using the T-O-E framework (technology-organization-environment), Srivastava et al. emphasize that the support of top management and the ability of teaching staff (in technical institutes) is more important than the technological infrastructure itself (Srivastava et al., 2022). When it comes to the application of the Procurement 4.0 principle in the public sector and at the level of small and medium-sized enterprises, several findings have been identified. Gavrila and Ancillo focus on small and medium-sized enterprises. They see the cloud and e-invoice applications as accelerators that help small retailers survive in the fight against online giants (Gavrila, Ancillo, 2021). Hetmanenko and Tyvodar identify and analyze digitalization as an anti-corruption tool. They cite the example of the Ukrainian system "ProZorro", which minimizes the human factor and the subjective influence of officials by automating the process, which increases transparency and also serves as a tool against corruption (Hetmanenko, Tyvodar, 2025). Senna et al. find that governments in the EU are giving money for digitalization but ignoring practical barriers

such as the need to modernize old equipment, which slows down the adoption of the technology (Senna et al., 2023). Muñoz-Garcia and Vila identify small businesses that are leapfrogging the domestic market and using digital platforms to compete directly in international procurement markets (Muñoz-Garcia, Villa, 2019).

4. DIGITAL TOOLS IN PROCUREMENT

The evolution of the procurement business process in the last five years has been marked by a transformation towards the "Procurement 4.0" model, where digital tools are becoming key to ensuring the resilience of the supply chain, but also the competitiveness of the company as a whole (Surajit, Lincoln, Sachin, & Sunil, 2020). The integration of advanced technologies enables organizations to reduce uncertainty and optimize resources through proactive, data-driven decision-making (Trang et al., 2022). What was once a vision of a digital, procurement-based enterprise has now become an indisputable reality. Likewise, Enterprise Resource Planning (ERP) systems are no longer a novelty but an obligation. Research confirms the positive impact of the implementation or use of ERP systems on the entire organization (Nour, 2023), as well as on individual processes such as procurement (Faccia, Petratos, 2021). However, some authors also point out the potential ambiguities of the ERP system's effectiveness, especially in the implementation steps. While process integration and standardization can improve the speed of execution and the quality of decision-making, inadequately implemented ERP systems can generate organizational rigidity and reduce flexibility. On the contrary, well-implemented implementations that include the application of best practices, continuous updates and vertical and horizontal integration of processes usually have a positive effect on the agility of the company through increasing process efficiency and coordination. (Seethamraju, Krishna Sundar, 2013). However, most of the conclusions go in the direction that through the standardization of operational procedures, ERP systems become an analytical foundation that allows management to identify market disruptions and agilely adjust procurement strategies (Amini-Philips et al., 2023). Such a technological architecture is not only able to optimize resource allocation, but also serves as a foundation or necessary infrastructure prerequisite for the implementation of advanced tools such as artificial intelligence and robotic automation (Mannan et al., 2025).

Along with ERP systems, e-Procurement platforms represent the second key pillar of digitalization that automates the entire procurement transaction cycle. Electronic procurement systems cover the entire procurement process – from defining needs and conditions to approving orders and monitoring the receipt of services/products, all to final invoicing and billing (Ramp Business Corporation, 2025). By using this, as well as all other digital solutions in business, unnecessary administrative steps are eliminated and the possibility of errors in data entry is reduced (Dropulić, 2019). More specifically, the use of e-Procurement platforms (such as https://www.coupa.com/, https://www.gep.com/software/gep-smart or https://www.ivalua.com/) allows for greater transparency in supplier selection processes, which is critical for the integrity of a trading company. Special emphasis in the scientific literature is placed on supplier relationship management, i.e. SRM systems (Supplier Relationship Management). SRM information tools (lately increasingly supported by artificial intelligence) enable the transformation of relationships with suppliers from basic, sales to strategic and long-term partnerships (Klobučar, Erjavec, 2019). The integration of these ERP, e-Procurement and SRM tools enables organizations to reduce uncertainty through proactive decision-making. A logical continuation of the upgrade in procurement processes is Contract Management systems for contract management. Depending on the implementation, they can already be included in SRM solutions or independent subsystems with the possibility of different approaches depending on the authorizations (Icertis LTD., 2025). Maintaining systematic, defined and orderly relationships with suppliers is the key to today's successful business. Authors such as (Tipurić, 2008) argue that transparent and open contract management systems lead to more cost-effective outcomes and greater direct savings.

In the conditions of global competition and increasing pressures to reduce costs, their analysis systems have become more important than ever. Spend Analytics tools for cost and consumption analysis, transform sometimes fragmented data from ERP systems into clear dashboards, thus facilitating the monitoring and analysis of procurement that takes place outside of structured processes (Filani et al., 2020). The future of procurement, which is actually becoming a challenging present, lies in the application of disruptive technologies such as artificial intelligence (AI), blockchain, and robotic process automation (RPA). Scientific research indicates that the integration of artificial intelligence in procurement, especially through machine learning models, improves the accuracy of price estimation in public auctions (García Rodríguez et al., 2021). The authors also emphasize the role of predictive analytics in managing the risks of delivery delays, with algorithms such as *the Random Forest* model enabling the proactive identification of bottlenecks in the supply chain (Amaka, Awele, 2025). Contemporary trends, supported by the development of information technology and the availability of AI tools, confirm the accelerated adoption of generative artificial intelligence (GenAI), which automates the generation of documents such as requests for quotation (RFQ), resulting in an increase in the productivity of procurement teams by up to 10% (Deloitte US, 2024). According to currently available predictions, by 2027, half of the leading organizations will be using AI systems for procurement processes (Gartner LTD., 2024). The technology that is overshadowed by cryptocurrencies (CNBC, 2026), and on which they are based – Blockchain – certainly has room in logistics and procurement. Research such as (Barić, 2019) describes the application of blockchain for supply chain management through digital platforms that enable the exchange of documents between cargo owners, ports and customs institutions. The benefits of blockchain such as immutability, consistency, transparency, and security can be of utmost importance in logistics flows or procurement processes. The decentralized nature of blockchain solves product traceability issues, which is essential for modern trade operations particularly emphasized in food production (Business Journal, 2023).

Finally, robotic process automation (RPA) automates repetitive administrative tasks, and its use is increasing. There have been successful case studies where this technology has been used to automate repetitive tasks such as invoice processing and order entry (Asatiani & Penttinen, 2016). Various authors (Van der Aalst et al., 2018; Durão, dos Reis, 2024) highlight the role of robotic automation in increasing operational efficiency and reducing operating costs through mimicking human actions with high precision. RPA tools, integrated with artificial intelligence capabilities, but also with the previously mentioned ERP and SRP or SA tools, make process monitoring more autonomous and reliable, freeing up employees for tasks of strategic value (Kitsantas et al., 2024). With the additional development of all the mentioned technology segments, it remains to be seen the further direction of development and their implementation in modern procurement processes that must ensure the competitiveness of companies regardless of their activities or size.

5. RESEARCH RESULTS

Purchasing managers in trading companies participated in the research. The observed companies belong to medium (50-250 employees) and large (more than 250 employees) companies. The defined topics in the research results are automation of the procurement process, increasing the control of the procurement process, cooperation with suppliers, organization of procurement departments, further development of procurement digitalization in trading companies. When it comes to the automation of the procurement process, respondents state that the digitalization of procurement leads to a faster operational process, especially in the phase of ordering products and tracking inventory. The integration of ERP systems in procurement has reduced the need for manual data entry and has set the goal for complex tasks. Digital tools in procurement increase the control of the process itself, reduce errors in ordering and logistics. Respondents have greater confidence in digital tools in procurement compared to e-mail, excel and telephone. Most of the observed companies use ERP systems that enable monitoring of the entire supply chain; two companies do not use

digital tools in procurement; In addition to the ERP system, two companies also use e-Procurement platforms for the digitalization of the procurement process (request creation, approval, purchase orders, e-catalogs; one company uses several digital tools in procurement (ERP system, e-Procuremenz platforms, SRM tools for supplier relationship management, Contract Management system for contract management and AI and predictive analytics for demand forecasting, inventory optimization and identification of risks in the supply chain). Respondents state that the most automated activities are: orders, communication with suppliers and automatic replenishment of inventory.

Respondents state that digitalization in procurement enables better cooperation with suppliers, transparency of the ordering process, fewer conflicts with the production department, faster data processing, easier communication, better output of goods from the central warehouse, fewer errors and delays in delivery, shortening deadlines in the procurement process. However, some respondents cite the limited sharing of information with suppliers as a negative, which can lead to poor business communication between companies (procurement) and suppliers. After the introduction of digital tools in procurement, respondents noticed a reduction in costs of 3-15%. Specifically, digital tools in procurement have contributed to reducing business costs because the introduction of the ERP system has become the central point of the company, the customer and the supplier. Automatic orders are formed according to the current stock status in the company, thus reducing the frequency of errors by employees. The introduction of digital tools reduces the costs of transportation and storage of goods. The time required for return on investment is 6 - 24 months due to high initial costs, and depends on the size of the company, employee education, integration with the existing system.

As for the impact of digitalization on the organization of work in the procurement department, the most frequently mentioned challenges are: employee education, employee resistance to change, employee differences in digital competencies, especially among older employees, problems with the operation of the system at the beginning of implementation. Adaptation to the new digital tools takes from a few months to a year. Respondents emphasize the need for further development of procurement with the use of digital tools due to the existing technical limitations of existing systems, e.g. poor integration with other systems, dependence on the stability of IT infrastructure and lack of analytical functionalities. A majority of respondents highlight the need for further investment in AI and predictive analytics. Table 1 provides an overview of thematic analysis topics in the research results with a description of the topics and examples from the data.

Table 1. Overview of thematic analysis topics in research results

Theme	Description of the topic	Examples from the data
Procurement automation	Speeding up the procurement process and relieving employees	Automated orders, ERP systems
Increasing control of the procurement process	Precision and reliability of the process	Fewer wrong orders, better records
Cooperation with suppliers	Better visibility of processes and relationships with suppliers	Traceability of deliveries, cross-dock
Organization of the procurement department	Employee resistance and the need for education	Slower adaptation of older workers
Development of digitalization of procurement	System disadvantages and the need for an upgrade	Integration, AI, Analytics

Source: author's creation

6. CONCLUSION

Digital transformation undeniably brings benefits that are visible in every segment of business, including procurement. Successful implementation of digital tools must not only improve the efficiency of the process, but also provide additional (saved) time for each employee. Of course, the entire process also requires the adaptation of human resources. Resistance from employees, especially older workers, has been identified as a significant obstacle. In some cases, employees still prefer traditional methods like phone orders because they find them simpler. The key to success lies in continuous education and increasing awareness of the reasons for the implementation of new technologies and the savings they achieve. A modern company must constantly monitor the progress of IT tools, implement them wisely and use them to successfully optimize business in order to survive in today's challenging and unstable market.

The conducted research indicates numerous advantages of using digital tools in the procurement process in trading companies. Given this, the digitalization of procurement is no longer an option, but a necessity for successful business and increasing competitiveness in the market. There are many advantages of digitalization of procurement in terms of increasing the speed of the process and reducing business costs, but the success of the implementation of digital tools primarily depends on the readiness of the human factor to adapt. Successful digitalization of procurement is a long-term process that requires continuous investments in employee education, technology and adaptation of business processes. Hypothesis H1 – Digitalization of procurement contributes to the successful business of procurement in a trading company is accepted. The results of the research confirm the previous theoretical findings on the impact of digitalization on the procurement process and the organization of the procurement department.

The implications of the research results on trading companies are that trading companies that successfully implement digital tools in procurement can achieve a competitive advantage in the market and reduce costs by educating employees. However, there are also negative aspects of business digitization, such as security risks, technology dependency, high implementation costs, technology obsolescence, privacy issues, and job losses. Therefore, a future business strategy is needed when digitizing a business. Digitization can lead to job losses, especially in jobs that involve simpler operational tasks, such as data entry and administration. Therefore, education and possible retraining of employees is necessary. Small commercial enterprises that do not have the funds to invest in digital business face weaker market competitiveness, inefficient inventory management, outdated marketing, and market visibility. All of this leads to slow business processes and limited growth. However, there are also digital solutions for small businesses that do not require large investments, such as social networks, web sales, and digital tools to help with organization and communication.

The limitation in the research was the type of research; A qualitative research has been conducted, so it prevents the application of statistical data processing. Procurement work often involves data confidentiality, so the availability of responses can be limited due to access to certain information. Recommendations for future research are: suppliers' experiences towards the digitalization of procurement, a survey that has IT experts in the field as a sample, quantitative research in trading companies through a questionnaire that would achieve a generalization of the results. A recommendation for future research is also a longitudinal approach, i.e. monitoring the same companies over a longer period of time for the purpose of analyzing changes and long-term effects of digitalization on the performance of procurement operations.

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Prethodno priopćenje

ULOGA DIGITALIZACIJE U OPTIMIZACIJI PROCESA NABAVE U TRGOVINSKOM PODUZEĆU

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SAŽETAK

Nabava je funkcija poduzeća koja izravno utječe na troškove poslovanja, kvalitetu proizvoda, prodajne količine i zadovoljstvo kupaca. Digitalizacija nabave predstavlja jedan od ključnih čimbenika povećanja učinkovitosti i konkurentnosti trgovinskih poduzeća u suvremenom poslovnom okruženju. Digitalizacija nabave obuhvaća uporabu digitalnih tehnologija za optimizaciju poslovnih procesa. Uvođenjem digitalnih alata i sustava u procese nabave npr. ERP sustava, e-Procurement platforme za digitalizaciju procesa nabave, SRM alati za upravljanje odnosima sa dobavljačima, AI i prediktivna analitika, Blockchain rješenja za praćenje porijekla materijala i robe, poduzeća nastoje povećati učinkovitost, transparentnost i smanjiti operativne troškove. Prednosti digitalizacije nabave su: smanjenje troškova, skraćivanje vremena narudžbi, bolja kontrola zaliha, prediktivno planiranje, povećanje transparentnosti i poboljšanje odnosa sa dobavljačima. Digitalizacijom nabave ona se transformira od administrativne funkcije u stratešku funkciju poduzeća.
Cilj rada je analizirati utjecaj digitalnih tehnologija na procese nabave, izazove pri uvođenju te koristi za poslovanje. Istraživanje obuhvaća pregled relevantne literature dosadašnjih istraživanja u području digitalizacije nabave te kvalitativni pristup istraživanju pomoću osobnog intervjua sa menadžerima nabave u trgovinskim poduzećima. Rezultati istraživanja ukazuju kako uvođenje digitalnih alata u nabavi ima pozitivne učinke; utjecaj digitalne transformacije nabave na brže donošenje odluka, lakšu komunikaciju sa drugim odjelima, smanjenje troškova, bolju kontrolu zaliha i veću razinu suradnje s dobavljačima.

***Ključne riječi**: digitalizacija nabave, digitalni alati i sustavi, prednosti digitalizacije nabave, istraživanje*

Pregledi rad

DIGITALNE VJEŠTINE U FUNKCIJI KONKURENTNOSTI PODUZEĆA NA LOGISTIČKOM TRŽIŠTU

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SAŽETAK

Konstantna unapređenja u području digitalne tehnologije te sveprisutna umjetna inteligencija stavlja nove izazove pred poslovne subjekte. Ti izazovi zahtijevaju stalna inoviranja poslovnih modela, implementaciju novih tehnologija, ulaganja u digitalne vještine ljudskih resursa, kontinuirano usavršavanje i obrazovanje zaposlenika. Cilj ovoga rada je istražiti ulogu digitalnih tehnologija u suvremenom poslovanju, posebice logističkoj industriji. Logistička industrija pogotovo je involvirana i pod stalnim pritiskom implementacije suvremenih tehničko-tehnoloških dostignuća kako bi bili konkurentni ne samo logistički operatori, već i poslovni subjekti koji su uključeni u globalne lance opskrbe. Stoga se u radu istražuju i analiziraju ključni sudionici na logističkom tržištu, digitalne tehnologije, ali i vještine koje su neophodne za svakodnevno poslovanje, a sve kako bi se postigla održiva konkurentnosti i veća otpornost na tržištu. U istraživanju i prezentaciji rezultata istraživanja o logističkom tržištu te digitalnim tehnologijama i vještinama korišteni su sekundarni izvori, dostupni bibliografski izvori te baza podataka Statista. Rad doprinosi valorizaciji digitalnih tehnologija i vještina kao ključnim elementima za postizanje konkurentnosti subjekta opskrbnih lanaca i logističke industrije.

Ključne riječi: *logistički operatori, digitalizacija, digitalne vještine, opskrbni lanci, ljudski resursi*

1. UVOD

Suvremeno poslovanje karakterizira konstantno ulaganje u ljudske resurse jer je neosporno da obrazovanje i implementacija suvremenih tehničko-tehnoloških rješenja može doprinijeti gospodarskom rastu i razvoju države, društva u cjelini, a samim time i održivom poslovanju. Ulaganje u implementaciju digitalnih tehnologija neminovno je u današnjem poslovanju te nema gospodarskog sektora u kojem nije prisutan neki oblik digitalne tehnologije.

Digitalna transformacija, potaknuta razvojem koncepta Industrije 4.0, omogućuje održivi razvoj poslovnih subjekata (Tubis *et al.,* 2023). Nužnost je za poslovne subjekte, a podrazumijeva restrukturiranje organizacijskih procesa, promjene u organizaciji rada te načinima komunikacije s kupcima (Kozak *et al*. 2025). Poslovni subjekti oslanjaju se na računalne i automatizirane sustave koji se stalno nadograđuju, ali se i razvijaju novi računalni alati, međutim, nezaobilazna karika još uvijek su ljudski resursi u većini procesa, posebice u upravljanju opskrbnim lancima (Macura, Čišić, 2012).

Cilj rada je istražiti i prezentirati rezultate istraživanja o digitalizaciji, digitalnim tehnologijama i njihovoj uporabi u svakodnevnom poslovanju. Također, istražuju se i predstavljaju sudionici na logističkom tržištu i izazovi s kojima se suočavaju u cilju postizanja održivih i konkurentnih opskrbnih lanaca, kao i potrebne digitalne vještine neophodne za održivo poslovanje. Metodologija istraživanja obuhvaća primjenu metoda analize i sinteze, kao i komparativne metode, posebice analizu dostupne literature i sekundarnih podataka, konkretno podataka iz baze Statista. Statistički podaci iz baze Statista omogućuju uvid u najnovije podatke i informacije, a prikupljeni su iz različitih izvora kao što su: Research and Markets, Armstrong

& Associates, World Economic Forum. Doprinos ovoga rada je u valorizaciji digitalnih tehnologija i vještina općenito te utvrđivanju kako digitalne tehnologije i vještine mogu imati utjecaj na poslovanje poduzeća i doprinijeti konkurentnosti poslovnih subjekata i opskrbnih lanaca.

Nakon Uvoda u kojemu su navedeni problematika i ciljevi istraživanja, slijedi drugi dio koji se odnosi na učinke digitalne tehnologije u suvremenom poslovanju. Treći dio daje uvid u logističko tržište, s analizom ključnih logističkih subjekata u logističkoj industriji, bez kojih nesmetano kretanje roba i usluga ne bi bilo moguće jer omogućuju da pravi proizvod bude dostupan u pravo vrijeme, na pravo mjesto, pravoj količini, pravim uvjetima i pravom kupcu. Digitalne vještine koje su neophodne za konkurentno i održivo poslovanje obrađuju se u četvrtom dijelu rada, nakon čega slijedi Zaključak kao sinteza rezultata istraživanja.

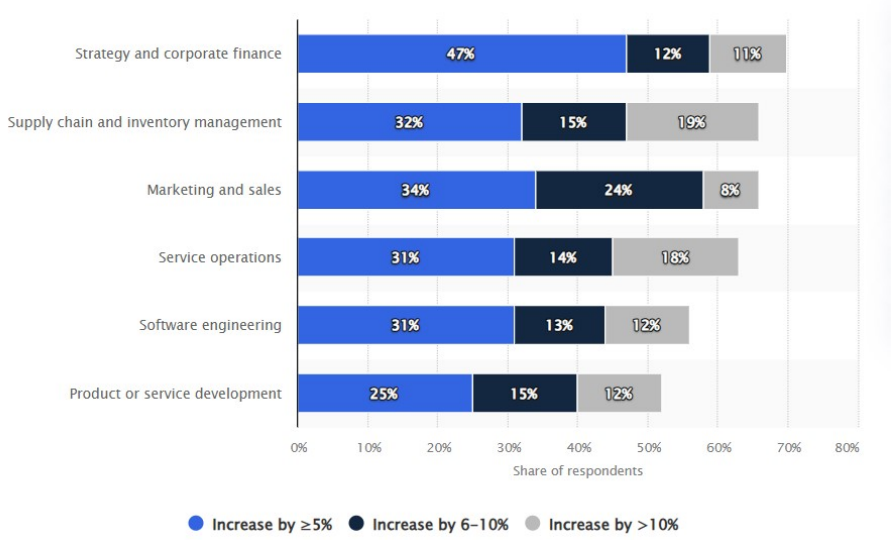
2. DIGITALNE TEHNOLOGIJE U SUVREMENOM POSLOVANJU

Digitalizacija i digitalna transformacija pojmovi su koji su se pojavili razvojem četvrte industrijske revolucije (Theotokas *et al*., 2024). Suvremeno poslovanje karakterizira upotreba digitalne tehnologije u svakom segmentu poslovanja. Brzina pristupa informacijama, produktivnost na radu, učinkovitost u poslovnim procesima, dostupnost u svakom kutku svijeta nameće pred kompanije rapidnu implementaciju digitalnih tehnologija kako bi se zadržala konkurentna pozicija i ostvarilo održivo poslovanje. Neosporno je da je pandemija doprinijela ubrzanju digitalne transformacije poduzeća i društva općenito te dovela do novih poslovnih modela i implementaciju novih tehničko-tehnoloških postignuća u svakodnevno poslovanje, što se odrazilo na promjene u komunikaciji između poslovnih klijenata i zaposlenika, promjene organizacije rada, implementacija automatizacije, fleksibilna radna mjesta (Brkljača *et al*., 2024). Utjecaj digitalne tehnologije na transformaciju poslovanja posebno dolazi do izražaja u međunarodnom poslovanju, gdje zahvaljujući digitalnim platformama poslovni subjekti imaju pristup partnerima i klijentima diljem svijeta (Mirzaye, Mohiuddin, 2025).

Kahveci (2025) u svom radu ističe brojne prednosti digitalizacije, ali i čimbenike koji utječu na rezultate poslovanja djelujući na učinkovitost, produktivnost te konkurentnosti malih i srednjih poduzeća. Kazak *et al*. (2025, p. 47) ističu kako korištenje alata velikih podataka, cloud tehnologija, umjetne inteligencije, blockchaina i Interneta stvari mijenjaju poslovne procese, a automatizacija operativnih aktivnosti, omnichannel u radu s kupcima, individualizacija usluge i fleksibilno određivanje cijena temelj su za održavanje tržišnih pozicija.

Prema Artificial Intelligence Index Report 2025 (Maslej *et al*., 2025), kompanije su u 2024. godini, u odnosu na prethodne godine, povećale primjenu umjetne inteligencije u poslovanju, ukazujući na učinkovitost primjene umjetne inteligencije u različitim segmentima poslovanja. Osim toga, istraživanje je pokazalo da je uporaba generativne umjetne inteligencije doprinijela i povećanju prihoda i smanjenju troškova u različitim poslovnim funkcijama, a što se zorno može vidjeti na sljedećem grafikonu.

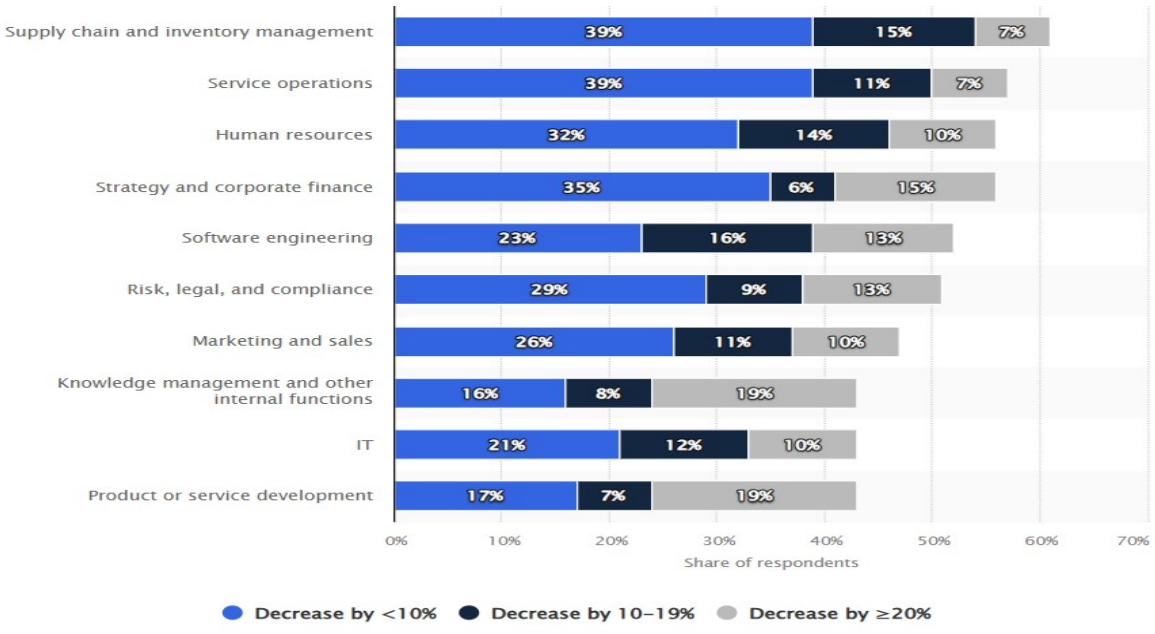
Grafikon 1. Povećanje prihoda korištenjem generativne umjetne inteligencije (AI) u poduzećima diljem svijeta u 2024. godini, po funkcijama



Izvor: Stanford University (2025a) u Statista (2026)

Iz grafikona je vidljivo kako umjetna inteligencija utječe na povećanje prihoda poslovanja u pojedinim poslovnim funkcijama. Najveći porast prihoda ostvaren je u segmentu Strategija i korporativne financije (*strategy and corporate finance*), gdje je zabilježen rast od 70 %. Ukoliko se analiziraju podaci prema postotku povećanja (povećanje do 5 %, između 6 i 10 % te više od 10 %), onda se može uočiti da je najveći učinak bio u segmentu upravljanja opskrbnim lancem i zalihama (*supply chain and inventory management*) gdje je 19 % posto ispitanika istaknulo da je u toj poslovnoj funkciji zabilježen rast prihoda od preko 10 %. Osim toga, ukupno povećanje prihoda u navedenom segmentu je 63 %, što stavlja upravljanje opskrbnim lancima na drugo mjesto prema učincima primjene umjetne inteligencije na prihode. Na narednom grafikonu su prikazani rezultati istraživanja kako umjetna inteligencija doprinosi smanjivanju troškova u pojedinim poslovnim funkcijama.

Grafikon 2. Smanjenje troškova korištenjem analitičke umjetne inteligencije u pojedinim poslovnim funkcijama, 2024.



Izvor: Stanford University (2025b) u Statista (2026)

Prema prikazanim podacima, najveće uštede troškova ostvarene primjenom umjetne inteligencije su u funkciji upravljanja opskrbnim lancem i zalihama (61%), nakon čega slijede uslužne operacije (58%) te ljudski resursi i strategija i korporativne financije (56%). Zanimljivo je uočiti da kompanije u svim poslovnim funkcijama ističu smanjenje troškova, bez obzira da je je riječ o smanjenju od 10 % ili više.

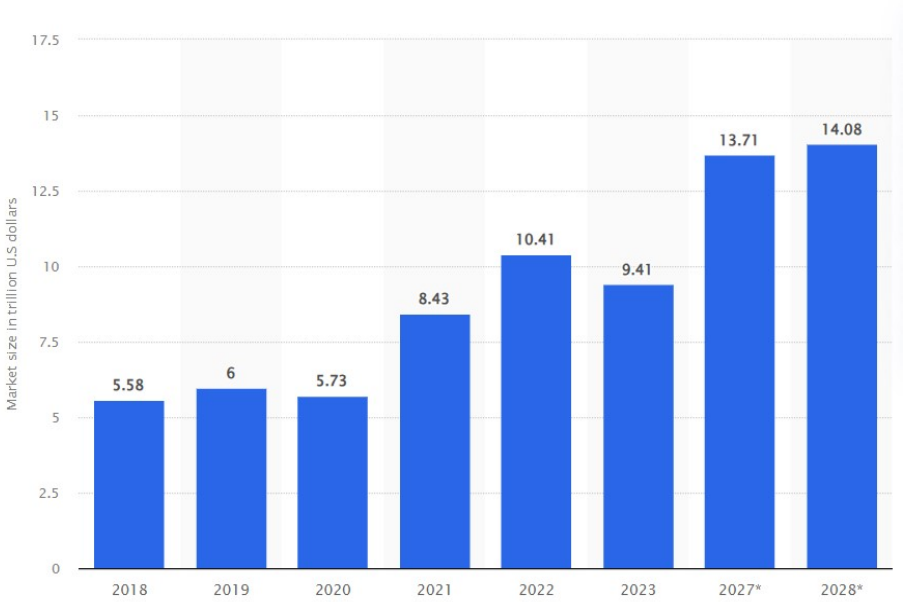
Globalni lanci opskrbe značajno su izloženi digitalnim tehnologijama, tako da se već može govoriti o digitalnim opskrbnim lancima koje karakteriziraju digitalne tehnologije kao što su blockchain, Internet stvari, veliki podaci i umjetna inteligencija (Lu, Taghipour, 2025). Digitalizacijom logističkih procesa omogućuje se razmjena podataka u stvarnom vremenu, što predstavlja pokretačku snagu funkcioniranja poslovnih subjekata, posebice opskrbnih lanaca, čime digitalna transformacija omogućuje održivi razvoj (Tubis *et al*. 2023).

Stoga je i za očekivati da će primjena umjetne inteligencije, ali i drugih digitalnih tehnologija biti i veća, a to će se odraziti i na strukturu znanja i vještina koje će se tražiti od zaposlenika u svim industrijama, a samim time i u logističkoj industriji.

3. ANALIZA I STANJE LOGISTIČKOG TRŽIŠTA

Trendovi i kretanja međunarodne trgovine utječu na cjelokupnu logističku industriju, što znači da logističko tržište prati trendove i kretanja koja obilježavaju međunarodnu trgovinu. U cilju zadovoljavanja potražnje za njihovim uslugama, subjekti logističkog tržišta suočavaju se s izazovima primjene digitalnih tehnologija kako bi pružili kvalitetne logističke usluge (Pavlić Skender, 2023). Unatoč turbulencijama koje pogađaju globalno tržište, nakon razdoblja usporavanja trgovinskih aktivnosti, slijedi razdoblje rasta, a to za sobom povlači i porast ostalih pratećih aktivnosti, posebice aktivnosti logističkih subjekata aktivno uključenih u globalne opskrbne lance. Na sljedećem grafikonu može se vidjeti veličina logističke industrije u razdoblju od 2018. do 2023. godine, s predviđanjima rasta do 2028. godine.

Grafikon 3. Veličina globalne logističke industrije od 2018. do 2023., s prognozama do 2028.

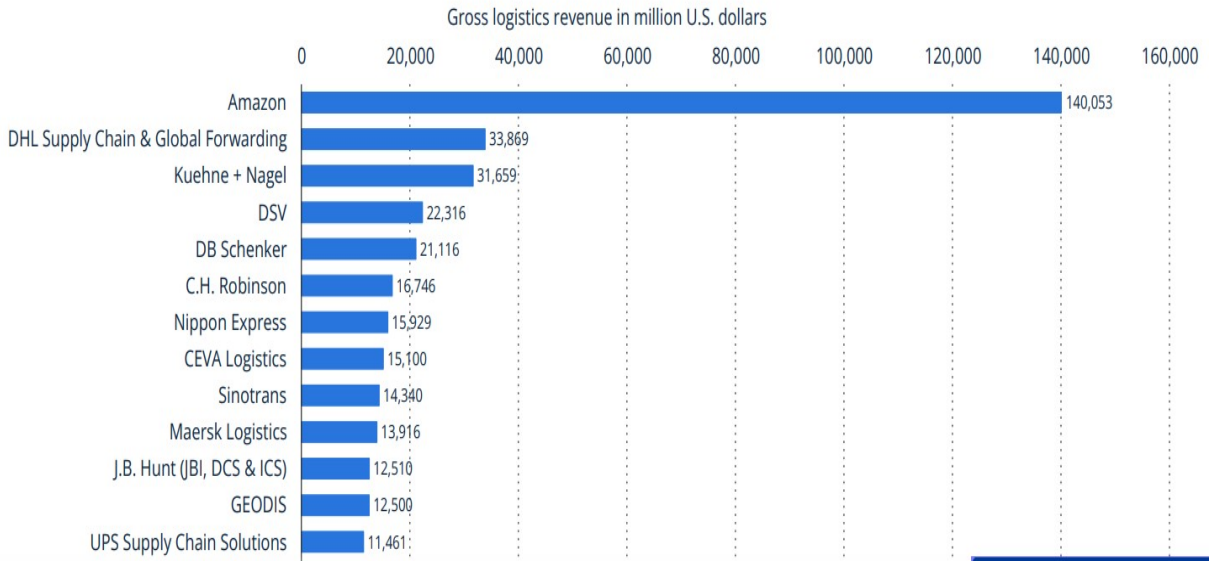


Izvor: Research and Markets (2024) u Statista (2026)

Kao što je vidljivo iz grafikona, iako su zbivanja na globalnoj sceni usporila rast logističke industrije u pojedinim godinama (pandemija uzrokovana Covid-19, što se odrazilo na pad u 2020. godini te politička zbivanja na 2023. godinu), može se uočiti kontinuirani rast logističke industrije od 2018. godine. Za 2027. i 2028. godinu predviđa se daljnji rast, što će zasigurno biti posljedica i novih tehničko-tehnoloških postignuća, umjetne inteligencije i digitalnih tehnologija općenito.

Logističke usluge pružaju brojni logistički poslovni subjekti koji su aktivni sudionici u opskrbnim lancima (kao što su 3PL pružatelji logističkih usluga, poznatiji pod nazivom *third-party logistics providers*, špediteri, prijevoznici te brojni drugi). Na sljedećem grafikonu prikazani su vodeći pružatelji logističkih usluga.

Grafikon 4. Vodeći svjetski pružatelji logističkih usluga 3PL u 2023. godini

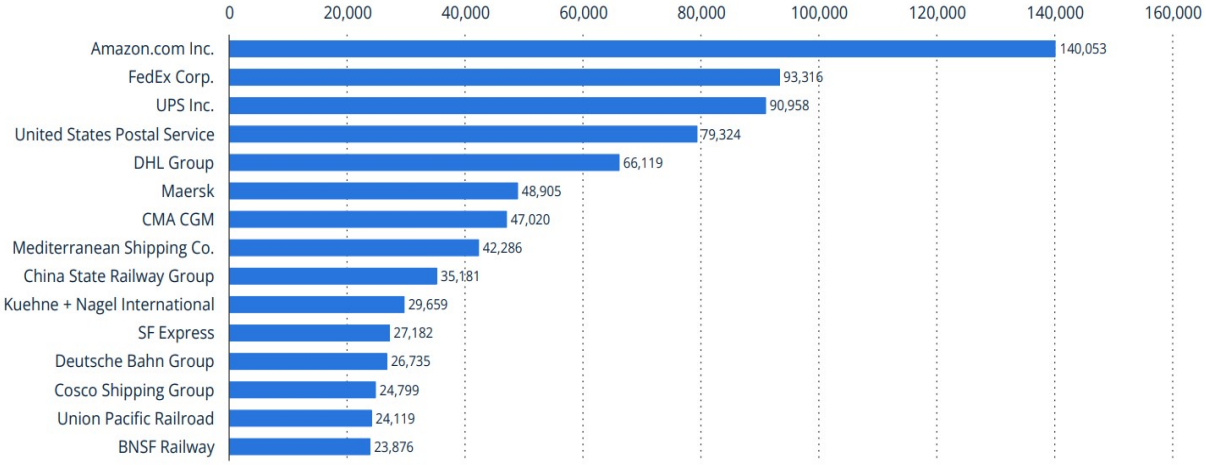


Izvor: Armstrong & Associates (2024) u Statista (2026)

Podaci navedeni u grafikonu ukazuju da su tri vodeća pružatelja logističkih usluga (3PL) u 2023. godini bili Amazon, Kuehne+Nagel, DB Schenker, nakon čega slijede DSV, DB Schenker, CH. Robinson i ostali. Ako bi se podaci usporedili s podacima iz prethodnih godina o vodećim 3PL subjektima na logističkom tržištu, desetljećima su vodeće mjesto imali Kuehne+Nagel, DHL Supply Chain & Global Forwarding, DB Schenker, DSV, CEVA Logistics, Nippon Express (Pavlić Skender *et al*., 2016; Pavlić Skender *et al*., 2019). Kompleksnost mreže vlastitih opskrbnih lanaca omogućilo je svrstavanje Amazona na listu vodećih 3PL pružatelja logističkih usluga.

Vodeće kompanije za prijevoz tereta u svijetu u 2023. godini, prema ostvarenim prihodima od prijevoza tereta (izraženo u milijunima američkih dolara), navedene su u sljedećem grafikonu.

Grafikon 5. Vodeće prijevozničke kompanije u svijetu 2023. godine

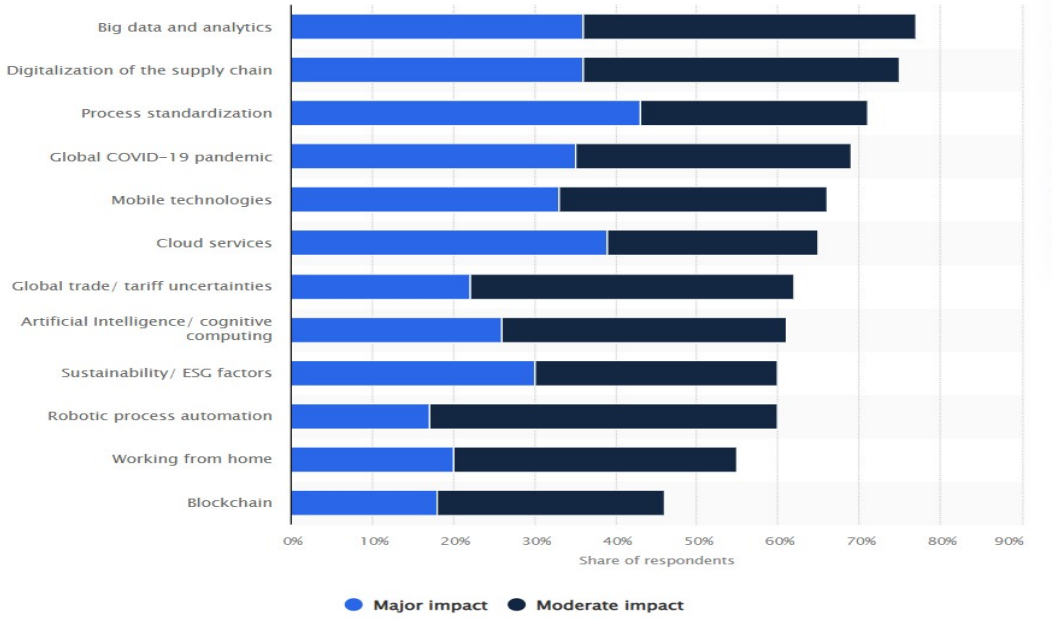


Izvor: Transport Topics (2024) u Statista (2026)

Uspoređujući podatke o vodećim kompanijama u svijetu za prijevoz tereta, mogu se uočiti sličnosti s podacima navedenim o vodećim kompanijama za pružanje logističkih usluga (3PL). Naime, vodeća imena u pružanju logističkih usluga su ujedno i vodeće kompanije u pružanju prijevoznih usluga, što je razumljivo, budući da su upravo usluge prijevoza temelj u pružanju logističkih usluga i osnova poslovanja vodećih logističkih subjekata.

Budući da su opskrbni lanci pod stalnim pritiskom novih tehničko-tehnoloških dostignuća, političkih i drugih izazova, zahtjeva tržišta za sve većom brzinom, točnošću, ali i pritiskom na troškove, upravljati opskrbnim lancima na globalnoj razini je izrazito kompleksno. Istraživanje provedeno 2022. godine (APQC 2022 u Statista 2026) izdvojilo je trendove za koje su sudionici istraživanja ukazali da će imati izrazit utjecaj na lance opskrbe. Iako su se predviđanja odnosila na razdoblje do 2025. godine, ti trendovi će i u budućnosti imati snažan utjecaj na uspješnost opskrbnih lanaca, a što se zorno može vidjeti na sljedećem grafikonu.

Grafikon 6. Vodeći trendovi od utjecaja na lance opskrbe do 2025. godine



Izvor: APQC (2022) u Statista (2026)

Vodeći trendovi koji imaju veliki i umjereni utjecaj na funkcioniranje opskrbnih lanaca su upravo veliki podaci i analitika (*Big data and analytics*) te digitalizacija lanca opskrbe (*Digitalization of the supply chain*), nakon čega slijede standardizacija procesa i usluge u oblaku (*process standardization and cloude services*). Iako su se istraživanja odnosila na predviđanja za 2025. godine, to su trendovi koji će i dalje imati utjecaja na globalne opskrbne lance.

Naime, u prethodnom dijelu rada istaknuto je kako digitalizacija utječe na poslovne procese, pri čemu se ističu veliki podatci, cloud tehnologija, umjetna inteligencija, blockchain i Internet stvari. Sve navedeno o utjecaju digitalnih tehnologija na suvremeno poslovanje, učincima koje imaju na poslovne rezultate i pojedine poslovne funkcije, a samim time i na poslovanje subjekata logističkog tržišta, zasigurno će se odraziti i na znanja i vještine koje će se očekivati od zaposlenika, a sve u funkciji postizanja 7R's, odnosno logističkih ciljeva.

4. DIGITALNE TEHNOLOGIJE I VJEŠTINE – ŠTO OČEKIVATI?

Primjena novih znanja nameće potrebu kontinuiranog ulaganja u obrazovanje ljudskih resursa. Znanje i obrazovanje preduvjet su kako bi se ljudski resursi mogli razvijati, primjenjivati i koristiti nove tehnologije te poticati tehnološki napredak (Karaman Aksentijević, Ježić 2009). Nova znanja traže i nove vještine, posebice u ovo novo digitalno doba. Umjetna inteligencije i veliki podaci (*AI and big data*) vještine su koje su poslodavcima diljem svijeta najvažnije u suvremenom poslovanju, što se zorno može vidjeti iz sljedećeg grafikona.

Grafikon 7: Vještine bitne za poslovanje od 2025. do 2030.

Izvor: World Economic Forum (2025b) u (Statista 2026)

Prema istraživanju World Economics Forum (2025b), *AI i Big data* su vještine za koje 87 % poslodavaca u svijetu smatra da će biti najvažnije u razdoblju do 2030. godine. Nakon toga slijede vještine povezane uz mreže i kibernetičnu sigurnost (*networks and cybersecurity)* za što se izjasnilo 70% poslodavaca. Slijede vještine povezane uz tehnološku pismenost, kreativno razmišljanje, otpornost, fleksibilnost i agilnost, zajedno sa znatiželjom i cjeloživotnim učenjem. Upravo ove potonje vještine nephodne su za implementaciju i razumijevanje prve dvije grupe vještina. I rezultati istraživanja Lehutova *et al*. (2025) ukazuju da su ključne kompetencije u budućnosti tehničke vještine povezane s umjetnom inteligencijom, velikim podacima, kibernetičkom sigurnošću, ali i meke kompetencije poput analitičkog razmišljanja, kreativnosti i timskog rada.

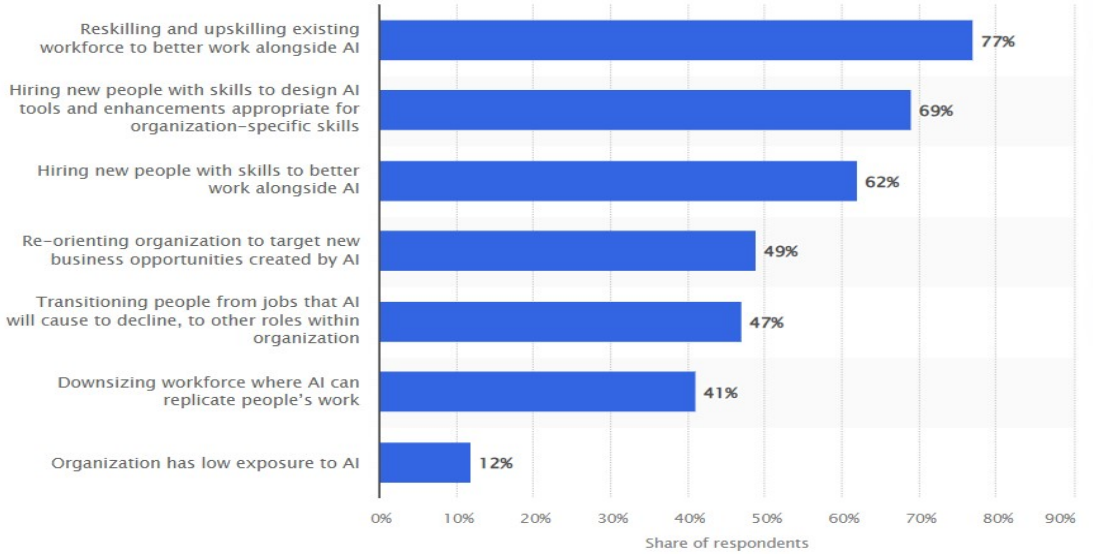
Navedene vještine bit će neohodne u svim industrijama, uključujući i logističku industriju, posebice za upravljanje opskrbnim lancima i prijevoz. Prema istraživanjima provedenim

među poslodacima u vezi potrebnih vještina zaposlenika za upravljanje opskrbnim lancima i prijevoz, za razdoblje od 2025. do 2030. godine, 94 % poslodavaca smatra da će posebno biti značajne vještine povezane s *AI i big data*, 76 % smatra važnim vještine povezane s mrežama i kibernetičkom sigurnošću, 77 % vještine povezane uz tehnološku pismenost, a 69 % ističe kreativno razmišljanje (World Economic Forum 2025a). Vodeći logistički operatori, kao što su DHL, Nippon Express, DB Schenker, već primjenju inteligenta rješenja u svojem poslovanju kako bi ostala konkrentna na međunarodnom tržištu, postigla efikasnost i održivost poslovanja (Pavlić Skender *et al.*, 2023).

U istraživanju 2023. godine (Inbound Logistics 2024 u Statista 2026), u vodeće logističke izazove s kojima se logističke kompanije 3PL susreću je i problem pronalaska, zadržavanja i osposobljavanja kvalificirane radne snage, za što se izjasnilo 59 % ispitanika. Problem kvalificirane radne snage koja će se uspješno nositi sa svim izazovima koje impliciraju digitalne tehnologije, vidljiv je u svim industrijama, ne samo u logističkoj industriji. Iako su evidentne prednosti digitalnih tehnologija u logistici, Zajac *et al*. (2025) ističu da je njihova primjena otežana zbog organizacijskih i strukturnih ograničenja, a stupanj implementacije ovisi o veličini poduzeća, zrelosti tržišta i internoj spremnosti za transformaciju.

Implementacija novih vještina nije moguća bez radne snage koja će biti spremna za prilagodbu novim uvjetima poslovanja. Istraživanje *The Future of Jobs Survey* navodi strategije koje poslodavci planiraju provesti kao odgovor na sve izazove koji se stavljaju pred njih zbog umjetne inteligencije. U 2025. godini, 77 % kompanija stavilo je kao prioritet prekvalifikaciju i usavršavanje radne snage za rad uz umjetnu inteligenciju, a potom zapošljavanje novih ljudi s vještinama za dizajniranje alata umjetne inteligencije i poboljšanja prikladnih za vještine specifične za organizaciju (69 %), dok se 62 % izjasnilo za strategiju traženja novih zaposlenikasa s vještinama za rad / integraciju umjetne inteligencije u svakodnevne zadatke (World Economic Forum 2025a), što se zorno može vidjeti na sljedećem grafikonu.

Grafikon 8. Strategije zapošljavanja za integraciju umjetne inteligencije (UI) diljem svijeta od 2025. do 2030.



Izvor: World Economic Forum (2025c) u Statista (2026)

Prema Future of Jobs Report 2025, predviđanja su da će se promijeniti 37 % vještina koje se koriste na radnom mjestu do 2030. godine. To se odražava i na logističku industriju, konkretno na opskrbne lance i prijevoz gdje su kompanije već uložile u prekvalifikaciju i usavršavanje zaposlenika, što ukazuje podatak da je 57 % zaposlenika završilo programe osposobljavanja. Sve je to posljedica digitalne transformacije logističkih subjekata, odnosno prilagodbe novim uvjetima te je i razumljivo i da ove kompanije imaju potrebu, odnosno

potražnju za vještinama poput umjetne inteligencije i velikih podataka, tehnološke pismenosti te mreža i kibernetičke sigurnosti. Analitičko razmišljanje također je identificirano kao prioritet, a 79 % kompanija očekuje povećanje njegove upotrebe (World Economic Forum 2025a). Sve navedeno ukazuje na zaključak da se globalni trendovi u svijetu odražavaju i na logističku industriju. Svi izazovi se prelijevaju u logistički sektor, koji treba zadovoljiti sve zahtjevnije tržište, i tržište ponude i tržište potražnje za logističkim uslugama. Biti konkurentan znači ulagati u znanje i obrazovanje radne snage, cjeloživotno učenje jer biti u toku s novim tehničko-tehnološkim postignućima znači kontinuirano ulaganje u znanje i obrazovanje. Samo tako može se ostati aktivni igrač i partner u suvremenim opskrbnim lancima.

5. ZAKLJUČAK

Brzina, kvaliteta, konkurentnost, održivost zahtjevi su koji se stavljaju pred subjekte koji su svakodnevno uključeni u brojne složene logističke procese. Nova tehničko-tehnološka postignuća u svijetu digitalnih tehnologija nameću implementaciju svih tehnologija i rješenja koja mogu omogućiti ostvarivanje zacrtanih ciljeva poslovanja, a najvažniji je zadovoljni kupac. Digitalne tehnologije omogućavaju brojne koristi za korisnike, od brzine dostupnih informacija, rješenja, praćenje pošiljaka, brz odgovor na izazove koji se javljaju tijekom opskrbnog lanca, inteligentna rješenja koja ubrzavaju, olakšavaju i omogućavaju održivo poslovanje. Implementacija digitalnih tehnologija donosi brojne koristi, koje se očituju kroz smanjenje troškova te povećanje prihoda. Međutim, istodobno traži od poslovnih subjekata i ulaganja u obrazovanje postojećih, ali i zapošljavanje nove radne snage koja će uspješno koristiti digitalne tehnologije.

I u logističkoj industriji, tendencije u vezi potrebnih digitalnih vještina iste su kako i u svakoj drugoj industriji. Zahtjevi za vještinama u vezi umjetne inteligencije, velikih podataka, tehnološke pismenosti te druge vještine predstavljene u radu još više dolaze do izražaja zbog specifičnog zadatka koji se stavlja pred logističke subjekte, a to je sigurna, brza i ekonomična isporuka proizvoda i usluga krajnjem potrošaču. I logistička poduzeća zasigurno će morati ulagati u nova znanja i vještine svojih zaposlenika kako bi opstala na globalnom tržištu.

Rezultati istraživanja predstavljeni u ovome radu rezultat su analize sekundarnih podataka iz dostupnih baza podataka i istraživanja. To ujedno predstavlja i ograničenje ovoga rada, stoga je preporuka za buduća istraživanja provesti primarno istraživanje sa subjektima logističkog tržišta o učincima digitalnih tehnologija na svakodnevno poslovanje, a posebice o vještinama zaposlenika u uvjetima digitalizacije.

Napomena: Ovaj je rad napisan u okviru projekta „Od obrazovanja do održivosti: ljudski potencijali, obrazovanje i tehnologija u ekonomskom razvoju“ (uniri-iz-25-203), koji je financiran sredstvima Europske unije – NextGenerationEU putem Nacionalnog plana oporavka i otpornosti Republike Hrvatske 2021.–2026., u suradnji s Ekonomskim fakultetom Sveučilišta u Rijeci kroz Programsko financiranje. Stavovi i mišljenja izneseni u ovom radu isključivo su autorova i ne odražavaju službeno stajalište Europske unije ili Europske komisije. Europska unija niti Europska komisija ne mogu se smatrati odgovornima za njih.

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Review

THE ROLE OF DIGITAL SKILLS IN ENHANCING THE COMPETITIVENESS OF COMPANIES IN THE LOGISTICS MARKET

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ABSTRACT

Constant improvements in the field of digital technology, omnipresent artificial intelligence pose new challenges for business entities. These challenges require constant innovation of business models, implementation of new technologies, investment in digital skills of human resources and continuous training and education of employees. The aim of this paper is to explore the role of digital technologies in contemporary business, especially in the logistics industry. The logistics industry is particularly involved and under constant pressure to implement contemporary technical and technological achievements in order to be competitive not only logistics operators, but also business entities involved in global supply chains. Therefore, the paper explores and analyses key participants in the logistics market, digital technologies and the skills that are necessary for everyday business, all in order to achieve sustainable competitiveness and greater resilience in the market. The analysis is based on the available secondary bibliographic sources and the Statista database. The paper contributes to the valorisation of digital technologies and skills as key elements for achieving competitiveness of supply chain entities and the logistics industry.

Key words: *logistics operators, digitalization, digital skills, supply chains, human resources*

Stručni rad

PAMETNA RJEŠENJA U DISTRIBUCIJI – DIGITALIZACIJA I OPTIMIZACIJA LANACA OPSKRBE KAO ALAT POVEĆANJA UČINKOVITOSTI

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SAŽETAK

Digitalizacija distribucijskih procesa predstavlja ključan čimbenik povećanja učinkovitosti opskrbnog lanca i ukupne poslovne uspješnosti poduzeća. U radu se analiziraju pametna tehnološka rješenja u distribuciji (TMS, IoT, RFID, GIS, robotika i AI) te njihov doprinos optimizaciji troškova distribucije, skraćivanju vremena isporuke i povećanju logističke pouzdanosti. Metodološki okvir temelji se na konceptualnom modelu i pilot empirijskom istraživanju na uzorku od 45 poduzeća iz Republike Hrvatske. Rezultati ukazuju na pozitivnu povezanost između primjene pametnih distribucijskih rješenja i ključnih ekonomskih pokazatelja (smanjenje troškova –8,4 %, povećanje točnosti isporuke +17 %, ubrzanje protoka informacija +22 %). Rad pruža teorijski i analitički okvir za razumijevanje ekonomskih učinaka digitalizacije distribucijskih sustava u hrvatskim poduzećima te predstavlja temelj za buduća empirijska istraživanja u području logistike i upravljanja opskrbnim lancima.

Ključne riječi: *digitalizacija; distribucija; IoT; optimizacija troškova; pametna logistika; TMS.*

1. UVOD

Distribucija predstavlja završnu fazu logističkog procesa te ključnu vezu između poduzeća i krajnjeg korisnika. U okolnostima snažne tržišne konkurencije, volatilnosti (kolebljivosti) potražnje i tehnološkog razvoja, optimizacija distribucijskih procesa postaje temeljni izvor konkurentske prednosti. Teorijska i praktična važnost distribucije ogleda se u njezinoj ulozi posrednika između proizvodnje i potrošnje, pri čemu svaki poremećaj u distribucijskom procesu izravno utječe na učinkovitost opskrbnog lanca (Christopher, 2016). U uvjetima dinamičnog tržišta i rasta e-trgovine, distribucija sve više postaje funkcija strateškog upravljanja, a ne samo operativne izvedbe.

Digitalna transformacija omogućuje poduzećima povećanje učinkovitosti kroz bolji protok informacija, smanjenje grešaka u isporuci i smanjenje troškova distribucije. Digitalna rješenja pritom omogućuju smanjivanje transakcijskih troškova, povećanje transparentnosti i unapređenje donošenja odluka, što potvrđuju recentna istraživanja u području logističke digitalizacije (UNCTAD, 2022; Deloitte, 2023). Cilj rada je utvrditi može li implementacija pametnih rješenja u distribuciji imati mjerljiv ekonomski učinak na poslovanje poduzeća.

2. TEORIJSKI OKVIR

2.1. Distribucija u suvremenoj logistici

Distribucija obuhvaća fizički tok robe i informacijskih tokova od proizvođača do krajnjeg potrošača, pri čemu učinkovitost ovog procesa značajno utječe na ukupnu profitabilnost poduzeća (Porter i Heppelmann, 2015).

U suvremenim uvjetima poslovanja, distribucija nadilazi tradicionalno shvaćanje fizičkog premještanja robe i obuhvaća strateško upravljanje materijalnim i informacijskim tokovima kao integriranom cjelinom. Prema modelu integrirane logistike, distribucija se povezuje s nabavom, zalihama, transportom, skladištenjem i sustavima praćenja, čime čini ključni podsustav lanca opskrbe (Lambert, 2022). U tom kontekstu, logistička distribucija postaje generator dodane vrijednosti, pri čemu se učinkovitost mjeri kroz pokazatelje kao što su vrijeme ciklusa isporuke, točnost isporuka, trošak po jedinici distribucije i razina zadovoljstva kupaca (World Bank, 2023).

Rast e-trgovine i očekivanja korisnika za bržom i transparentnijom isporukom dodatno naglašavaju potrebu za modernizacijom distribucijskih procesa i integracijom digitalnih tehnologija koje omogućuju praćenje pošiljaka u stvarnom vremenu, prediktivnu analitiku i automatizaciju ključnih aktivnosti.

2.2. Industrija 4.0 i pametna logistika

Industrija 4.0 podrazumijeva digitalnu integraciju fizičkih i informacijskih struktura i označava četvrtu industrijsku revoluciju obilježenu povezivanjem fizičkih procesa i digitalnih tehnologija u jedinstvene kiber-fizičke sustave (Kagermann, 2013). U logističkom okruženju, to znači implementaciju tehnoloških rješenja koja omogućuju autonomno planiranje, nadzor i optimizaciju distribucijskih aktivnosti.

Ključne tehnologije u distribuciji su:

- **TMS** (Transport Management System)
- **IoT** (Internet stvari)
- **RFID** (radiofrekvencijska identifikacija)
- **GIS** (geoinformacijski sustavi)
- **AI** (umjetna inteligencija)
- **RPA** (robotska automatizacija procesa)

TMS sustavi automatiziraju planiranje ruta i kapaciteta prijevoza, IoT i RFID osiguravaju sljedivost pošiljaka kroz senzorske mreže i identifikacijske točke, dok GIS sustavi omogućuju prostornu analitiku i optimizaciju rješenja u realnim geografskim uvjetima (Kumar, 2025). RFID i IoT tehnologije predstavljaju temelj stvaranja integriranih logističkih mreža u kojima fizički tokovi robe postaju digitalno vidljivi i upravljivi u realnom vremenu (Hofmann & Rüsch, 2022).

U naprednijim sustavima, AI i RPA koriste se za prediktivno upravljanje potražnjom, automatizaciju administrativnih procesa (npr. dokumentacija prijevoza, carinske evidencije) i donošenje odluka temeljenih na podacima.

Takva integracija tehnologija stvara koncept „pametne logistike“ (smart logistics), u kojem distribucijski procesi postaju agilniji, transparentniji i ekonomičniji (Tiwari, 2023).

2.3. Ekonomska logika optimizacije

Ekonomski učinci digitalne distribucije proizlaze iz smanjenja transakcijskih i operativnih troškova te povećanja produktivnosti postojećih resursa.

Digitalizacija distribucije rezultira:

- smanjenjem troškova transporta,
- skraćivanjem vremena isporuke,
- smanjenjem troškova pogrešnih isporuka,
- rastom zadovoljstva kupaca.

Optimizacija ruta smanjuje potrošnju goriva i održavanje voznog parka, digitalizacija dokumentacije smanjuje administrativne troškove, a preciznije planiranje isporuka smanjuje broj povrata i reklamacija (EC, 2024).

U distribucijskim sustavima koji koriste TMS i RFID tehnologije moguće je ostvariti 5–15 % uštede troškova i 10–25 % skraćenja vremena isporuke (PwC, 2024), što izravno utječe na profitabilnost poduzeća.

Ekonomsku logiku optimizacije moguće je povezati i s pojmom oportunitetnog troška, jer poduzeća koja ne uvode digitalna rješenja zaostaju u odnosu na konkurenciju koja koristi prednosti analitike, automatizacije i mrežne integracije (Singh, 2023).

3. METODOLOGIJA

Istraživanje ima karakter pilot empirijskog istraživanja kojim se preliminarno ispituje odnos između digitalizacije distribucijskih sustava i poslovne učinkovitosti poduzeća. Cilj istraživanja bio je utvrditi u kojoj mjeri implementacija pametnih distribucijskih tehnologija doprinosi optimizaciji troškova, povećanju točnosti isporuke i poboljšanju ukupnih logističkih performansi.

Podaci su prikupljeni tijekom 2025. godine putem online anketnog upitnika provedenog među poduzećima u Republici Hrvatskoj. Anketa je bila usmjerena na organizacije koje u poslovanju koriste distribucijske i logističke procese, uključujući poduzeća iz sektora proizvodnje, trgovine i logističkih usluga.

U istraživanju je sudjelovalo 45 poduzeća. Struktura uzorka prema djelatnostima bila je sljedeća: trgovina – 40 %, proizvodnja – 33 %, logističke usluge – 22 % i ostale djelatnosti – 5 %. Ciljana skupina ispitanika bili su voditelji logistike, menadžeri distribucije, voditelji opskrbnih lanaca te članovi uprave odgovorni za operativne procese. Takav izbor ispitanika omogućuje prikupljanje relevantnih informacija o primjeni digitalnih tehnologija u distribucijskim procesima i njihovim ekonomskim učincima. S obzirom na veličinu uzorka, istraživanje ima pilot karakter, a dobiveni rezultati imaju indikativnu vrijednost te služe kao osnova za buduća empirijska istraživanja na većem i reprezentativnijem uzorku poduzeća.

Anketni upitnik sastojao se od 12 pitanja raspoređenih u tri tematske cjeline:

a) Stupanj digitalizacije distribucijskih procesa (implementacija tehnologija poput TMS, IoT, RFID, GIS, AI i robotike); b) Operativna učinkovitost distribucije (točnost isporuke, vrijeme isporuke, protok informacija, logistička pouzdanost); c) Ekonomski učinci digitalne transformacije (smanjenje troškova distribucije, povećanje produktivnosti i utjecaj na profitabilnost).
Mjerenje varijabli provedeno je pomoću Likertove skale od 1 do 5, gdje je vrijednost 1 označavala vrlo nizak stupanj slaganja, a vrijednost 5 vrlo visok stupanj slaganja s ponuđenim tvrdnjama. Primjer tvrdnje korištene u istraživanju bio je: „Digitalne tehnologije u distribucijskim procesima našeg poduzeća doprinose smanjenju operativnih troškova i povećanju učinkovitosti logističkih aktivnosti.“ Pouzdanost mjernog instrumenta provjerena je primjenom Cronbach α koeficijenta, koji je iznosio 0,79, što ukazuje na zadovoljavajuću razinu interne konzistentnosti skale (Hair et al., 2021).

Prikupljeni podaci analizirani su primjenom deskriptivne statistike i Pearsonove korelacijske analize. Deskriptivna statistika korištena je za izračun prosječnih vrijednosti (M) i standardnih devijacija (SD) kako bi se dobio uvid u distribuciju ključnih varijabli istraživanja.

Pearsonov koeficijent korelacije primijenjen je za ispitivanje povezanosti između razine digitalizacije distribucijskih sustava i ekonomskih pokazatelja poslovne uspješnosti.

Procjene ekonomskih učinaka digitalizacije distribucije (–8,4 % smanjenja troškova distribucije, +17 % povećanja točnosti isporuke i +22 % ubrzanja protoka informacija) temelje se na percepciji ispitanika prikupljenoj putem Likertovih skala. Prosječne vrijednosti odgovora transformirane su u indikativne postotne promjene kako bi se olakšala interpretacija rezultata i usporedba s postojećim istraživanjima u području logistike i digitalizacije opskrbnih lanaca.

Na temelju teorijskog okvira i pregleda literature formulirane su sljedeće istraživačke hipoteze:

H1: Viša razina digitalizacije distribucijskih procesa povezana je sa smanjenjem troškova distribucije.

H2: Implementacija pametnih distribucijskih tehnologija (TMS, IoT, RFID) pozitivno utječe na točnost isporuka.

H3: Digitalizacija distribucijskih sustava pozitivno utječe na ukupnu poslovnu uspješnost poduzeća.

4. REZULTATI I RASPRAVA

Prije analize odnosa među varijablama provedena je deskriptivna statistička analiza kako bi se dobio osnovni uvid u distribuciju ključnih konstrukata istraživanja. Deskriptivna statistika omogućuje preliminarnu procjenu razine digitalizacije distribucijskih procesa te percepcije ekonomskih učinaka digitalne transformacije među promatranim poduzećima. Prosječne vrijednosti (M) i standardne devijacije (SD) korištene su kao indikatori centralne tendencije i disperzije podataka.

Tablica 1 – Deskriptivna statistika varijabli

Varijabla	M	SD
Digitalizacija distribucije	3.68	0.82
Operativna učinkovitost	3.74	0.76
Smanjenje troškova distribucije	3.55	0.71
Točnost isporuke	3.91	0.64
Profitabilnost	3.48	0.79

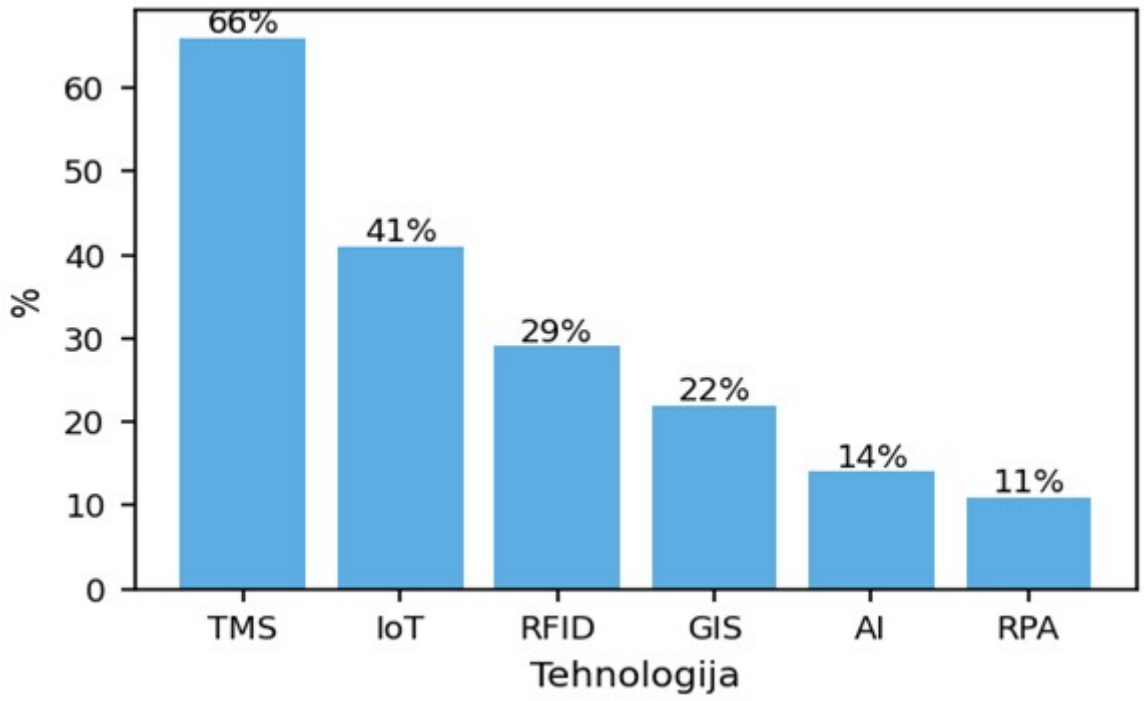
Izvor: autori

Dobiveni rezultati pokazuju umjereno visoku razinu digitalizacije distribucijskih sustava u promatranom uzorku poduzeća. Najvišu prosječnu vrijednost bilježi varijabla operativne učinkovitosti distribucije, što upućuje na činjenicu da ispitanici digitalne tehnologije prvenstveno povezuju s povećanjem operativne učinkovitosti i boljom koordinacijom logističkih aktivnosti. Najniža prosječna vrijednost zabilježena je kod varijable profitabilnosti, što potvrđuje da financijski učinci digitalizacije često nastupaju s vremenskim odmakom i ovise o stupnju integracije tehnologije u poslovne procese.

4.1. Učestalost primjene tehnologija

U nastavku slijedi analiza učestalosti implementacije tehnologija u poduzećima na području Republike Hrvatske (Grafikon 1).

Grafikon 1. Implementacija pametnih tehnologija u distribuciji poduzeća u RH



Izvor: Autori

Analizom je vidljivo kako poduzeća u Hrvatskoj najčešće uvode TMS sustave (66 %), što odražava razvojnu fazu digitalizacije u kojoj je naglasak stavljen na optimizaciju osnovnih operacija prijevoza.

Niža primjena IoT i RFID tehnologije (41 % i 29 %) upućuje na činjenicu da se napredna rješenja implementiraju selektivno, uglavnom u poduzećima s većim financijskim kapacitetom ili onima koja posluju u internacionalnim logističkim mrežama.

Slične trendove potvrđuje Zhu (2024), koji navodi da se najveći pomaci u profitabilnosti kod RFID-a i IoT-a ostvaruju tek kada sustavi prijeđu iz faze parcijalne u fazu integrirane primjene, odnosno kada se povežu s TMS i ERP sustavima na razini cijelog opskrbnog lanca.

Primjena AI i robotskih sustava (14 % i 11 %) najniža je, što je u skladu s globalnim trendovima razvoja MSP sektora (OECD, 2023).

Ovi podaci ukazuju da digitalna transformacija distribucije u Hrvatskoj ima postupan karakter, s izraženim tranzicijskim obilježjima i potrebom za financijskim i edukacijskim poticajima.

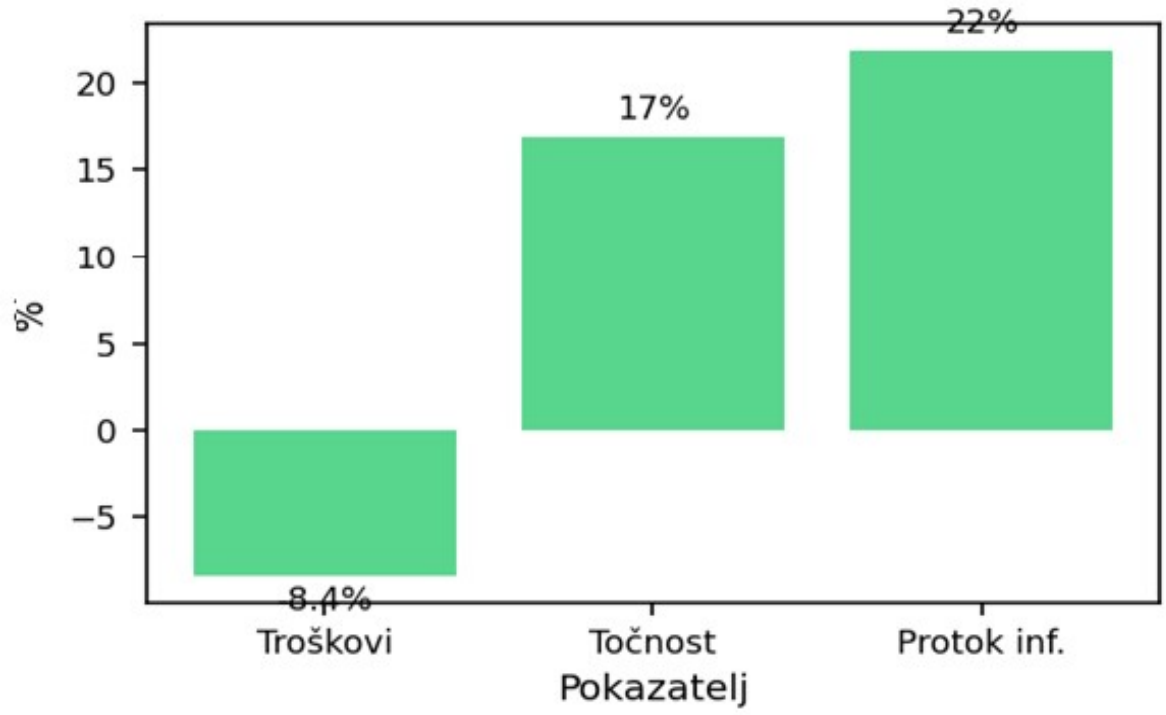
7.2 4.2. Ekonomski učinci

Pokazatelji ekonomske uspješnosti kroz digitalizaciju distribucije (Grafikon 2) ukazuju na:

- smanjenje troškova distribucije: –8,4 **%**
- poboljšanje točnosti isporuke: +17 **%**
- ubrzanje protoka informacija: +22 **%**
- pozitivan utjecaj na profitabilnost (Likert): 3,8/5

Rezultati ukazuju da je TMS tehnologija najraširenija, što potvrđuje njezinu važnost u operativnom planiranju ruta i optimizaciji transportnih kapaciteta, dok niža primjena IoT i RFID tehnologija sugerira tehnološke i financijske barijere u MSP sektoru (Björklund, 2021).

Grafikon 2. Ekonomski učinci digitalizacije distribucije (%)



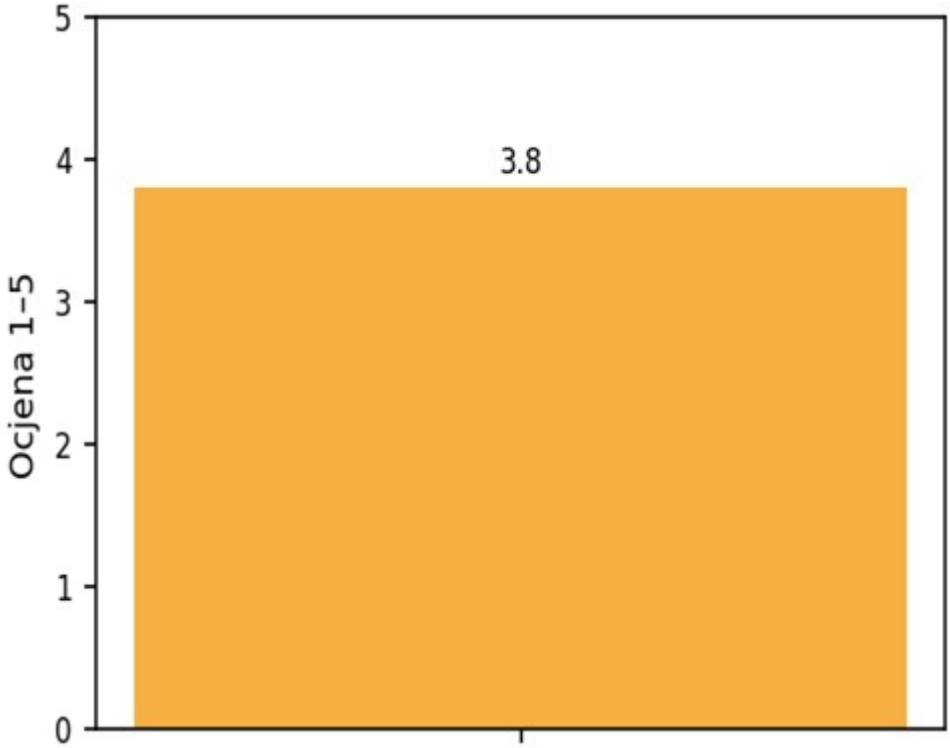
Izvor: Autorova obrada (2025).

Dobiveni pokazatelji ekonomske uspješnosti potvrđuju da digitalizacija distribucije generira mjerljive koristi, iako je varijabilnost učinaka prisutna ovisno o sektoru i stupnju digitalne zrelosti poduzeća. Ovaj nalaz je usklađen s recentnim istraživanjima koja ukazuju na 7–15 % prosječnog smanjenja troškova logističkih aktivnosti implementacijom pametnih tehnologija (World Bank, 2023; EC, 2024).

Detaljnijom analizom prikazanih pokazatelja može se uočiti da je najveći doprinos digitalizacije vidljiv u komponenti protoka informacija (+22 %), što je logična posljedica integracije informacijsko-komunikacijskih tehnologija u distribucijske procese. Povećanje brzine i točnosti prijenosa podataka smanjuje potrebu za ponovnim manipulacijama i korekcijama u isporučenim dokumentima, čime se posredno smanjuju i operativni troškovi (Lambert, 2022). Istodobno, poboljšanje točnosti isporuke (+17 %) ima pozitivan utjecaj na korisničko iskustvo i zadovoljstvo kupaca, što u srednjem roku smanjuje financijski pritisak zbog reklamacija i logističkih povrata, koji u praksi mogu iznositi i do 1–3 % ukupnih godišnjih troškova distribucije (OECD, 2023).

Uočenih –8,4 % smanjenja troškova distribucije pokazuje da digitalizacija primarno djeluje kroz optimizaciju uporabe resursa, prije svega voznog parka i skladišno-transportne opreme. Najveći učinci pritom su identificirani u fazama planiranja i izvršenja transporta, dok su učinci na administrativno-financijske aspekte distribucije slabiji, što ukazuje na potrebu za integriranim pristupom digitalnoj transformaciji (Deloitte, 2023). U MSP sektoru, u kojem su investicijski kapaciteti ograničeni, najvažniji izazovi odnose se na početne troškove nabave tehnologija i nedostatak stručnog kadra za rad s naprednim sustavima.

Grafikon 3. Percepcija profitabilnosti digitalizirane distribucije (Likert 1–5)



Izvor: Autorova obrada (2025).

Dobiveni rezultat (prosječna ocjena 3,8) upućuje na umjereno pozitivan utjecaj digitalizacije distribucije na poslovnu profitabilnost, uz izraženu varijabilnost među poduzećima ovisno o sektoru, razini tehnološke infrastrukture i stupnju integracije sustava (TMS/IoT/RFID). Ovaj nalaz djelomično potvrđuje hipotezu H3, uz napomenu da je učinak profitabilnosti uvjetovan i vanjskim čimbenicima poput cijene goriva, tržišne volatilnosti i logističke sezonalnosti, što zahtijeva dodatna empirijska istraživanja (PwC, 2024; Deloitte, 2023).

Na temelju dobivenih rezultata mogu se predložiti sljedeći koraci za poduzeća u fazi digitalne transformacije distribucije:

1.) Fazno uvođenje tehnologija: TMS → IoT → RFID → AI, ovisno o razini digitalne zrelosti i financijskim mogućnostima.
2.) Integracija podataka: povezivanje TMS sustava s računovodstvenim i prodajnim modulima radi smanjenja dupliciranja podataka i pogrešaka.
3.) Model povrata ulaganja: izrada ROI projekcija prije uvođenja tehnologije, s naglaskom na operativne i nefinancijske koristi (vrijeme, točnost, zadovoljstvo korisnika).

Ovakav pristup omogućuje smanjenje rizika i povećanje vjerojatnosti uspješne implementacije, osobito u sektorima s visokom osjetljivošću na troškovne strukture.

Usporedba rezultata Grafikona 2 i Grafikona 3 potvrđuje da se operativni učinci i financijski učinci digitalizacije ne razvijaju istim intenzitetom. Dok operativni pokazatelji bilježe značajnije pomake, percepcija profitabilnosti (Likert prosjek 3,8/5) upućuje na to da financijske koristi za upravu postaju vidljive tek nakon određenog perioda, što je u skladu s investicijskom logikom i očekivanim povratom na uloženi kapital (ROI) u tehnološke sustave.

U tom smislu, može se zaključiti da digitalna transformacija distribucije ima karakteristike postupnog akumulativnog učinka — učinci se ne manifestiraju trenutno, ali se multipliciraju s razinom digitalne zrelosti poduzeća.

4.3. Ilustrativni primjer primjene digitalnih rješenja u distribuciji

Poduzeće Y (srednje trgovačko poduzeće iz Istočne Hrvatske) implementiralo je TMS i RFID sustav.

Nakon 6 mjeseci:

- troškovi distribucije smanjeni za 8,1 **%**,
- vrijeme isporuke skraćeno za 15 **%**,
- točnost isporuka povećana na 95 **%**.

Prikazani ilustrativni primjer potvrđuje nalaze empirijskog dijela rada.

Ključni pokretač pozitivnih rezultata bila je integracija TMS i RFID sustava, čime je poduzeće Y dobilo mogućnost planiranja ruta na dnevnoj osnovi prema kriteriju minimalnog troška i dostupnih kapaciteta. Istodobno, RFID je omogućio automatizirano praćenje pošiljaka kroz sve faze isporuke, što je rezultiralo smanjenjem administrativnih pogrešaka i bržim rješavanjem reklamacija. Iako se radi o ilustrativnom primjeru primjene tehnologije, pokazatelji koji se odnose na smanjenje troškova i povećanje učinkovitosti usporedivi su s empirijski potvrđenim nalazima istraživanja Deloitte (2023), PwC (2024) i World Bank (2023), što upućuje na realističnost prikazanog modela.

4.4. Rasprava

Provedeno istraživanje potvrđuje da implementacija pametnih rješenja u distribuciji generira mjerljive operativne koristi, pri čemu su najveći učinci vidljivi u segmentu optimizacije prijevoza i upravljanja voznim parkom.

Dobiveni rezultati u skladu su s recentnim istraživanjima u području digitalne transformacije opskrbnih lanaca koja naglašavaju važnost digitalnih tehnologija u povećanju učinkovitosti logističkih procesa. Ivanov (2022) ističe da integracija digitalnih tehnologija u opskrbne lance omogućuje veću fleksibilnost i otpornost logističkih sustava, dok Hofmann i Rüsch (2022) naglašavaju kako digitalizacija logistike doprinosi optimizaciji operativnih troškova i povećanju transparentnosti distribucijskih procesa. Metodološki pristup temeljen na deskriptivnoj statistici i korelacijskoj analizi uobičajen je u preliminarnim istraživanjima digitalizacije logističkih sustava, osobito u studijama pilot karaktera (Hair et al., 2021).

Dobiveni rezultati potvrđuju da digitalizacija distribucijskih sustava ne predstavlja samo tehnološku inovaciju već i važan ekonomski instrument povećanja konkurentnosti poduzeća u suvremenim opskrbnim lancima.

Rezultati sugeriraju da primjena TMS sustava ima najveći učinak na smanjenje operativnih troškova (–8,4 %) i povećanje točnosti isporuka (+17 %), što je u skladu s nalazima autora Deloitte (2023) i Lambert (2022), koji ističu da je digitalizacija transportnog planiranja najbrže isplativ element logističke transformacije. Upravo je ova tehnologija prepoznata kao „nukleus“ digitalizacije i u hrvatskom MSP sektoru, što je indikator tranzicijske faze digitalne zrelosti poduzeća. Međutim, niža zastupljenost RFID i AI rješenja (29 % i 14 %) upućuje na prisutne tehnološko-investicijske barijere, osobito kod manjih poduzeća s ograničenim financijskim kapacitetima. Ovaj nalaz je u skladu s radovima OECD-a (2023), prema kojima je MSP sektor u logistici najosjetljiviji na visoke inicijalne troškove digitalizacije, kako u pogledu nabave opreme i softvera, tako i u pogledu potrebe za stručnim kadrom. Prema Indeksu digitalnog gospodarstva i društva (DESI), Hrvatska još uvijek zaostaje za prosjekom EU u integraciji digitalnih tehnologija u poslovne procese, posebno u logistički intenzivnim sektorima.

Dodatno, implementacija naprednijih rješenja zahtijeva organizacijske promjene i redefiniranje poslovnih procesa, što za dio poduzeća predstavlja strateški rizik koji odgađa investicijsku odluku.

Time se u potpunosti potvrđuje hipoteza H1, prema kojoj je viša razina digitalizacije distribucijskih procesa povezana sa smanjenjem troškova distribucije, kao i hipoteza H2, koja

pretpostavlja pozitivan utjecaj implementacije pametnih distribucijskih tehnologija na točnost isporuka. Hipoteza H3, koja se odnosi na ukupnu poslovnu uspješnost, potvrđuje se djelomično, budući da financijski učinci ovise i o nizu vanjskih čimbenika. Ova se interpretacija podudara s konceptom odgođene monetizacije digitalne transformacije, gdje se povrat investicije (ROI) ostvaruje kumulativno i tek nakon stabilizacije operativnih promjena (PwC, 2024).

Dobiveni rezultati otvaraju prostor za daljnja istraživanja, osobito u obliku longitudinalnih studija koje bi omogućile praćenje promjena u razdoblju od 3–5 godina, kao i komparativnih istraživanja između poduzeća s različitim razinama digitalne zrelosti. Također je preporučljivo istražiti i utjecaj regulatornih poticaja, programa digitalizacije i sve veće prisutnosti e-trgovine na ubrzavanje uvođenja pametnih logističkih rješenja. U tom smislu, prezentirani rezultati predstavljaju temelj za razvoj modela strateške primjene digitalnih tehnologija u distribuciji, primjenjivog za hrvatska i regionalna poduzeća.

5. ZAKLJUČAK

Digitalizacija distribucije predstavlja strateški potencijal za povećanje učinkovitosti logističkih procesa i ukupne poslovne uspješnosti poduzeća.

Rezultati potvrđuju da pametna rješenja, osobito TMS i IoT sustavi, imaju mjerljiv ekonomski učinak.

U kontekstu hrvatskih poduzeća, posebno MSP sektora, preporučuje se korištenje dostupnih fondova i poticanje ulaganja u tehnološku opremu i edukaciju zaposlenika.

Istraživanje je pokazalo da digitalizacija distribucije predstavlja sustavni i višedimenzionalni proces koji obuhvaća tehnološke, organizacijske i ekonomske elemente poduzeća. Ključni zaključak jest da primjena pametnih rješenja, osobito TMS, IoT i RFID sustava, generira pozitivne učinke na operativnu učinkovitost i financijske pokazatelje, iako je intenzitet učinaka uvjetovan digitalnom zrelošću poduzeća.

Provedena analiza potvrđuje hipoteze H1 i H2, dok se H3 potvrđuje djelomično, zbog prisutnosti eksternih faktora koji mogu umanjiti kratkoročne financijske učinke. U kontekstu hrvatskog gospodarstva, preporučuje se daljnje jačanje poticajne politike za ulaganje u digitalnu infrastrukturu, edukaciju zaposlenika i međunarodnu integraciju distribucijskih mreža.

Na temelju provedenog istraživanja mogu se izdvojiti sljedeće ključne implikacije:

- digitalizacija distribucije ima najveći učinak na operativne procese, osobito planiranje i praćenje isporuka;
- ekonomski učinci imaju postupni karakter, a povrat investicije vidljiv je tek nakon stabilizacije integracije sustava;
- tehnologije prve razine (TMS, IoT) predstavljaju preduvjet za uvođenje naprednijih rješenja (RFID, AI, RPA);
- u MSP sektoru digitalna transformacija često ovisi o eksternim potporama (fondovi, subvencije, edukacijski programi);
- rezultati potvrđuju nužnost faznog pristupa digitalizaciji te strateškog planiranja investicijskog ciklusa.

Za buduća istraživanja preporučuje se:

- provođenje longitudinalnog istraživanja u razdoblju od 3–5 godina radi provjere stabilnosti učinaka digitalizacije;
- komparativna analiza između poduzeća različite veličine i djelatnosti kako bi se ustanovile razlike u strategijama digitalne transformacije;
- istraživanje utjecaja regulacije i poticajnih mehanizama na brzinu i uspješnost digitalizacije u distribucijskim sustavima.

Navedene preporuke mogu poslužiti kao temelj za buduća empirijska istraživanja i razvoj primjenjivih modela digitalne zrelosti u hrvatskom i regionalnom kontekstu.

Rad potvrđuje teorijske i praktične aspekte utjecaja digitalne distribucije na poslovanje te pruža konceptualni i analitički okvir za razumijevanje ekonomskih učinaka digitalizacije distribucijskih sustava u hrvatskim poduzećima. Na taj način rad povezuje rezultate istraživanja s obrazovnim i stručnim kontekstom te nudi model za ocjenu digitalne zrelosti distribucijskih sustava primjenjiv u poslovnoj praksi i budućim istraživanjima.

U širem europskom kontekstu, rezultati upućuju na to da digitalizacija distribucijskih sustava predstavlja važan mehanizam jačanja otpornosti i konkurentnosti poduzeća u uvjetima rastuće tržišne neizvjesnosti i transformacije opskrbnih lanaca. Time se rad uključuje u suvremenu znanstvenu raspravu o ulozi pametne logistike i digitalne zrelosti kao strateških odrednica održive poslovne učinkovitosti.

Buduća istraživanja trebala bi uključiti veći i reprezentativniji uzorak poduzeća te primjenu naprednijih statističkih metoda kako bi se preciznije utvrdili uzročno-posljedični odnosi između digitalizacije distribucije i poslovne uspješnosti poduzeća.

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Professional paper

SMART SOLUTIONS IN DISTRIBUTION - DIGITALISATION AND SUPPLY CHAIN OPTIMISATION AS A TOOL FOR INCREASING EFFICIENCY

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ABSTRACT

The digitalisation of distribution processes represents a key driver of supply chain efficiency and overall business performance. This paper analyses smart technological solutions in distribution, including Transport Management Systems (TMS), Internet of Things (IoT), RFID technologies, geographic information systems (GIS), robotics and artificial intelligence (AI), and their contribution to optimising distribution costs, reducing delivery times and improving logistics reliability. Based on a conceptual framework and a pilot empirical study conducted on a sample of 45 companies in the Republic of Croatia, the research examines the relationship between the level of distribution digitalisation and key economic indicators. The results indicate a positive relationship between the implementation of digital technologies and operational efficiency, including cost reduction (–8.4%), improved delivery accuracy (+17%) and faster information flows (+22%). The paper provides a theoretical and analytical framework for understanding the economic effects of distribution systems digitalisation in Croatian companies and offers a basis for future empirical research in the field of logistics and supply chain management.

Keywords: *digitalisation; distribution; IoT; cost optimisation; smart logistics; TMS.*

Prethodno priopćenje

MODEL PROBLEMA TRGOVAČKOG PUTNIKA (TSP) I ALGORITMA DETALJNE PRETRAGE U PRONALAŽENJU OPTIMALNIH I SUBOPTIMALNIH RJEŠENJA SLOŽENE TRANSPORTNE MREŽE

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SAŽETAK

U radu se istražuje uporaba metode trgovačkog putnika i algoritma detaljne pretrage u identificiranju i pronalaženju optimalnih i suboptimalnih rješenja s ciljem optimizacije i modeliranja fleksibilne transportne mreže. Vizualnim i objektnim metodama programiranja i modeliranja u oblikovanju algoritma detaljne pretrage mogu simulirati modeli s više optimalnih riješenja za manje uzorke (do 10 robno transportnih centara) uz jasnu interpretaciju rezultata ne samo za iste optimalne vrijednosti nego i približno jednake vrijednosti i uz definiranje dopuštenih odstupanja od optimalnih vrijednosti. U razmatranom primjeru transportna mreža sastoji se od 13 čvorova i razmatra se kao složena transportna mreža. Konceptualnim modeliranjem složene transportne mreže cilj je omogućiti pronalaženje optimalnih i suboptimalnih riješenja za uzorke veće od 10 čvorova. U tom okviru predloženog modela transportna mreža je podijeljena u više parova skupova (segmenta): 1) skup gradova (čvorova) koji su locirani (smješteni) na istom prometnom pravcu koji predstavlja optimalni transportnim put (transportnu relaciju) i 2) skup gradova (čvorova) koji se povezuju putem različitih transportnih relacija i koji su uključeni u izračun pomoću algoritma iscrpne pretrage. Pri tome se definiraju krajnji čvorovi koji su zajednički za oba dva člana u paru skupa i koji se u modelu izračuna povezuju virtualnom transportnom relacijom.

Ključne riječi: *problem trgovačkog putnika (TSP), algoritam detaljne pretrage, složena transpotna mreža, optimalna i suboptimalna rješenja, modeliranje i optimizacija*

1. UVOD

U radu se analizira metoda segmentiranja transportne mreže u sinergiji sa uporabom algoritma detaljne pretrage u pronalaženju više optimalnih i suboptimalnih rješenja na primjeru transportne mreže u obliku složene piramide. Fleksibilnost i prilagodljivost prometnih mreža mogu se postići optimizacijom ruta kretanja vozila između jednog od izvora i više odredišta u prometnoj mreži [8]. Najvažnija operativna odluka vezana uz prijevoz u opskrbi s gledišta analogije prometne mreže i piramidalne strukture može se postaviti prema analogiji prema kojoj je broj optimalnih rješenja faktor fleksibilnosti i prilagodljivosti prometne mreže. Model prometne mreže koji koristi bazu kvadratne piramide omogućuje nam prezentaciju i analizu mogućnosti generiranja velikog broja optimalnih rješenja koja imaju jednake ili slične vrijednosti [9]. Pronalaženje više optimalnih prometnih ruta (optimalno rješenje i suboptimalna rješenja) omogućuje veću fleksibilnost u optimizaciji i modeliranju prometne mreže s ciljem izračuna nekoliko različitih prometnih ruta koje zadovoljavaju različite kriterije, kao što su različite prometne potrebe u različitim vremenskim razdobljima.

Osnovni kriterij za odabir optimalnog rješenja je udaljenost između čvorova transportne mreže. U slučajevima iste ili slične udaljenosti postoji mogućnost dinamičkog odabira više transportnih relacija za različita vremenska razdoblja, pa s gledišta drugih relevantnih kriterija može postojati jedna optimalna relacija za određeno vremensko razdoblje, a druga optimalna

relacija za ostala razdoblja. Većina postojećih softverskih rješenja omogućuje izračun i uvid u jedno optimalno rješenje. Pronalaženje velikog broja optimalnih transportnih relacija omogućuje veću fleksibilnost u donošenju višekriterijskog odabira optimalne transportne relacije, posebno tijekom različitih vremenskih razdoblja (Vukmirović i Pupavac, 2013). Metodološki okvir korištenja Visual Basica kao razvojnog alata u vizualnom modeliranju algoritma detaljne pretrage u sučelju proračunske tablice Excel može poslužiti kao poticaj u stvaranju novih visoko sofisticiranih algoritama, koji omogućavaju izračunavanje optimalnih i suboptimalnih rješenja prometne mreže (Vukmirović, Čičin-Šain, Host, 2015).

Stoga se na temelju definiranog problema formulira sljedeća istraživačka hipoteza: sinergija metode segmentiranja transportne mreže i algoritma detaljne pretrage u sučelju proračunske tablice omogućava izračun više optimalnih i suboptimalnih rješenja za složene transportne mreže koje imaju više od devet čvorova.

2. TEORIJSKE ZNAČAJKE MODELA PROBLEMA TRGOVAČKOG PUTNIKA I ALGORITMA DETALJNE PRETRAGE U OPTIMIZACIJI TRANSPORTNE MREŽE U OBLIKU KVADRATNE PIRAMIDE

Problem trgovačkog putnika (TSP) se koristi kao metoda optimizacije transportnog problema kako bi se izračunao i pronašao pronašli najkraći put za putovanje (transport) kroz zadani broj gradova. Problem trgovačkog putnika (TSP) polazi od problemske situacije kod koje su zadani broj gradova N i udaljenosti između gradova, tako da putnik (vozilo) mora putovati kroz sve zadane gradove točno jednom i na kraju se vratiti u isti grad iz kojeg je krenuo (u kojem je počeo putovanje), pri čemu duljina puta (ukupne transportne rute između svih gradova) treba biti minimalna (Rao, I Hegde, 2015).

Problem trgovačkog putnika (TSP) je jedan od najinteresantnijih problema u menadžerskoj znanosti. Optimalan pristup u rješavanju problema trgovačkog putnika se temelji na matematičkom programiranju. Ali u stvarnosti, za veliki dio TSP problema nije moguće egzaktno i precizno utvrditi optimalno rješenje. U slučaju velike kompleksnosti problema (veliki broj čvorova u mreži) izračunavaju se aproksimativna rješenja i koriste se heurističke metode. Primjeri heursitičkih metoda u rješavanju problema trgovačkog putnika su algoritam najbližeg susjeda i Clark-Wrigtov algoritam ušteda (Heizer i Render, 2004).

Problem trgovačkog putnika (TSP; Travelling Salesman Problem) s motrišta kombinatoričke optimizacije može se formulirati na sljedeći način: Zadan je skup od n gradova C i udaljenosti dij putovanja iz grada i u grad j. Potrebno je, krenuvši iz zadanog grada, obići sve gradove točno jednom, tako da ukupna dužina prijevozne relacije bude minimalna. U skladu s navedenom definicijom izvode se sljedeće formule i izrazi: 1) Dužine prijevoznih relacija (udaljenosti između gradova) su simetrične: (1) dij = dji ; 2) Kao ulazna varijabla definiran je konačan skup gradova, izrazom C = (c1 … cn) a matrica udaljenosti definirana je izrazom d(ci,cj) koji označava udaljenost između grada ci i grada cj za svaki par i,j. S obzirom da je matrica udaljenosti simetrična vrijedi formula cij = cji ; 3) Kao rezultantne varijable izračunavaju se permutacije odnosno sve permutirane relacije koje se mogu postići za zadani broj gradova. Permutacije p(1), …, p(n) u skupu 1, …, n izračunavaju se i uspoređuju tako da je zbroj u formuli minimalan (Abdoun, Abouchabaka i Tajani, 2012).

Algoritam detaljne pretrage, poznat i kao algoritam grube sile (brute force), pripada općim metodama i tehnikama rješavanja Uporabom algoritma iscrpne pretrage u okviru problema trgovačkog putnika (TSP), svakoj transportnoj ruti turneji odgovara permutacija od n gradova (Fomin i Kratsch2010). Algoritam detaljne pretrage, numerira (označava) svaku moguću (alternativnu) rutu kao “kandidata” za rješenje (permutaciju) problema i računalno provjerava svakog kandidata (permutaciju) u kontekstu optimalnog rješenja (minimalne duljine transportne rute). Metoda iscrpne pretrage je prikladna za manje uzorke (n <= 10).

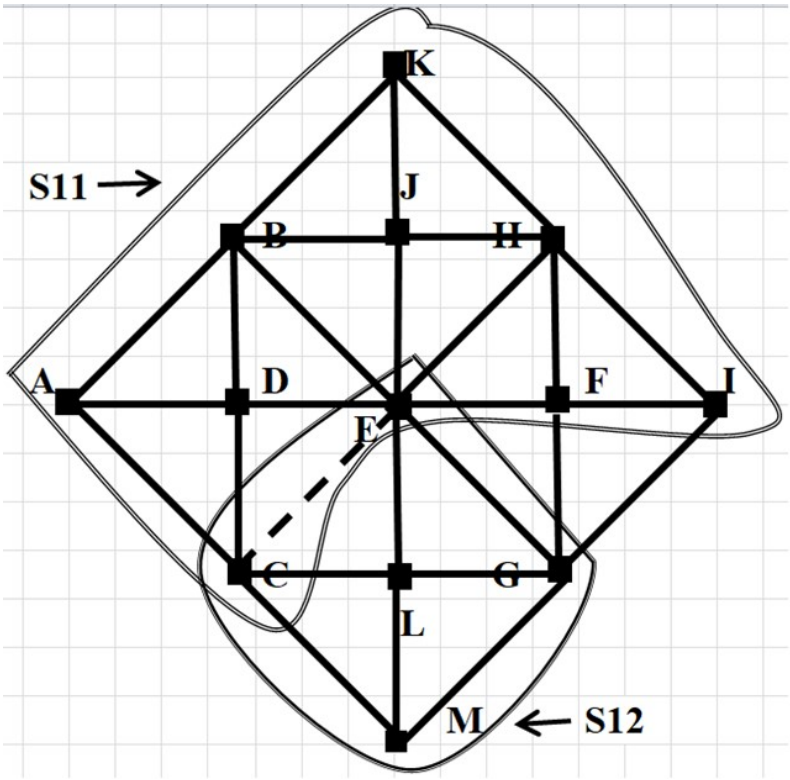
U tablici 1. prikazan je eksponencijalni (faktorijalni) rast broja mogućih rješenja i vremena izračunavanja u odnosu na broj čvorova u logističkoj mreži i vremena izračunavanja. Tablica prikazuje kompleksnost problema trgovačkog putnika (TSP).

Ako promatramo transport robe smatrati da je učinkovitost transporta razmjerna stupnju izgrađenosti transportne mreže, te da strateško planiranje transporta treba temeljiti na optimalnom kretanju kretanju vozila po transportnoj mreži. Strateško planiranje zahtijeva od menadžera da razumiju vrste čimbenika koji postoje u okolini (Certo i Certo, 2008), te da u skladu s tim izgrade fleksibilnu i adaptibilnu transportnu mrežu. Fleksibilnost i adaptibilnost transportne mreže može se postići pomoću optimiziranja ruta kretanja vozila između jednog mjesta izvorišta i određenog, većeg broja odredišta prijevoza. Najvažnija operativna odluka o transportu u opskrbnom lancu je vezana za upravljanje robnim tokovima u transportnoj mreži (Chopra I Meindl, 2001).

3. KONCEPTUALNI MODEL TRANSPORTNE MREŽE U OBLIKU SLOŽENE PIRAMIDE

Na slici 1. je prikazan i oblikovan konceptualni model transportne mreže u obliku složene piramide. U tablici su prikazane udaljenosti između čvorova mreže. Vrijednosti udaljenosti izražene su u kilometrima (km).

Slika 1. Konceptualni model transportne mreže u obliku prve kombinacije segmenata S11 i S12



Konceptualni model transportne mreže, kako je prikazano na slici 1. podijeljen je u dvije skupine (segmente) S11 i S12 s gledišta pronalaženja više optimalnih i suboptimalnih rješenja. Model pokazuje da segment S11 uključuje deset čvorova, a segment S12 uključuje per čvorova, pri čemu oba segmenta uključuju čvorove E i C.. U segmentima S1 i S2 analizirane su mogućnosti povezivanja gradova (čvorova) putem različitih prometnih ruta te su izračunata optimalna i suboptimalna rješenja korištenjem iscrpnog algoritma pretraživanja. U primjeru su definirani čvorovi E i C, koji su zajednički definiranim segmentima prometne mreže S11 i S12. Čvorovi E i C, označeni u modelu predstavljaju zajedničke točke i ujedno krajnje točke za segmente prometne mreže S11 i S12 te omogućuju povezivanje segmenata prometne mreže.

Konceptualni model transportne mreže u obliku složene piramide prikazan na slici 1. oblikovan je u funkciji pronalaženja više optimalnih i suboptimalnih rješenja. Konceptualni model transportne mreže prema kojem je transportna mreža podijeljena na dva skupa

(segmenta): skup čvorova S11 i skup čvorova S12 koji se povezuju putem različitih transportnih relacija i koji su uključeni u izračun pomoću algoritma detaljne pretrage. Pri tome su definirani krajnji čvorovi koji su zajednički za oba dva segmenta S11 i S12 i koji se u modelu izračuna povezuju virtualnom transportnom relacijom.

Na slici 1. se vidi da se čvorovi unutar segmenata S11 i S12 mogu povezivati putem različitih transportnih ruta, a koje mogu generirati više optimalnih i suboptimalnih rješenja. U primjeru na slici isprekidana linija označava virtualnu prometnu relaciju EC. Pri tome čvor E u segmentu S11 predstavlja polazište, a čvor C odredište transportne mreže. U segmentu S12, čvor C koji prestavlja odredište segmenta S11 je istodobno i polazište u segmentu S12 transportne mreže, Ishodište segmenta S12 transportne mreže je čvor E, koji je istodobno i čvor ishodišta i odredišta na razini cjelokupne transportne mreže u kojoj su objedinjeni segmenti S11 i S12.

4. JEDNOSTAVNO I SLOŽENO POVEZIVANJE SEGMENATA TRANSPORTNE MREŽE

Jednostavno povezivanje segmenata transportne mreže moguće je u slučaju kada u zadanom geometrijskom modelu segmenata transportne mneže za svako optimalno ili suboptimalno rješenje vezni čvorovi predstavljaju početni i krajnji čvor za oba segmenta [9], [10]. Tako se na temelju jedne kombinacija segmenata transportne mreže mogu izračunati sva optimalna i suboptimalna rješenja. Primjer jednostavnog povezivanja segmenta može se vidjeti na primjeru transportne mreže urbane aglomeracije Rijeka koji je prikazan na slici 1.

Zemljovid 1. Primjer jednostavnog povezivanja segmenta može se vidjeti na primjeru transportne mreže urbane aglomeracije Rijeka

Izvor: Vukmirović, S:, Čapko, Z., Džido, A. (2023).

U slučaju transportne mreže u obliku složene piramide vidljivo je da postoji više kombinacija segmenata transportne mreže koje generiraju optimalan i suboptimalna rješenja. Na slici 1. je vidljiva kombinacija segmenata transportne mreže kod koje su vezni čvorovi E i C. U primjeru je analizirana još jedna kombinacija segmenata transportne mreže (druga kombinacija segmenata) kod koje su vezni čvorovi E i B. Kombinacija segmenata kod koje su vezni čvorovi E i C predstavlja prvu kombinaciju segmenata transportne mreže S11 i S12 (slika 1.) Kombinacija segmenata kod koje su vezni čvorovi E i B predstavlja drugu kombinaciju segmenata transportmne mreže S21 i S22.

5. METODA DETALJNE PRETRAGE U IZRAČUNU OPTIMALNIH I SUBOPTIMALNIH RJEŠENJA TRANSPORTNE MREŽE

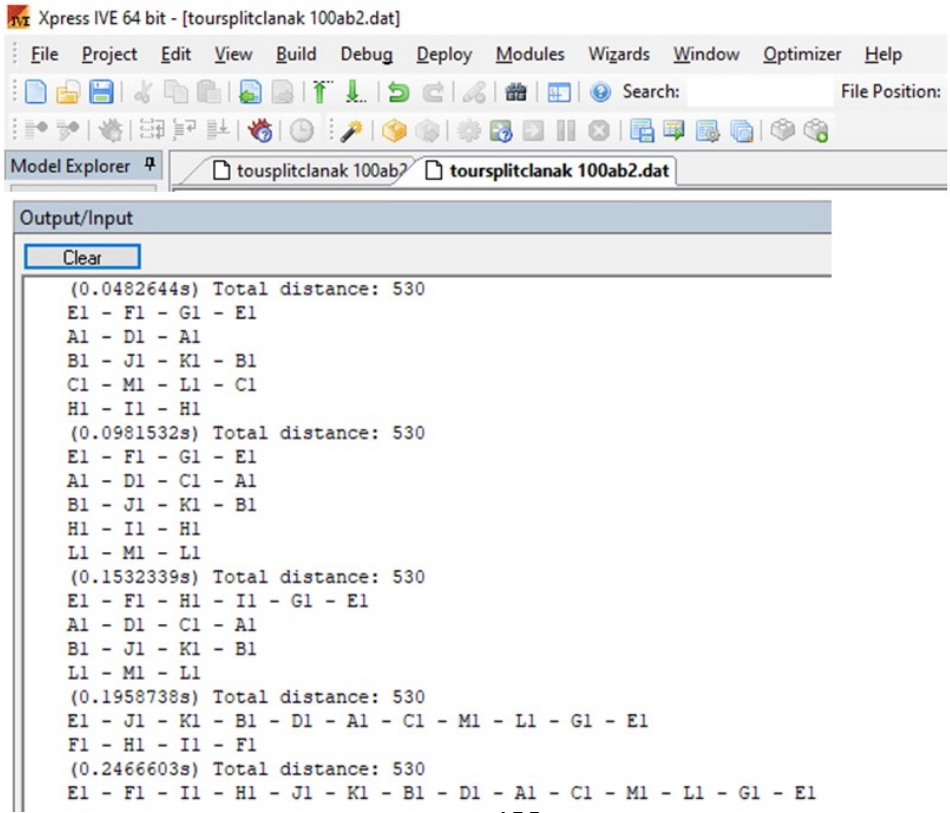
Transportna mreža u obliku složene piramide koja je prikazana na slici 1. sastoji se od 13 čvorova ili spojnica u prometnoj mreži, kako je objašnjeno u poglavlju 3. Tablica 1 prikazuje udaljenosti između čvorova. U primjeru vrijednosti udaljenosti između čvorova u tablici 1. su izražene u kilometrima (km).

Tablica 1. Udaljenosti između čvorova transportne mreže

1,0	7,0	5,0	5,0	3,5	3,5	5,0	5,0	7,0	3,5	7,0	3,5	7,0	**E**
7,0	1,0	5,0	5,0	3,5	10,5	11,0	11,0	14,0	8,0	10,0	8,0	10,0	**A**
5,0	5,0	1,0	7,0	3,5	8,0	10,0	7,0	11,0	3,5	5,0	8,0	11,0	**B**
5,0	5,0	7,0	1,0	3,5	8,0	7,0	10,0	11,0	8,0	11,0	3,5	5,0	**C**
3,5	3,5	3,5	3,5	1,0	7,0	8,0	8,0	10,5	7,0	8,0	7,0	8,0	**D**
3,5	10,5	8,0	8,0	7,0	1,0	3,5	3,5	3,5	7,0	8,0	7,0	8,0	**F**
5,0	11,0	10,0	7,0	8,0	3,5	1,0	7,0	5,0	8,0	11,0	3,5	5,0	**G**
5,0	11,0	7,0	10,0	8,0	3,5	7,0	1,0	5,0	3,5	5,0	8,0	11,0	**H**
7,0	14,0	11,0	11,0	10,5	3,5	5,0	5,0	1,0	8,0	10,0	8,0	10,0	**I**
3,5	8,0	3,5	8,0	7,0	7,0	8,0	3,5	8,0	1,0	3,5	7,0	10,0	**J**
7,0	10,0	5,0	11,0	8,0	8,0	11,0	5,0	10,0	3,5	1,0	10,5	14,0	**K**
3,5	8,0	8,0	3,5	7,0	7,0	3,5	8,0	8,0	7,0	10,5	1,0	3,5	**L**
7,0	10,0	11,0	5,0	8,0	8,0	5,0	11,0	10,0	10,0	14,0	3,5	1,0	**M**
E	**A**	**B**	**C**	**D**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	

Optimalno rješenje transportne mreže u oblik složene piramide testirano je i izračunato korištenjem programskog jezika za matematičko modeliranje Xpress (Slika 1).

Slika 1. Optimalno rješenje transportne mreže izračunato uporabom programskog jezika za matematičko modeliranje Xpress



U optimizaciji transportne mreže korišten je algoritam detaljne pretrage razvijen u Visual Basicu. Objektno orijentirano programiranje u Visual Basicu korišteno je za stvaranje i vizualizaciju algoritma iscrpnog pretraživanja kako bi se izračunao jedan ili više optimalnih transportnih putova. U tablicama 2. i 3. prikazan je izračun optimalnog rješenja za prvu kombinaciju segmenata transportne mreže S11 i S12.

Tablica 2 prikazuje optimalno rješenje za prvi segment (S11) prometne mreže korištenjem algoritma iscrpnog pretraživanja. Rezultati su izračunati korištenjem programa Visual Basic u Excelu (VBA za Excel) koje je kreirao autor ovog rada. Iz Tablice 3 vidljivo je da je izračunata minimalna duljina rute 36 km. Tablica 2 prikazuje optimalno rješenje i za drugi segmenta (S12) prometne mreže prema metodi detaljne pretrage korištenjem programa Visual Basic u sučelju proračunskih tablica Excel. Iz tablice 2 može se vidjeti da su izračunate četiri optimalne prometne rute (relacije) s minimalnom duljinom rute od 17 km.

Tablica 3. prikazuje objedinjena optimalna i suboptimalna rješenja prometne mreže u kojima su povezani segmenti S11 i S12 prometne mreže te za koje su izračunate vrijednosti minimalnih udaljenosti. Čvor E definiran je i prikazan kao početno/krajnji čvor. Vrijednost optimalnih rješenja koja su izračunata pomoću programa VBA za Excel i iznosi 53 km jednaka je izračunatoj vrijednosti uporabom programskog jezika za matematičko modeliranje Xpress. U tablici 3. može se vidjeti da je izračunato 12 optimalnih transportnih relacija minimalnom duljinom relacije od 53 km.

Tablica 2. Optimalno rješenje segmenata S11 i S12 transportne mreže

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
1	E	F	I	H	J	K	B	D	A	36	0,0	3,5	7,0	5,0	3,5	7,0	5,0	3,5	7,0	1	E
2	E	F	I	H	J	K	B	A	D	36	8,5	1,0	3,5	3,5	7,0	8,0	8,0	7,0	10,5	2	F
3	E	F	I	H	K	J	B	A	D	36	11,5	3,5	1,0	5,0	8,0	10,0	11,0	10,5	14,0	3	I
4	E	F	I	H	K	J	B	D	A	36	10,0	3,5	5,0	1,0	3,5	5,0	7,0	8,0	11,0	4	H
5	E	I	F	H	K	J	B	D	A	38	8,5	7,0	8,0	3,5	1,0	3,5	3,5	7,0	8,0	5	J
6	E	I	F	H	K	J	B	A	D	38	12,0	8,0	10,0	5,0	3,5	1,0	5,0	8,0	10,0	6	K
7	E	I	F	H	J	K	B	A	D	38	7,0	8,0	11,0	7,0	3,5	5,0	1,0	3,5	5,0	7	B
8	E	I	F	H	J	K	B	D	A	38	3,5	7,0	10,5	8,0	7,0	8,0	3,5	1,0	3,5	8	D
9	E	F	I	H	J	K	D	B	A	40,5	5,0	10,5	14,0	11,0	8,0	10,0	5,0	3,5	1,0	9	A
10	E	F	I	H	J	B	K	D	A	40,5	10	2	3	4	5	6	7	8	9		
11	E	F	I	H	K	B	J	A	D	40,5	C	F	I	H	J	K	B	D	A		
12											Segment S21										
13																					
14											Segment S22										
15	C	M	G	L	E					17	1,0	5,0	7,0	3,5	0,0	1	C				
16	C	M	L	G	E					17	5,0	1,0	5,0	3,5	7,0	2	M				
17	C	L	M	G	E					17	7,0	5,0	1,0	3,5	5,0	3	G				
18	C	E	L	G	M					17	3,5	3,5	3,5	1,0	3,5	4	L				
19	C	E	G	L	M					17	0,0	7,0	5,0	3,5	1,0	5	E				
20	C	E	G	M	L					17	1	2	3	4	5						
21											C	M	G	L	E						

Tablica 3. Objedinjeno rješenje prve kombinacije segmenata transportne mreže S11 i S12

E	F	I	H	J	K	B	D	A	C	M	G	L	E	
	3,5	3,5	5	3,5	3,5	5	3,5	3,5	5	5	5	3,5	3,5	53
E	F	I	H	J	K	B	D	A	C	M	L	G	E	
	3,5	3,5	5	3,5	3,5	5	3,5	3,5	5	5	3,5	3,5	5	53
E	F	I	H	J	K	B	D	A	C	L	M	G	E	
E	F	I	H	J	K	B	A	D	C	M	G	L	E	
E	F	I	H	J	K	B	A	D	C	M	L	G	E	
E	F	I	H	J	K	B	A	D	C	L	M	G	E	
E	F	I	H	K	J	B	A	D	C	M	G	L	E	
E	F	I	H	K	J	B	A	D	C	M	L	G	E	
E	F	I	H	K	J	B	A	D	C	L	M	G	E	
E	F	I	H	K	J	B	D	A	C	M	G	L	E	
E	F	I	H	K	J	B	D	A	C	M	L	G	E	
E	F	I	H	K	J	B	D	A	C	L	M	G	E	

Usporedba izračuna vrijednosti optimalnih rješenja koja su izračunata pomoću programa VBA za Excel i vrijednosti uporabom programskog jezika za matematičko modeliranje Xpress pokazuje da se rezultati poklapaju. U tablici je uokvireno optimalno rješenje koje je jednako rješenju izračunatom pomoću programskog jezika za matematičko modeliranje Xpress.

U tablicama 4. i 5. prikazan je izračun optimalnog rješenja za drugu kombinaciju segmenata transportne mreže S21 i S22.

Tablica 4. Optimalno rješenje segmenata S21 i S22 transportne mreže

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
1	E	F	I	G	M	L	C	D	A	36	0,0	3,5	7,0	5,0	3,5	7,0	5,0	3,5	7,0	1	E
2	E	F	I	G	L	M	C	D	A	36	3,5	1,0	3,5	3,5	7,0	8,0	8,0	7,0	10,5	2	D
3	E	F	I	G	L	M	C	A	D	36	5,0	3,5	1,0	5,0	8,0	10,0	11,0	10,5	14,0	3	A
4	E	F	I	G	M	L	C	A	D	36	7,0	3,5	5,0	1,0	3,5	5,0	7,0	8,0	11,0	4	C
5	E	I	F	G	M	L	C	D	A	38	8,0	7,0	8,0	3,5	1,0	3,5	3,5	7,0	8,0	5	L
6	E	I	F	G	L	M	C	D	A	38	11,0	8,0	10,0	5,0	3,5	1,0	5,0	8,0	10,0	6	M
7	E	I	F	G	L	M	C	A	D	38	10,0	8,0	11,0	7,0	3,5	5,0	1,0	3,5	5,0	7	G
8	E	I	F	G	M	L	C	A	D	38	8,0	7,0	10,5	8,0	7,0	8,0	3,5	1,0	3,5	8	F
9	E	D	A	C	L	M	G	I	F	40,5	11,0	10,5	14,0	11,0	8,0	10,0	5,0	3,5	1,0	9	I
10	E	D	A	C	M	L	G	I	F	40,5	10	2	3	4	5	6	7	8	9		
11	E	F	I	G	L	M	D	C	A	40,5	B	D	A	C	L	M	G	F	I		
12											Segment S21										
13																					
14											Segment S22										
15	B	K	H	J	E	B				17	1,0	5,0	7,0	3,5	0,0	1	B				
16	B	K	J	H	E	B				17	5,0	1,0	5,0	3,5	7,0	2	K				
17	B	J	K	H	E	B				17	7,0	5,0	1,0	3,5	5,0	3	H				
18	B	E	J	H	K	B				17	3,5	3,5	3,5	1,0	3,5	4	J				
19	B	E	H	J	K	B				17	0,0	7,0	5,0	3,5	1,0	5	E				
20	B	E	H	K	J	B				17	1	2	3	4	5						
21	1	5	2	3	4	1				19	B	K	H	J	E						

Tablica 5. Objedinjeno rješenje druge kombinacije segmenata transportne mreže S21 i S22

E	F	I	G	M	L	C	D	A	B	K	H	J	E		53
	3,5	3,5	5	5	3,5	3,5	3,5	3,5	5	5	5	3,5	3,5	=	53
E	F	I	G	M	L	C	D	A	B	K	J	H	E		53
E	F	I	G	M	L	C	D	A	B	J	K	H	E		53
E	F	I	G	L	M	C	D	A	B	K	H	J	E		53
E	F	I	G	L	M	C	D	A	B	K	J	H	E		53
E	F	I	G	L	M	C	D	A	B	J	K	H	E		53
E	F	I	G	L	M	C	A	D	B	K	J	H	E		53
E	F	I	G	L	M	C	A	D	B	K	J	H	E		53
E	F	I	G	L	M	C	A	D	B	J	K	H	E		53
E	F	I	G	M	L	C	A	D	B	K	H	J	E		53
E	F	I	G	M	L	C	A	D	B	K	J	H	E		53
E	F	I	G	M	L	C	A	D	B	J	K	H	E		53

6. ZAKLJUČAK

Dokazana je hipoteza da sinergija metode segmentiranja transportne mreže i algoritma detaljne pretrage u sučelju proračunske tablice omogućava izračun više optimalnih i suboptimalnih rješenja za transportne mreže koje imaju više od devet čvorova. U primjeru transportne mreže u obliku složene piramide korišten je model kreiranja više kombinacija segmenata transportne mreže koje generiraju optimalan i suboptimalna rješenja. Pri tome je izračunato 24 optimalna rješenja transportne mreže. Identificiranjem više optimalnih i suboptimalnih transportnih relacija, može se postići značajan utjecaj na sinergiju parametara

učinkovitosti i transportnih performansi od polazišta do odredišta: minimalna prijeđena udaljenost, najkraće vrijeme uz minimalne troškove i maksimalno iskorištenje transportnog kapaciteta. Također mogućnost izračuna više optimalnih i suboptimalnih rješenja transportne mreže može biti korisna u projektiranju transportnih mreža pametnih gradova i robno-transportnih centara.

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Preliminary Communication

THE TRAVELING SALESMAN PROBLEM (TSP) MODEL AND THE EXHAUSTIVE SEARCH ALGORITHM IN FINDING OPTIMAL AND SUBOPTIMAL SOLUTIONS FOR A COMPLEX TRANSPORT NETWORK

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ABSTRACT
This paper explores the use of the Traveling Salesman Problem method and the exhaustive search algorithm in identifying and finding optimal and suboptimal solutions with the aim of optimizing and modeling a flexible transport network. By means of visual and object-oriented programming and modeling methods, algorithms based on exhaustive search can simulate models with multiple optimal solutions for smaller samples (up to 10 freight transport centers), with a clear interpretation of results not only for identical optimal values, but also for approximately equal values, while defining permissible deviations from the optimal values. In the example considered, the transport network consists of 13 nodes and is treated as a complex transport network. Through conceptual modeling of a complex transport network, the aim is to enable the identification of optimal and suboptimal solutions for samples larger than 10 nodes. Within the framework of the proposed model, the transport network is divided into several pairs of sets (segments): (1) a set of cities (nodes) located on the same traffic route representing the optimal transport path (transport relation), and (2) a set of cities (nodes) connected through different transport relations and included in the calculation using the exhaustive search algorithm. In this process, terminal nodes common to both members of the set pair are defined, and in the computational model they are connected by a virtual transport relation.

Keywords: *Traveling Salesman Problem (TSP), exhaustive search algorithm, complex transport network, optimal and suboptimal solutions, modeling and optimization*

Preliminary Communication

REWARD-DRIVEN RECYCLING: USING MOBILE APPS AND INCENTIVES TO FIX CROATIA'S WASTE MANAGEMENT GAP

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ABSTRACT

The aim of this study was to analyse attitudes towards the current municipal solid waste management system and potential strategies to improve municipal solid waste collection. An empirical study was conducted with a sample of 877 respondents from Primorje-Gorski Kotar County in the Republic of Croatia. The research instrument was an online questionnaire comprising 11 questions. As 76.9% of respondents are willing to actively recycle waste when rewarded, and 60.9% are interested in using mobile applications that support waste handling, waste management apps based on rewards may optimise municipal solid waste management processes. However, such apps will be effective only when they are optimally integrated into larger infrastructural, IoT, and machine learning systems. The analysis revealed a statistically significant positive correlation between interest in using the waste management app and the perceived level of self-awareness about the importance of proper waste separation ($\tau b = .102$, $p < .01$). The most popular functions of waste management apps are interactive maps showing waste container GPS locations (41.7%), an overview of municipal recycling statistics (39%), and content with advice on waste reduction (38.7%). Other functions include ordering bulky waste collection, an overview of collection dates, notifications about containers to be emptied, and tips on waste disposal. Respondents motivated by rewards for waste separation show a higher interest in using waste management apps than those who are not motivated by rewards for waste separation ($U = 50852.5$, $z = -5.783$, $p < .001$, $r = .04$).

Key words: *waste management, mobile application, attitudes, rewards, satisfaction*

1. INTRODUCTION

The main strategic objectives of the European Green Deal (EGD) are to make the European Union environmentally sustainable, for example climate neutral, by 2050 and to take a leading global role in tackling climate change (Teevan et al., 2021). Although the Green Deal will be shaped through a series of policy documents, action plans and legislation, its main component is the development and implementation of technological solutions to enable this transition. According to recent reports, 4.8 tonnes of waste were generated per EU inhabitant in 2020, while the Republic of Croatia was below the EU average with 1.48 tonnes per capita (Eurostat, 2024a). Slightly less than one tenth (8.9%) of the total waste generated in the European Union is municipal waste: everyday waste collected and treated by municipalities, mainly generated by households (European Parliament, 2024). In 2022, 48% of municipal waste in the EU was recycled. The EU has set a target of 60% for the reuse and recycling of

municipal waste by 2030 (European Parliament, Council of the European Union, 2018). Although some countries, such as Germany, Bulgaria, Austria and Slovenia, have already reached or exceeded this 60% target, the absolute amount of municipal waste is still increasing to such an extent that the current target should be raised to at least 70%. In the Republic of Croatia, 478 kg of municipal waste per capita was generated in 2022, which was close to the EU average of 513 kg per capita (Eurostat, 2024b).

The first group of problems related to waste reduction concerns production technologies. This includes the transition to green energy, the use of IoT and AI devices to optimise energy consumption, and the development of new green packaging technologies. Over the past decade, various studies have shown a direct positive relationship between environmentally friendly packaging and sustainability (Ker[en]Xin et al., 2019). The second group of problems relates to the collection and recycling of waste to return some of it to the production process. Although most EU countries have increased their municipal waste recycling rates over the last two decades, some countries have not been particularly successful in this transition. While Germany, Austria, Slovenia, the Netherlands, Denmark, Belgium, Luxembourg, Switzerland and Italy achieved recycling rates of 50% or more, countries such as Cyprus, Malta, Bulgaria and Romania recycled less than 20% of municipal waste in 2023. According to the same European Environment Agency report, the Republic of Croatia recycled only 36% of its municipal waste in 2023 (European Environment Agency, 2025). With many EU countries still lagging behind in recycling, the EU tends to export some of its waste. In 2022, 39% of EU waste was sent to Turkey (12.4 million tonnes), followed by India (3.5 million tonnes), the United Kingdom (2.0 million tonnes), Switzerland (1.6 million tonnes) and Norway (1.6 million tonnes) (Eurostat, 2024c). The third group of problems concerns consumer culture and ecological awareness. Increasingly, scientists emphasise that waste management problems cannot be solved within the existing consumer culture and that, to achieve sustainability, society must change its production and distribution processes to a circular economy [Smart, 2010; Subedi et al., 2023). Such a paradigm shift may require radical changes to current business structures, consumer behaviour and governance models (Singh et al., 2014).

To help address the above-mentioned problems, particularly those related to municipal waste collection, the authors have sought to answer the following research questions:

- How satisfied are users with the current municipal solid waste management system?
- How can the current municipal solid waste management system be improved?

Although waste management applications are available on the Croatian market, their popularity remains extremely low. The main hypothesis of this research is that waste management applications not aligned with customer wants and needs cannot improve municipal waste management. The main contribution of this article is to provide better insight into strategies that could improve the efficiency of municipal solid waste management systems. This article is intended for all managers and decision-makers in the waste management sector. In addition, the conclusions of this research may be useful for professors and students interested in sustainability, information and communication sciences, and ecology, as well as researchers focused on the development of municipal solid waste management applications.

2. LITERATURE REVIEW

Over the past decade, the number of researchers discussing innovative apps and software designed to revolutionise waste management in smart cities has increased significantly (Mangalure et al., 2023). Some authors, such as Bonino et al. (2016), state that recycling waste is still perceived as an arduous task and that a lack of user-centred design in waste recycling tools may be a contributing factor. More recently, authors including Mavropoulos et

al. (2013), Deepa (2020), and Saptaputra et al. (2023) have highlighted that mobile products and apps can serve as valuable tools for authorities, businesses, civilians, and other stakeholders in environmental protection, waste prevention, and recycling. Henrys (2021) also claims that mobile apps for solid waste collection will improve the quality of waste disposal and reduce the environmental footprint. After analysing the ten most popular waste management software solutions, Tarlengco (2026) concludes that the most important functions of such software are real-time information on vehicle locations, monitoring waste from generation to end point, reporting and analysis tools to manage and reduce waste, reporting problems and assigning corrective actions, advising on waste prevention, categorising waste types, measuring waste with specific trackers, waste management checklists, setting specific targets (such as benchmarking), and route planning to save time and fuel in waste collection. To improve the efficiency of waste management systems, Wandee et al. (2022) suggest implementing QR codes, Kunwar (2023) recommends deep learning for household waste management, and Chalkias and Lasaridi (2011) propose the use of Geographic Information System (GIS) technology in waste management procedures.

In the Republic of Croatia, scientific literature on users' attitudes towards waste management remains limited. After analysing students' attitudes and activities regarding recycling and waste disposal, Stanić and Buzov (2009) conclude that ecological attitudes are not reflected in practical actions. Vinšalek Stipić (2017) suggests that the circular economy model offers potential for the development of small and medium-sized enterprises. However, in the Republic of Croatia, companies implementing IoT waste bins, e-waste kiosks, recycling robots, and artificial intelligence (AI) waste sorting are still relatively rare. Dražić (2020) highlights the importance of raising public awareness about recycling, providing appropriate waste infrastructure, and continually educating and encouraging people to include such activities in their daily routines. In his paper on designing the user interface of mobile waste recycling apps, Mozara (2020) suggests that sorting waste using recycling icons would make it easier for users to perform this activity. Most major cities in the Republic of Croatia have invested public resources in developing various waste management apps. The city of Pula, for example, has developed “Sort me out” (Croatian: Razvrstaj.me), which provides advice on waste separation and disposal. The “My Waste” app (Croatian: Moj otpad) has been developed in the capital, Zagreb, and offers users monthly and annual waste calendars. “Put it off wisely” (Croatian: Pametno odloži) has been developed by the city of Karlovac, while “E-Apostates” (Croatian: E-Otpadnici) has been developed by the city of Rijeka to enable the active participation of citizens in improving the quality of waste management, environmental protection, and city cleanliness. Additionally, another waste management app on the Croatian market, "InterGO", facilitates the monitoring of waste disposal, the preparation of reports on the origin and flow of waste, and the control of the circulation of disposable packaging.

Although there may be various reasons for the low popularity of some products on the market, such as lack of marketing, insufficient infrastructure to support implementation, or lack of expertise in using the solution, the most important reason is usually a low level of compliance with user needs. When products are not developed in accordance with users' wants and needs, users have no incentive to use them. To address this problem, it was necessary to conduct empirical research to identify end user needs and strategies that could motivate them to recycle solid municipal waste properly. As the Republic of Croatia is one of the EU countries that needs to significantly improve its waste management and recycling, the authors decided to analyse end users' attitudes towards the current waste collection system and their interest in various features that a mobile app for waste management could offer.

3. RESEARCH METHODOLOGY

To analyse end-users' attitudes towards the municipal solid waste management system in Primorje-Gorski Kotar County, Croatia, the authors developed an anonymous online questionnaire comprising 11 questions. The research questions were created from scratch, as no similar Croatian studies existed regarding attitudes towards waste management

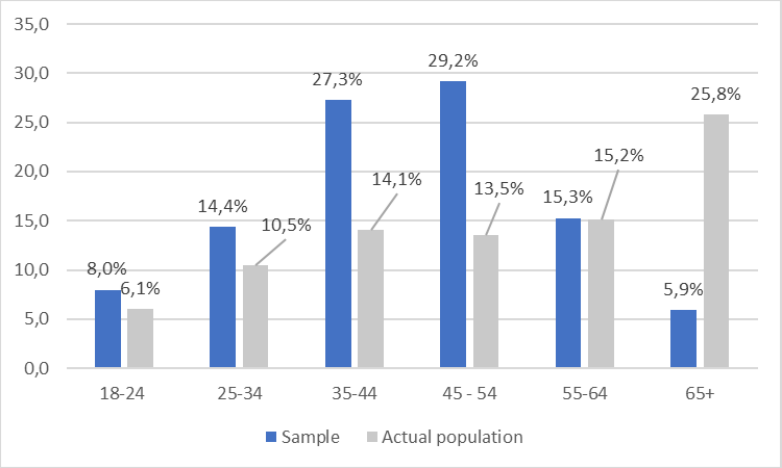
application functionalities. The questionnaire collected demographic data (age) and assessed current habits and satisfaction. Key questions included use of a waste management app and frequency of solid waste disposal (Likert scale 1–5), satisfaction with the current waste collection system (Likert 1–5), collection frequency (Yes/No), and frequency of problems with waste disposal (Likert 1–5). The survey also gauged interest in a dedicated waste disposal app (Likert 1–5), allowing respondents to select desired app functions. Furthermore, it measured personal awareness of proper waste separation (Likert 1–5) and whether a reward system would encourage better separation or reduction (Yes/No). The final question offered a free-form option for comments and suggestions to improve the municipal waste management system experience.

Descriptive statistical analysis methods, the Shapiro-Wilk test, the Mann-Whitney U test, the Kruskal-Wallis test, and Kendall's tau-b test were used to analyse the data. These methods were applied to identify and measure differences in user attitudes towards specific functionalities and strategies that could improve the end-user waste management experience. The study is empirical, the sample is simple, and it was randomly selected. Data were collected from 14 April 2024 to 11 May 2024. The invitation to participate in the survey was published in open social networking groups on Facebook, which have more than 69,000 members from Primorje-Gorski Kotar County in the Republic of Croatia. This approach was chosen to obtain as many relevant responses as possible. The research sample consists of people living in Primorje-Gorski Kotar County in the Republic of Croatia, and the sample size is 877 (N). Primorje-Gorski Kotar County is the fifth largest county in Croatia.

4. RESULTS AND DISCUSSION

In the first question, respondents were asked to indicate their age by selecting one of the available options. As shown in Figure 1, the research sample only partially represents the population of Primorje-Gorski Kotar County in terms of age structure. Specifically, the research sample included twice as many respondents in the 35–44 age group (whose actual share according to the 2021 census was 14.07%) and the 45–54 age group (actual share 13.49% according to the 2021 census), and five times fewer respondents in the 65 and over age group (actual share 28.82% according to the 2021 census) (DZS, 2021). Given that respondents over the age of 65 often do not have access to online questionnaires posted on social networks, this result was expected. An additional reason why people between 35 and 54 years of age are the dominant age group in this research is that people in this age range usually run their own households, which means they are responsible for waste management activities.

Figure 1. Comparison of age distribution between the research sample (N = 877) and general population (N = 265,419)



Source: Made by authors

As shown in Table 1, the Shapiro-Wilk test revealed a significant deviation from normality for the age of respondents, W (877) = .938, p < .01. The test also indicated significant deviations from normality for all other statements, such as frequency of garbage disposal, W (877) = .877, p < .01, and satisfaction with the current garbage collection system, W (877) = .914, p < .01. Therefore, non-parametric tests were used in further analysis.

Table 1. Normality test results by age group

	Kolmogorov-Smirnova			Shapiro-Wilk		
	Statistic	Df	Sig.	Statistic	df	Sig.
The age of the respondent	0,162	877	0.000	0,938	877	0.000

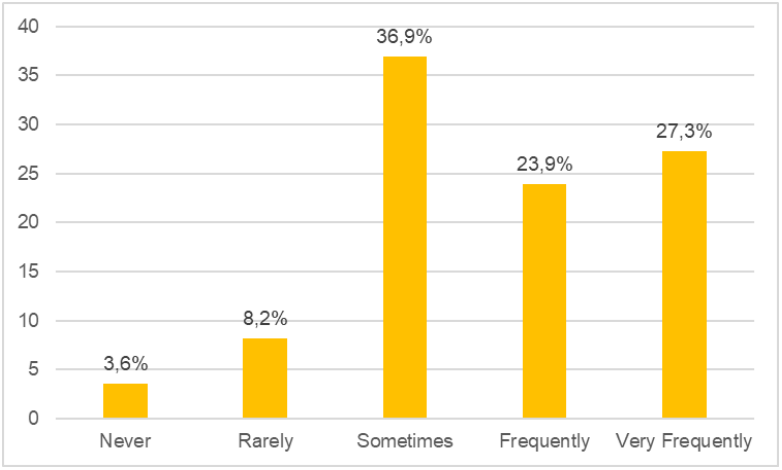
a Lilliefors Significance Correction.

Source: Made by authors

In the second question, respondents were asked whether they currently use a waste management app. The results showed that 96.2% of respondents do not yet use a waste app. This indicates that waste management apps are very rarely used in Primorje-Gorski Kotar County, Republic of Croatia. There are at least three possible reasons for this. The first is that existing IT solutions are not adequately presented to citizens (Behnamifard et al., 2021). The second is that current apps do not support all the functions users require. The third possible reason is the low technical and financial capacity of municipalities to manage and separate waste collection and improve recycling (Frajtić, Mackedon, 2020). This research confirms that, without infrastructure to support information exchange (e.g. smart waste containers, machine learning), waste management apps cannot meet end user needs.

As shown in Figure 2, more than half of the respondents dispose of their waste frequently or very frequently. The results suggest that most respondents in the study sample are well acquainted with the problems and activities related to waste disposal. Furthermore, these results confirm that waste disposal is an important human activity.

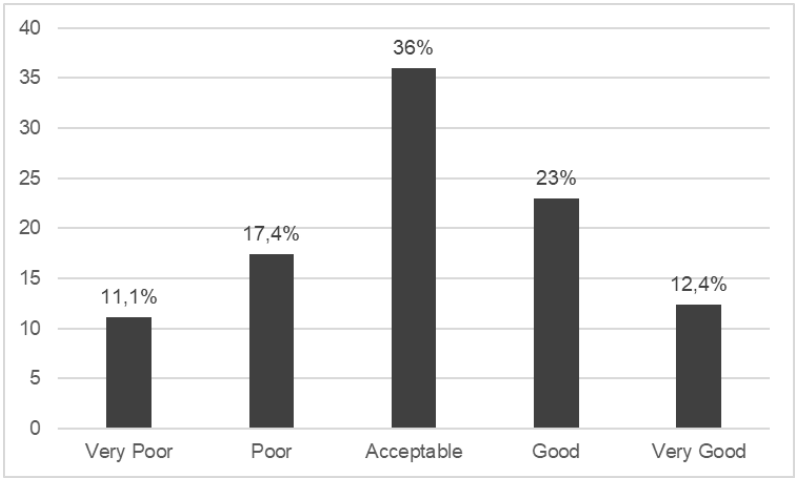
Figure 2. Respondent distribution by waste disposal frequency (N = 877)



Source: Made by authors

As shown in Figure 3, 28.5% of respondents are not satisfied with the current waste collection system, representing a significant proportion of citizens. The proportion of respondents who rate their level of satisfaction as very poor or poor in Primorje-Gorski Kotar County is 20.3% higher than in Malaysia (Padfield, Zakaria, 2014), 15.6% higher than in the Peace River district in British Columbia, Canada (PRRD, 2016), and 24.5% higher than in King County, outside the City of Seattle (Cascadia Consulting Group, 2016).

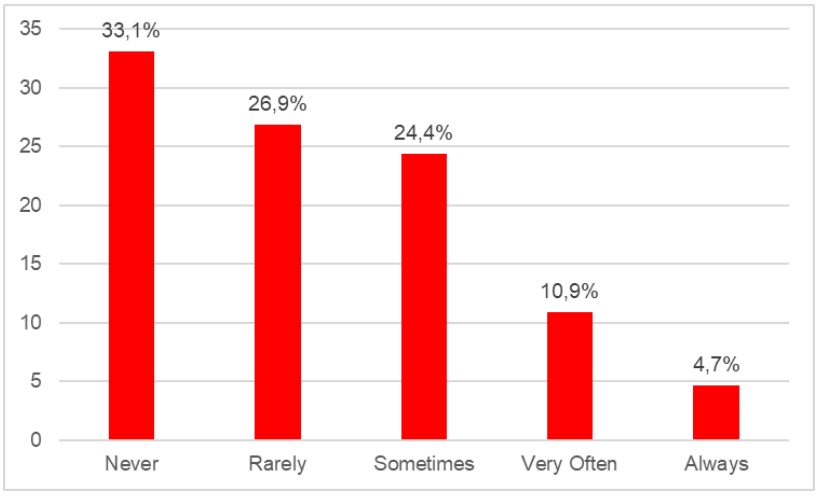
Figure 3. Respondent distribution by satisfaction level with the waste collection system (N = 877)



Source: Made by authors

The Kruskal-Wallis test indicated no statistically significant differences between respondents in different age groups regarding their perceived satisfaction with the current waste collection system, H (5) = 7.813, p = .167. The Mann-Whitney U test also showed no statistically significant differences between users of the waste management app (Mr = 506.15, n = 33) and non-users (Mr = 436.37, n = 844) in terms of satisfaction with the current waste collection system, U = 11710, z = -1.608, p = .108. In the fifth question, respondents indicated the frequency of their problems with solid waste disposal on a Likert scale, where 1 means "never" and 5 means "always". These problems usually relate to irregular waste collection, defective bins, and too few available disposal sites, mainly due to seasonal peaks in tourism. During successful tourism years (such as 2017, 2018, and 2019), the average proportion of municipal waste generated by tourist activity in the total annual volume of municipal waste for the Republic of Croatia was 9.3% (Ministry of Economy and Sustainable Development, 2023). As Figure 4 shows, 40% of respondents experience problems with municipal waste disposal at least occasionally. As improper waste disposal poses a major threat to nature and human well-being, it is important to continue developing new technologies and solutions that reduce pollution and damage to the natural environment.

Figure 4. Distribution of respondents by frequency of municipal waste disposal issues (N = 877)

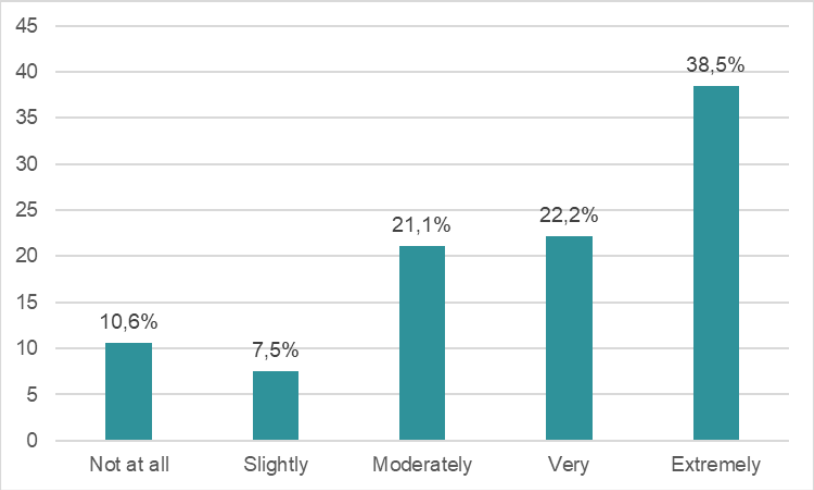


Source: Made by authors

The Kruskal-Wallis test was used to compare six age groups of respondents regarding the perceived frequency of problems with waste disposal. The analysis showed no statistically significant differences between respondents in different age groups in terms of the perceived frequency of waste disposal problems, H (5) = 6.512, p = .260. The Mann-Whitney U test indicated no statistically significant differences between users of the waste management app (Mr = 359.67, n = 33) and non-users (Mr = 442.10, n = 844) regarding satisfaction with the current waste collection system, U = 11308, z = -1.903, p = .06. Kendall's tau-b test revealed a statistically significant negative correlation between the perceived frequency of municipal waste disposal problems and the perceived level of satisfaction with the current waste collection system (τb = .390, p < .01). This correlation is statistically significant at the 1% level (p < .01), and the relationship is considered rather strong since the coefficient is τb > .30 (Walker, 2003). Citizens who experience problems with garbage collection less frequently report higher satisfaction with city waste collection. In the sixth question, respondents were asked to indicate explicitly whether they were satisfied with the frequency of waste collection in their municipality by answering yes or no. The results showed that 55% of respondents were satisfied with the frequency of waste collection, which is substantially lower than in the study conducted in South Oxfordshire and Vale of White Horse (UK), where 86% of respondents expressed satisfaction with the waste and recycling collection service (South Oxfordshire City Council, Vale of White Horse City Council, 2024).

Figure 5 shows that 60.9% of respondents are very or extremely interested in using the waste management app. As many citizens believe waste management apps can improve their experience of disposing of waste, it was necessary to investigate which functionalities potential users might find useful and important.

Figure 5. Distribution of respondents by interest in waste management application usage (N = 877)

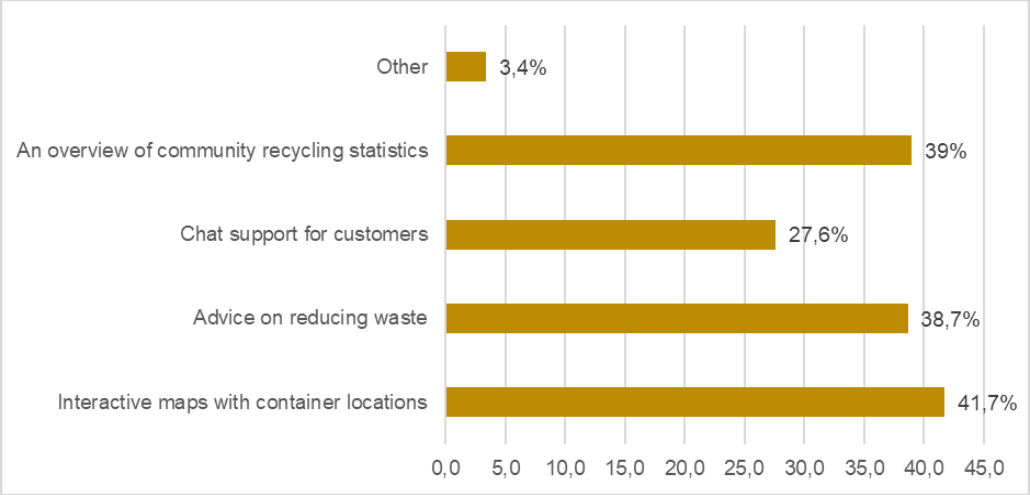


Source: Made by authors

The Kruskal-Wallis test indicated no statistically significant differences between respondents in different age groups regarding their interest in the waste management app, H (5) = 5.793, p = .327. Kendall's tau-b test showed a statistically significant positive correlation between interest in using the waste management app and the perceived level of self-awareness of the importance of proper waste separation (τb = .102, p < .01). This correlation is statistically significant at the 1% level (p < .01), but the relationship is weak, as the coefficient τb is less than .30 (Walker, 2003). Although this conclusion should be interpreted with caution due to the weak correlation, the research results suggest that people with a higher perceived level of recycling self-awareness are slightly more willing to use waste management apps, and vice versa.

As shown in Figure 6, the most popular features in waste management apps are interactive maps showing waste container GPS locations (41.7%), an overview of the municipality's recycling statistics (39%), and content with advice on waste prevention (38.7%). In the free-entry section, respondents suggested additional features they would like to see in the app, such as the ability to order bulky waste collection online, an overview of collection dates, smart bins that send notifications when they need to be emptied, and waste disposal instructions.

Figure 6. Analysis of respondent interest in waste management application functionalities (N = 877)



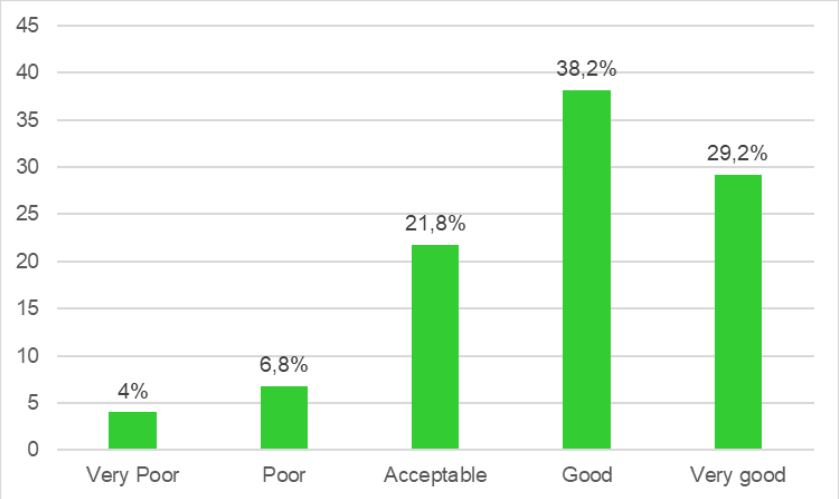
Source: Made by authors

In the ninth question, respondents were asked to rate their personal awareness of proper waste separation. As shown in Figure 7, 67.4% of respondents rated their awareness of waste separation as good or very good. Similar studies by other authors also indicate that citizens of Puchong, Malaysia, have a high level of awareness about the importance of recycling (Yap & Sharaai, 2022). Additionally, students at a State College in Zamboanga City, Philippines, demonstrate sufficient knowledge of the definition of solid waste, the effects of improper solid waste disposal, prohibited activities, initiatives related to solid waste, the importance of solid waste management, and associated responsibilities, but have limited knowledge of the various laws relevant to solid waste management (Molina & Catan, 2021).

The Kruskal-Wallis test was used to compare six age groups of respondents regarding their perceived awareness of the importance of proper waste separation. The analysis showed statistically significant differences between respondents in different age groups in terms of their interest in the waste management app, $H(5) = 49.912$, $p < .001$. The Mann-Whitney U post hoc test with Bonferroni adjustment (.003) indicated no statistically significant difference between the “18–24” ($Mr = 92.84$, $n = 70$) and “35–44” ($Mr = 101.65$, $n = 126$) groups in their perceived awareness of the importance of proper waste separation, $U = 4013.5$, $z = -1.088$, $p = .276$. However, the Mann-Whitney U post hoc test with Bonferroni adjustment (.003) showed a statistically significant difference between the “18–24” ($Mr = 124.43$, $n = 70$) and “35–44” ($Mr = 163.95$, $n = 239$) groups in perceived awareness of the importance of proper waste separation, $U = 6225$, $z = -3.412$, $p = .001$, $r = .03$. In addition, the Mann-Whitney U post hoc test with Bonferroni adjustment (.003) showed a statistically significant difference between the “18–24” ($Mr = 128.06$, $n = 70$) and “45–54” ($Mr = 173.19$, $n = 256$) groups in perceived awareness of the importance of proper waste separation, $U = 6479$, $z = -3.720$, $p < .001$, $r = .04$. The Mann-Whitney U post hoc test with Bonferroni adjustment (.003) also showed a statistically significant difference between the “18–24” ($Mr = 72.99$, $n = 70$) and “55–64” ($Mr = 117.9$, $n = 134$) groups in awareness of the importance of proper waste separation, $U = 2624.5$, $z = -5.460$, $p < .001$, $r = .14$. Furthermore, the Mann-Whitney U post hoc test with Bonferroni adjustment (.003) showed a statistically significant difference

between the “18–24” (Mr = 49.99, n = 70) and “65 or more” (Mr = 77, n = 134) groups regarding perceived awareness of the importance of proper waste separation, U = 1014, z = -4.354, p < .001, r = .16.

Figure 7. Respondent distribution by awareness level of proper waste separation importance (N = 877)



Source: Made by authors

Respondents in the younger groups are probably less aware of the importance of recycling, while older respondents with more experience are increasingly aware that waste management problems cannot be solved without recycling. However, a study from France suggests that ageing is associated with lower levels of enthusiasm for recycling (Guiot et al., 2019), while a study from Poland found a strong correlation between annual per capita waste generation rate and the number of unemployed women (r = 0.70) and the female to male ratio (r = 0.81) (Talalaj, Walery, 2015).

In the tenth question, respondents were asked whether the reward system would encourage them to separate and reduce waste properly on a regular basis. A total of 76.9% of respondents stated that the reward system would encourage them to do so. Other studies also suggest that digital technologies enhance the efficiency of waste management (Azheganova, Nedashkovskiy, 2020), and that both rewards and penalties significantly impact recycling intentions (Amini et al., 2014). These results indicate that waste management apps with reward systems could be among the most effective strategies for improving the municipal solid waste management process. However, public decision-makers should exercise caution when determining the amounts of rewards and penalties, as excessively high values for these parameters are not always optimal for overall social welfare (Mu, Zhang, 2021). Furthermore, it is important to emphasise that implementing such a strategy requires upgrading existing waste management infrastructure with the Internet of Things (IoT) ecosystem (Ramyaa & Perarasi, 2019) and machine learning techniques (Sowmyashree et al., 2022).

The Mann-Whitney U test was used to determine whether there was a difference between those who would be encouraged by the reward system to properly segregate and reduce waste and those who would not, in terms of their awareness of the importance of proper waste segregation. The test showed no statistically significant difference between those who would be encouraged by the reward system (Mr = 432.63, n = 674) and those who would not be encouraged (Mr = 460.14, n = 203) in their attitudes regarding awareness of the importance of proper waste separation, U = 64119, z = -1.423, p = .155. The Mann-Whitney U test was also used to assess whether there was a difference between those who would be encouraged by the reward system to properly separate and reduce waste and those who would not, in terms of their interest in using a waste management app. The test revealed a

statistically significant difference between those who would be encouraged by the reward system (Mr = 465.054, n = 674) and those who would not be encouraged (Mr = 352.5, n = 203) in their attitude towards using a waste management app, U = 50852.5, z = -5.783, p < .001, r = .04. Respondents motivated by rewards to separate waste show greater interest in using waste management apps than those who are not motivated by rewards.

In the final question, respondents were invited to share their ideas and suggestions to improve the functionality or user experience of the waste management app. A total of 22 comments and suggestions were collected. The first respondent observed that the average number of bin collections varies by neighbourhood (e.g. six times per week in the centre) and suburbs, and suggested it would be useful to calculate and display the mass of municipal waste for each household. Another respondent expressed interest in knowing the exact location of bulky waste containers. One respondent highlighted the need for the app to be tailored for municipalities that sort waste and those that do not. For example, in the city of Rijeka, sorting is voluntary as there is no mandatory system. Two interviewees recommended introducing advice on waste sorting. One respondent emphasised that bins should not only be emptied regularly but also cleaned, and suggested this could be optimised through the app. Additionally, one respondent proposed creating incentives to reduce costs for those who separate waste properly. Another respondent raised the issue of disposing of medical waste. One respondent noted a shortage of waste collection staff. It was also suggested that effective disposal, separation, and recycling of waste via the app can only succeed through close cooperation with local authorities. Other proposals included greater transparency in waste collection and treatment; regular measurement of user experience; card-based bins and payment per kilogram of waste; accurate information on the processing of collected waste (secondary raw materials); feedback on whether waste has been properly separated; sanctions for those who do not comply with the rules; faster removal of bulky waste in certain districts; introduction of compost bins as waste containers; and improved education from an early age.

5. CONCLUSION

The empirical research aimed to understand the needs, preferences, and challenges faced by users in waste management, to identify strategies and solutions to improve this important process. The research confirms that end users are interested in using waste management apps, but these apps will not be adopted by the target audience unless they are properly integrated with related infrastructural, IoT, and machine learning systems. The main limitation of the study is the absence of questions regarding the gender and educational level of respondents. Further research should investigate whether attitudes towards the waste management system differ in relation to these two factors. Additionally, it would be useful for future studies to assess whether needs regarding different functions of waste management apps vary according to the average weekly amount of waste per respondent. It would also be valuable to examine attitudes towards systems of rewards and sanctions for breaches of official waste management regulations in future research on this topic.

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Prethodno priopćenje

RECIKLIRANJE VOĐENO NAGRADAMA: KORIŠTENJE MOBILNIH APLIKACIJA I POTICAJA ZA RJEŠAVANJE JAZA U GOSPODARENJU OTPADOM U HRVATSKOJ

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SAŽETAK

Cilj je ovog istraživanja analizirati stavove o postojećem sustavu gospodarenja komunalnim otpadom te ispitati potencijalne strategije za unapređenje procesa njegova prikupljanja. Empirijsko istraživanje provedeno je metodom anketiranja na uzorku od 877 ispitanika s područja Primorsko-goranske županije. Instrument istraživanja bio je strukturirani mrežni upitnik koji se sastojao od 11 pitanja. Rezultati ukazuju na to da je 76,9% ispitanika spremno aktivno reciklirati otpad uz sustav nagrađivanja, dok je njih 60,9% zainteresirano za korištenje mobilnih aplikacija u svrhe gospodarenja otpadom. Iz navedenoga proizlazi da aplikacije temeljene na nagrađivanju korisnika mogu optimizirati procese unutar sustava komunalnog otpada, pod uvjetom da su integrirane u širu infrastrukturu utemeljenu na Internetu stvari (IoT) i strojnom učenju. Analiza je potvrdila statistički značajnu pozitivnu korelaciju između interesa za korištenje aplikacije i percipirane razine samosvijesti o važnosti pravilnog odvajanja otpada ($r_b = .102$, $p < .01$). Kao najznačajnije funkcionalnosti aplikacije ispitanici su izdvojili interaktivne karte s lokacijama spremnika (41,7%), uvid u statistiku recikliranja po jedinicama lokalne samouprave (39%) te edukativni sadržaj o smanjenju količine otpada (38,7%). Dodatne funkcionalnosti obuhvaćaju naručivanje odvoza glomaznog otpada, kalendar odvoza te automatizirane obavijesti. Ispitanici motivirani nagradama iskazuju statistički značajno veći interes za korištenje digitalnih rješenja u odnosu na nemotivirane ispitanike ($U = 50852.5$, $z = -5.783$, $p < .001$, $r = .04$).

Ključne riječi: *gospodarenje otpadom, mobilna aplikacija, stavovi korisnika, sustav nagrađivanja, zadovoljstvo uslugom.*

III. TRANSPORT SAFETY AND RISK MANAGEMENT
III. SIGURNOST U PROMETU I UPRAVLJANJE RIZICIMA

Review

METHODOLOGICAL APPROACH TO RISK ASSESSMENT OF THE TRANSPORT OF DANGEROUS GOODS

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ABSTRACT

Hazardous materials are raw materials, semi-finished or finished products, which due to their characteristic chemical composition and certain properties have a number of desirable properties for purposeful use. However, in uncontrolled conditions, they can cause dangerous and harmful consequences for people, animals, material goods, watercourses, vegetation or the whole ecosystem in general. Dangerous goods are defined as an object or substance whose transport is prohibited or permitted if it is performed under the conditions determined by the International Agreement concerning the International Carriage of Dangerous Goods by Road. Transport of dangerous goods in road transport is an area of great importance for the economy and thus occupies the growing attention of the scientific and professional public. This area is regulated by regulations at the international and national level, which define the obligations of participants in the transport of dangerous goods in order to perform safe transport. Although defined measures are being taken, extraordinary events occur in the transport of dangerous goods. The goal of planning and organizing each transport of dangerous goods is to reduce the risk of an incident, and thus an emergency event whose consequences may be incalculable. There are methods for risk assessment during the transport of dangerous goods, on which the methodology of route selection for the transport of dangerous goods is based. The paper presents the methodology of risk assessment using FUZZY Method with defined factors.

Key words: *transportation, dangerous goods, methodology, risk, FUZZY Method.*

1. INTRODUCTION

Hazardous substances are substances that, due to their properties (toxicity, radiation hazard, corrosive properties, flammability) or chemical reactions (explosiveness, flammability, corrosiveness, volatility, solubility) during production, transportation, storage or handling, can endanger the health and life of people, cause damage to material goods or pollute the environment. Despite a certain level of danger, the need for this type of material is increasing.

According to data from the International Labor Organization, the largest number of accidents with hazardous materials occur in the production process 40%, then during transportation 35% and during storage 25%. Therefore, it can be concluded that the management of the risk of an accidental situation can play a major role in preventing the occurrence and mitigating the consequences of unwanted events.

Damage caused by accidents during the transportation of dangerous goods can have enormous negative consequences for people's health and life, environmental pollution, destruction of natural resources, damage to material goods, demolition of industrial facilities, residential buildings, roads, loading and unloading stations, etc. The risk can be reduced if all the necessary measures and activities are taken, and one of the key steps for effective risk management in the transport of dangerous goods is the choice of routes for the movement of vehicles transporting dangerous goods.

Risk is a measurable parameter of danger to which a process or phenomenon is exposed. It is not a physical quantity, but an abstract concept that unites the threat, the probability of an unwanted event, vulnerability, exposure and consequences (Sremac, Matijašević, 2021:179).

A large number of authors define risk as a combination of the probability of occurrence of an incident situation and the size of the possible consequences of the incident situation. On the other hand, a widely used conceptual definition of risk is that risk means the probability of harmful outcomes resulting from the interaction between hazards, community vulnerability and the natural environment (an element exposed to risk). Three elements of risk can be distinguished from the definition of risk (Milovanović, 2016:24):

- *hazard* – potential harmful events that can occur in the context of the vulnerability of the population, production and infrastructure, and which lead to economic and social losses and can reach the level of catastrophe (dangerous goods belong to technological hazards, i.e. hazards created by man);
- *vulnerability* – the tendency of the community, or part of it, to suffer damage or loss when they are exposed to physical events caused by natural or social factors and to face problems in rebuilding from losses or damage caused by the effects of physical events; and
- *element exposed to risk* – represents elements that may be partially or completely destroyed when they are exposed to the effect of hazards (population, infrastructure, economic activities, etc.).

The term "incident situation" means an uncontrolled event that occurred during the process of production, transportation or storage, in which certain amounts of chemical hazardous substances were released into the air, water or soil, and at different territorial levels, which may result in endangering the lives and health of people, material goods and environmental consequences.

The management of the risk of occurrence of an incident situation in the transport of dangerous goods is a very complex process consisting of several interdependent sub-processes (phases). The risk management methodology for the occurrence of an incident situation is applied when assessing the risk of operation and use of facilities, plants, devices, installations, equipment, means of transport and other means of work in which dangerous substances that can cause an incident situation are produced, processed, transported, stored or otherwise used, for the purpose of protecting people, natural and material goods and other objects in the vicinity of dangerous activities, i.e. within the zone of influence of dangerous goods.

Various parameters affect the probability of occurrence of an incident situation in relation to the magnitude of the consequences, and the biggest problem in defining the level of risk is

precisely defining the parameters that describe these two elements of risk (Milovanović, 2016).

The basic hypothesis of this research is: The risk in the transport of dangerous goods on the route can be reliably determined using the values of the factors that influence it using the Fuzzy method.

2. LITERATURE REVIEW

In doctoral dissertation (Milovanović, 2012) Milovanović defines a methodology for selecting routes for the transport of dangerous goods based on risk assessment. Based on previous research, methodologies for selecting routes for road transport of dangerous goods are presented based on individual and social risk and minimum costs, then on absolute and specific risk.

In order to improve the methodology for selecting routes for the transport of dangerous goods from the perspective of risk management, 11 steps for route selection have been defined.

The influential factors that determine the risk level are: type of dangerous goods, quantity of dangerous goods, attraction and production of source and destination points, road network congestion, presence of ecological zones on the route, legal restrictions (presence of tunnels, bridges and other sensitive infrastructure points). Each of these factors has certain subfactors, based on which weighting coefficients for determining the risk level per section of the road route have been established. Risk levels are divided into five groups: negligible, low, moderate, high and very high. Subfactors are divided into two groups: those that affect the probability of an incident situation and those that affect the magnitude of the consequences of an incident situation. Each of the subfactors was assessed by experts, based on which weighting coefficients of influence on the level of risk on the route section were determined. Considering that risk is the product of the probability of an incident situation and the magnitude of the consequences of an incident situation, a risk matrix (a graphical representation of the dependence of the magnitude of the consequences of an incident situation on the probability of an incident situation) was formed for each section of the route.

The paper (Planić, 2022) presents a model for selecting a route for the transport of dangerous goods using the DEA (Data Envelopment Analysis) model and a fuzzy logic system. The model consists of two phases. The first phase includes the application of the DEA model in which the formed input and output models are connected into the final DEA output form that shows routes with a satisfactory level of traffic safety and at the same time eliminates routes with a low level of traffic safety. The second phase involves the application of fuzzy logic systems, and as an output from the fuzzy system, preference is given to one route. Route evaluation is based on six criteria, namely: route length, number of access points, average annual daily traffic, number of traffic accidents with fatalities, number of traffic accidents with injuries and number of traffic accidents with material damage. The criteria used are defined based on expert assessments. In this paper, the priority in the selection of criteria is given to traffic safety parameters, which represent only one segment in the risk assessment during the transport of dangerous goods.

In the paper (El-Basyouny, Sayed, 2014), propose a framework that integrates existing climate conditions with a Geographic Information System (GIS) in order to develop a support system for routing the transport of dangerous goods. The data used when determining the route are: location data, data on the chemical properties of the dangerous goods, data on atmospheric conditions. Based on all the data, a chemical-dangerous goods dispersion model is developed. Also, the road network, demographic and socio-economic data must be taken into account, which are entered into the geographic information system, on the basis of

which a network of routes for the transport of dangerous goods is developed. In this case, a case study was conducted for Vancouver.

Yıldırım and Çatay in their paper (Yıldırım, Çatay, 2015) propose a mathematical model for solving several types of vehicle routing problems. The model is based on the Ant-Colony Optimization algorithm. The variants of the vehicle routing problem considered in the study are: the capacity vehicle routing problem – which aims to serve a set of geographically dispersed customers with known requirements using a homogeneous fleet of capacity vehicles located in a central depot, the open vehicle routing problem – which differs from the capacity problem in that vehicles do not have to return to the depot after the last customer visited, the heterogeneous fleet routing problem – which extends the capacity problem by introducing a fleet with a limited number of vehicles of different capacities, the multi-depot system – in which multiple depots are available to serve customers and there is no limit to the number of customers that each depot can serve, and the time-framed vehicle routing problem – which extends the capacity problem by introducing the earliest and latest visit times for each customer, or time frames. Optimal results were obtained in 62% of all cases.

Three optimal solutions to the time-framed vehicle routing problem using real-number data and three optimal solutions to the open-ended vehicle routing problem were improved. Relatively poor performance was observed in the heterogeneous fleet routing problem and multi-depot system variants. This shows that the decomposition of the problem into single-vehicle problems (in the heterogeneous fleet routing problem) and single-depot problems (in the multi-depot system variants) using the ant colony method may not be an efficient approach to achieving high-quality solutions.

Casté et al. in their study (Casté et al., 2023) describe a software solution to the end-user-oriented vehicle routing problem. The requirements for vehicle routing considered in the paper are: vehicle departure time, variable travel time, maximum travel time of an individual vehicle, end-user locations, end-users, unloading and return to the depot, additional vehicle engagements, avoiding low vehicle capacity utilization, multiple user time frames, driver breaks, costs, and route redefinition. After conducting an expert survey, the following problems affecting vehicle routing were identified: increasing number of end-users, compatibility between users and vehicles, and large distances. By implementing all these requirements in the software solution, optimal routes were obtained.

Izdebski et al. In their research (Izdebski et al., 2022) present the problem of determining routes in the transport of dangerous goods with an emphasis on reducing the probability of a traffic accident with serious consequences. The case study is based on a study conducted for the transport network in the Masovian Voivodeship region of central-eastern Poland. Data on traffic accidents and their consequences measured on certain sections of the road network were processed using statistical software and theoretical distributions. The ant colony algorithm and the genetic algorithm were used to determine the routes. The efficiency of heuristic algorithms in determining the routes for the transport of dangerous goods was verified using the Dijkstra algorithm. The study showed that the ant colony algorithm and the genetic algorithm are more efficient than the Dijkstra algorithm in terms of vehicle routing.

Milošević and Pamučar (Milošević et al., 2021) in their study define a model for choosing a route for the transport of dangerous goods using the fuzzy logic model. For the purposes of the study, five criteria were determined, which also represent linguistic variables. For each of these criteria, three membership functions were determined, and the output parameter was defined with five membership functions. The rules in the fuzzy logic system were determined by applying the premise weight aggregation method, which allows the formation of a database based on experience and intuition. Based on the number of input variables and the number of their membership functions, a basic base of 243 rules was defined. Finally, the

dependence of the output parameter on the input variables is shown, which allows determining the route for the transport of dangerous goods.

3. METHODOLOGY OF THE ANALYSIS

The two basic components that define risk, during risk analysis, are: the probability of an incident situation and the magnitude of the consequences or negative impact on the elements exposed to the risk of an incident situation. Certain parameters affect the probability of an incident situation, while another group of parameters defines the magnitude of the consequences of the incident situation.

3.1. Selection of parameters for determining the risk level

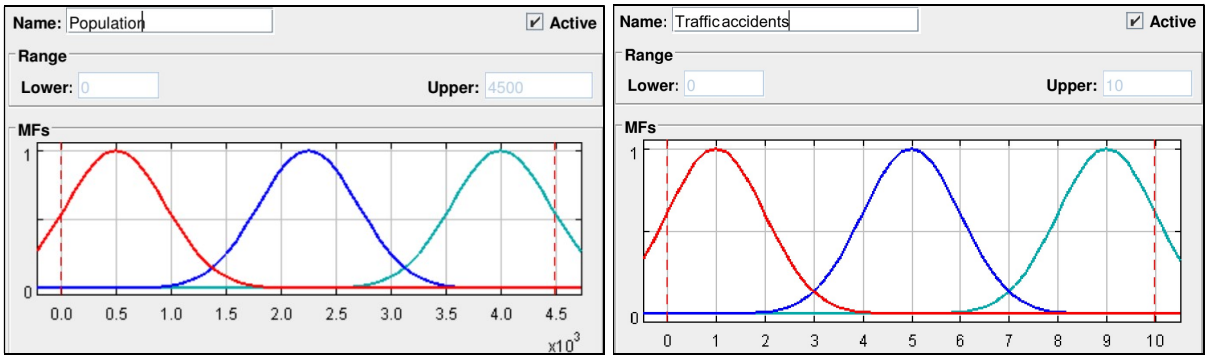
For the purposes of the research, five parameters were considered: traffic accidents on a road section (number of traffic accidents per kilometer), traffic flow size (average annual daily traffic on a road section), the share of freight vehicles in the traffic flow (percentage share of average annual daily freight vehicle traffic in relation to the total average annual daily traffic on a road section), road condition (road surface quality index) and population density. The values of the input and output variables include the intervals listed in the Table 1.

6. Table 6. Intervals of input and output linguistic variables

Input Parameters	Interval	
	From	To
Population Density	0	4500
Traffic Accidents on a Road Section	0	10
Traffic Flow Size	0	100.000
The Share of Freight Vehicles in the Traffic Flow	0	30
Road Condition	0	8
Output Parameter	**Interval**	
	From	To
Risk	0	100

For each of the input parameters, three membership functions were determined: small, medium and large. For the output parameter, five membership functions were determined: very low, low, moderate, high, very high. Gaussian bells functions were used in the system as they well describe the input and output variables and allow for satisfactory system sensitivity. Figures 1 and 2 show the membership functions of the input and output variables.

Figure 2. Membership functions of the input variables



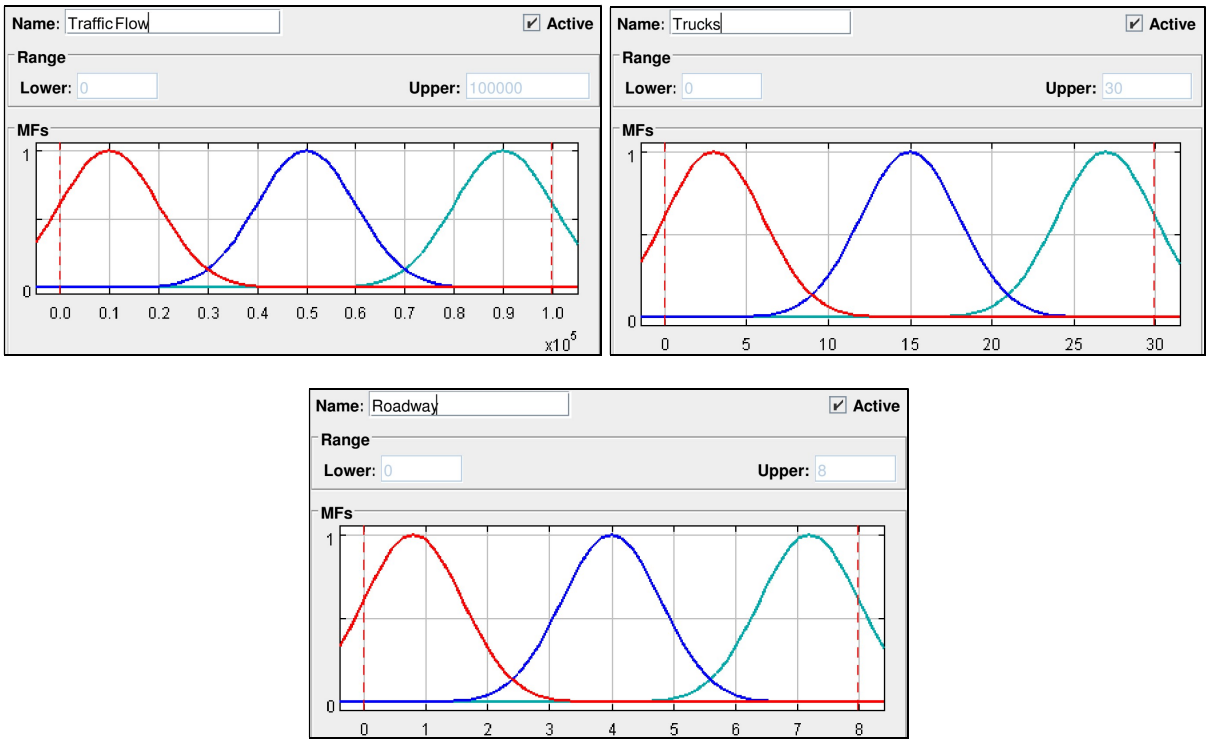
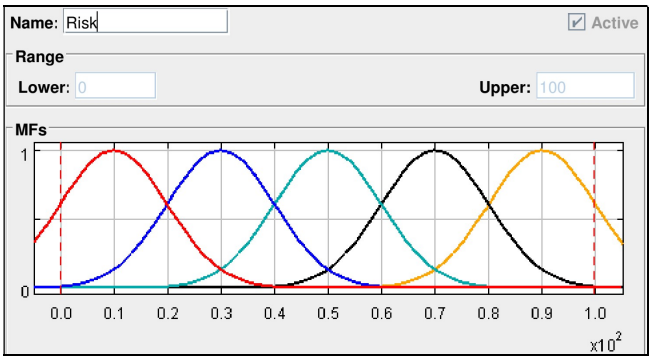


Figure 3. Membership functions of the output variable



The next step is forming of database of rules. As the system has five input linguistic variables (n=5) with three linguistic values each (M=3), they can be combined in the database with a total of $M(n) = 3^5 = 243$ rules. Rules for the fuzzy logic system are determined by applying the Aggregation Weight Premise rules method (ATPP) (Milošević et al., 2021).

3.2. Determination of the weight coefficients of the input variables

In order to create conditions for the results of the risk assessment analysis to be as close as possible to the real situation, it is necessary to determine the weighting factors for each parameter separately. For the purposes of this paper, the results of the expert survey according to Milovanović (Milovanovic, 2012), which was used by the experts to determine the rank of the parameters, were adopted.

In this research, out of a total of 15 experts who were asked to participate in the survey, 12 responded to the invitation and gave their opinion on the degree of influence of parameters on the level of risk in the transport of dangerous goods. The experts were divided into three competence groups, with the individual opinions of one group of experts being multiplied by a “competence weight”.

The survey form included 24 parameters and a 25th risk parameter ("other", in which experts could add a new parameter according to their opinion) and each of the experts, based on their opinion, expressed the magnitude of the impact of each parameter separately. The magnitude of the impact of each of the parameters separately listed in the survey form, depending on their degree of impact on the risk in the transport of dangerous goods, is defined on a scale from 0 to 4, where: 0 – no significance; 1 – low significance; 2 – significant; 3 – very significant; 4 – critical impact.

The mean value of the significance of each parameter was obtained by multiplying the opinion of each expert (from 0 to 4) on the degree of influence of a particular parameter on the level of risk in the transport of dangerous goods, by their level of competence (1, 1.2 or 1.5), summing it up, and then dividing this sum by the total number of expert opinions multiplied by their level of competence. The experts gave the highest degree of significance to the parameter "population density", with a mean significance value of 3.42, and the lowest degree of significance to the parameter "type of road drainage system", with a mean significance value of 1.46. For the purposes of this paper, considering the number of rules (M(n) = 3^5 = 243 rules) and complexity of defining and optimizing rules, five parameters were chosen with degree of significance given in Table 2.

The weighting coefficients of the parameters were determined based on the average rank value using the FUCOM method (MCDM Full Consistency Method) (Pamučar et al., 2018). The criteria Population density, Traffic accidents, Traffic flow size and Participation of traffic in the traffic flow tend to the minimum, and the criterion Road condition tends to the maximum.

When determining the weight coefficients of the membership functions, a uniform distribution was used and the results given in Table 2 were obtained.

7. Table 7. Weight coefficients of the input variables

Parameter	Degree of significance according to (Milovanović, 2012)	weighting coefficients	Small	Medium	Large
Population Density	3,42	0,2595	0,0865	0,1730	0,2595
Traffic Accidents on a Road Section	2,68	0,2033	0,0678	0,1356	0,2033
Traffic Flow Size	2,62	0,1988	0,0663	0,1325	0,1988
The Share of Freight Vehicles in the Traffic Flow	2,26	0,1715	0,0572	0,1143	0,1715
Road Condition	2,20	0,1669	0,1670	0,1113	0,0556

3.3. Defining and optimizing rules

Once the weight coefficients are determined, the initial "incomplete" rule base is defined. The initial rule base contains only the premises ("if" part of the rule) or combinations of all membership functions of the input variables. The total number of rules depends on the number of membership functions of the input variables and is calculated according to the expression:

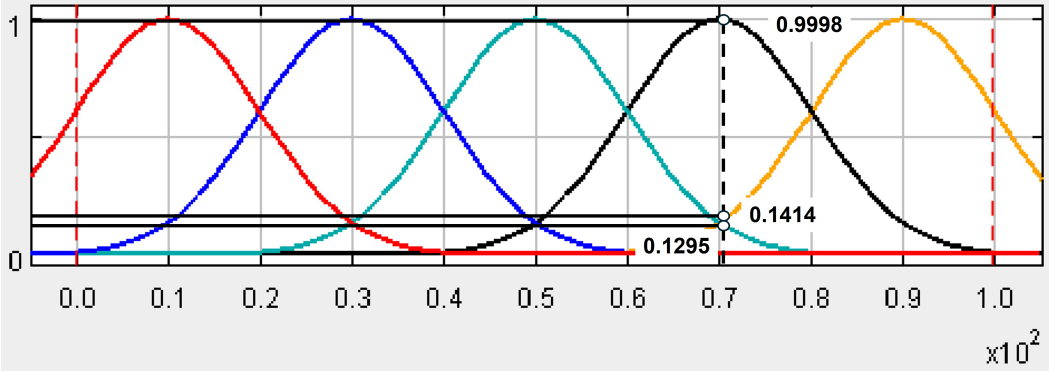
$$N_R = \prod_{i=1}^{n} k_{X_i} \quad (1)$$

The generation of a "complete" rule base begins by constructing a matrix in which combinations of input pairs are replaced by individual weight coefficients of the input

variables. After constructing the rule matrix, the weight coefficients are summed row by row, which will determine the degree of membership (crisp value) – a real number of the membership function of the output variable.

In a specific example, if the initial rule base is (Small – Medium – High – Medium – Small), then the sum of the weight coefficients will be w = 0.0865 + 0.1356 + 0.1988 + 0.1143 + 0.1670 = 0.7022. This weight coefficient value has a degree of membership for the "Medium" membership function of 0.1295, for the "High" membership function of 0.9998, and for the "Very High" membership function of 0.1414. This weight coefficient associates the rule with the conclusion value „High“ because it has the maximum membership value. Figure 3 shows the degree of membership functions of output variable.

Figure 4. The degree of membership functions of output variable



After assigning the conclusion value, the elimination of redundant rules is started, since they burden the system and the understanding of the rule base. There are rules in which the membership function values are repeated, while the conclusion remains the same. By applying this principle, out of 243 rules in the complete database, 82 rules were eliminated.

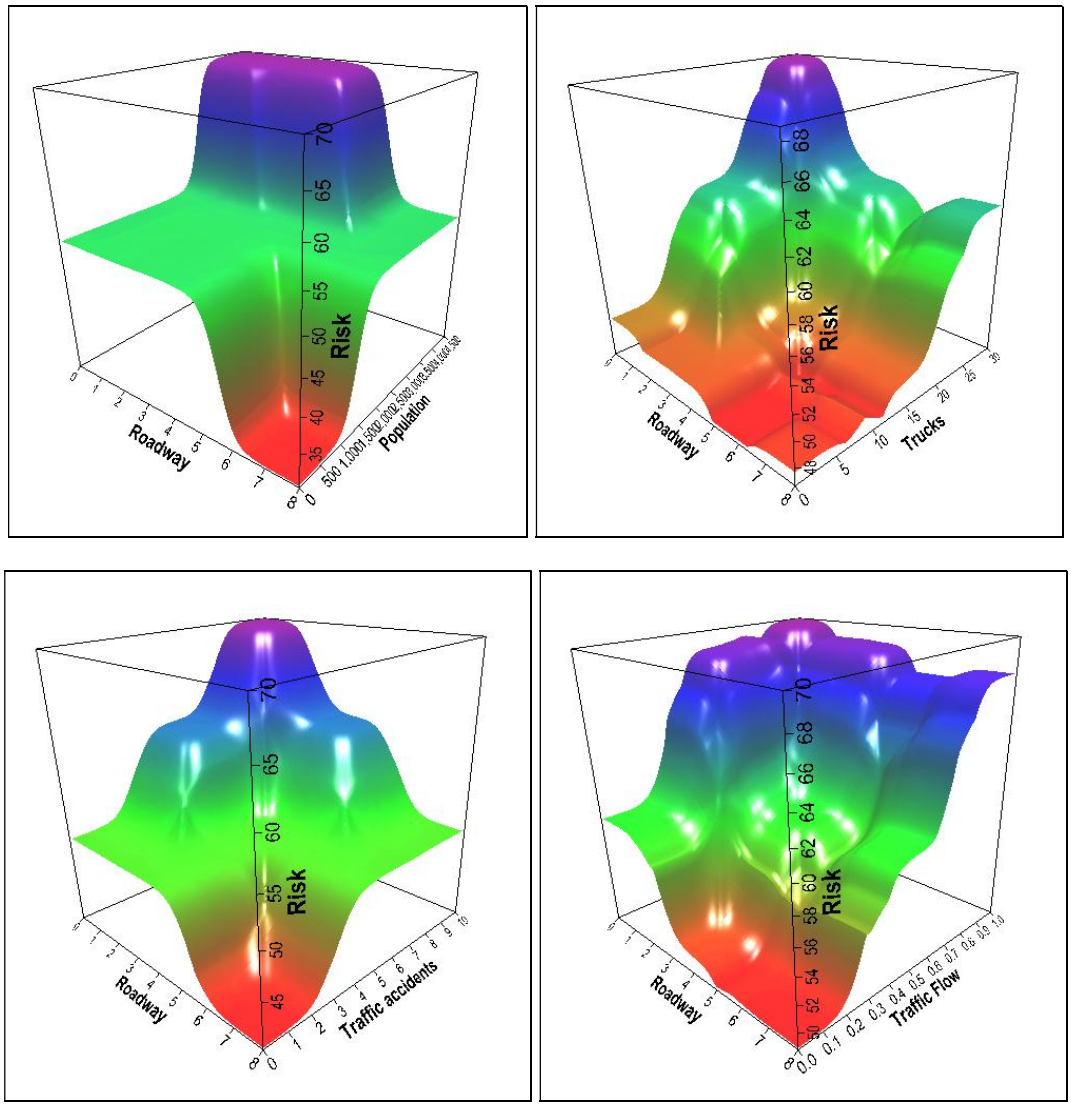
4. RESULTS AND DISCUSSION

Within the risk calculation model, data from the Reference System of the Public Enterprise "Roads of Serbia", data on traffic safety features in the Republic of Serbia from the Road Safety Agency, as well as data from the Map of Protected Areas of Serbia from the Serbian Institute for Nature Conservation, were used.

To obtain the results, the Mamdani method (PROD-SUM) in the FIS Pro software was used. The interdependencies of the two input variables and the solutions are given in Figure 4.

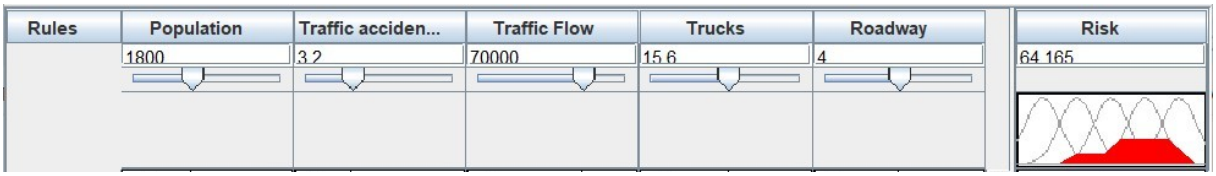
As can be seen from the figures, lower risk is achieved with a higher value for the „Road Condition“ parameter and lower values for the other parameters. The magnitude of the interdependence is variable in relation to the values of the three parameters that are not shown in the graphs. By entering predefined values for the three parameters, the interdependence can be specified and a more realistic picture of the level of risk on a particular section can be obtained.

Figure 5. Interdependencies of the two input variables and the solutions



When entering specific values for a specific road section, for example: traffic accidents on the road section (number of traffic accidents per kilometer) – 3.2, traffic flow size (average annual daily traffic on the road section) – 70,000, share of freight vehicles in the traffic flow (percentage share of average annual daily freight vehicle traffic in relation to total average annual daily traffic on the road section) – 15.6, road condition (road surface quality index) – 4 and population density – 1,800, the risk level is 64.165, as shown in Figure 5.

Figure 6. Inference for specific values of parameters



5. CONCLUSION

The main goal in the transport of dangerous goods is to reduce the risk of accidents. The assessment of risk in the transport of dangerous goods depends on a large number of factors. In order to obtain the level of risk when planning the transport of dangerous goods along a predetermined route, it is necessary to precisely select the factors and collect data

on their values. There are methods that process this data and can be used to assess the risk on a specific route and thus make a decision on the next steps in organizing the transport of dangerous goods.

For the purposes of this research, five input factors were selected, which can reliably determine the risk. Increasing the parameter values of certain factors affects the increase in risk, while on the other hand, increasing the parameter values of certain factors affects the decrease in the risk level. In order to apply the Fuzzy method, it was necessary to determine their membership functions. Also, membership functions were determined for the input factors, as well as for the output parameter – the risk level. When defining the rules in the Fuzzy method, and in order to increase the reliability of the results, weight coefficients were determined by membership functions, the sum of which determined the value of the output function by membership functions. In this way, the risk level on a certain route is determined. By changing the values of the input parameters, the values of the risk level also change, so it is possible to correct decisions in route selection.

In order to obtain reliable information about the risk, it is necessary to consider the interdependence of the input parameters, which was done in this research. In this way, interdependence graphs were obtained that indicate the conditions under which the transport of dangerous goods would be carried out with a lower risk.

Based on the results of this research, it can be concluded that the application of the Fuzzy method in risk assessment is very reliable, because it is not limited to specific values of individual factors, but rather expands the analysis by increasing the intervals of these parameters through the determination of membership functions. It should be noted that in this particular study, five input factors were selected, while other factors that may affect the level of risk were not considered. For this reason, it is very important to select all factors that affect or could affect the level of risk and to consider their interdependence, and thus to determine the level of risk more precisely. By selecting a larger number of factors, the reliability of the results would be greater, but the data analysis would be more complex and, specifically in the Fuzzy method, it would be necessary to define a larger number of inference rules. Considering that the Fuzzy method uses a base of inference rules, it is very important that these rules are defined objectively and comprehensively, for which it is necessary to use the opinions of experts. In this study, experts determined the weighting coefficients, and therefore the base of inference rules.

Based on the research conducted using the Fuzzy method on the values of important factors, the hypothesis is confirmed and it can be concluded that the risk in the transport of dangerous goods on the route can be reliably determined using the values of the factors that influence it using the Fuzzy method.

In further research, the analysis could consider the level of risk with a larger number of influential factors, and their weighting coefficients could be examined in more detail using expert opinion.

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Pregledni rad

METODOLOŠKI PRISTUP PROCJENI RIZIKA PRIJEVOZA OPASNIH TVARI

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SAŽETAK
Opasne tvari su sirovine, poluproizvodi ili gotovi proizvodi koji zbog svojega karakterističnog kemijskog sastava i određenih svojstava imaju niz poželjnih obilježja za namjensku uporabu. Međutim, u nekontroliranim uvjetima mogu izazvati opasne i štetne posljedice za ljude, životinje, materijalna dobra, vodotoke, vegetaciju ili cjelokupni ekosustav općenito. Opasna roba definira se kao predmet ili tvar čiji je prijevoz zabranjen ili dopušten samo ako se obavlja pod uvjetima utvrđenima Međunarodnim sporazumom o međunarodnom cestovnom prijevozu opasne robe. Prijevoz opasne robe u cestovnom prometu područje je od velike važnosti za gospodarstvo te stoga privlači sve veću pozornost znanstvene i stručne javnosti. To je područje uređeno propisima na međunarodnoj i nacionalnoj razini, koji definiraju obveze sudionika u prijevozu opasne robe kako bi se prijevoz odvijao sigurno. Iako se poduzimaju propisane mjere, u prijevozu opasne robe i dalje dolazi do izvanrednih događaja. Cilj planiranja i organizacije svakog prijevoza opasne robe jest smanjiti rizik od incidenta, a time i izvanrednog događaja čije posljedice mogu biti nesagledive. Postoje metode procjene rizika tijekom prijevoza opasne robe, na kojima se temelji metodologija odabira rute za prijevoz opasne robe. U radu je prikazana metodologija procjene rizika primjenom FUZZY metode s definiranim čimbenicima.

Ključne riječi: prijevoz, opasna roba, metodologija, rizik, FUZZY metoda

Preliminary Communication

CAUSES AND RISK FACTORS IN THE TRANSPORT OF MILITARY EQUIPMENT: STATISTICAL ANALYSIS, FIELD CHALLENGES, AND THE DIGITAL TRANSFORMATION OF MILITARY TRAINING

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ABSTRACT

Transport of military equipment represents a vital component of logistical support within modern armed forces. However, the conditions under which such transport is carried out, including unregulated road networks, complex terrain and stressful operational environments, contribute to a high incidence of accidents. Research indicates that rollovers, collisions, and roadway departures are among the most significant safety risks, particularly during military training activities. The aim of this scientific paper was to examine the most frequent causes of accidents through a statistical model based on simulated data and available literature. Analysing the relevant factors critical weaknesses in load-securing procedures and operational preparedness of drivers were identified. Special attention is given to the potential use of virtual reality (VR) technology in military driver training, which enables the rehearsal of complex scenarios within a safe, controlled environment. The findings suggest that VR-based training may contribute to the reduction of accident risk and operational costs while maintaining or improving overall readiness. It is therefore recommended that VR systems be integrated into both basic and advanced driver training programs within military units.

Key words: *military transport, military training, accident risk, virtual reality, load securing*

1. INTRODUCTION

Given the increasing complexity of international military missions, interoperability and force mobility have become key determinants of operational effectiveness (Jałowiec and Pietrzyk-Wiszowaty, 2022). This includes the rapid deployment of combat vehicles across diverse climatic and geographic environments, which elevates the risk of accidents, particularly under conditions of reduced visibility, low surface friction, or inadequately prepared infrastructure (AJP 4.4, 2013). This paper is structured as a conceptual and exploratory study combining a structured literature review with simulation-based modeling. Its primary contribution lies in integrating existing empirical findings with a simplified analytical framework to estimate the potential safety impact of virtual reality (VR)-based training interventions within military transport systems. The aim of this article is to analyze the most common causes of accidents through a synthesis of existing literature and the application of

a statistical model based on simulated data. Furthermore, the study seeks to identify key vulnerabilities in cargo-securing procedures and in the operational readiness of drivers and to evaluate the potential of VR training as a mitigation measure. A significant increase in military activity has been observed along the eastern flank of the North Atlantic Treaty Organization (NATO), primarily as a consequence of the situation in Ukraine, which was invaded by the Russian Federation on February 24, 2022. The escalation of threat levels in proximity to NATO member states, has necessitated dynamic changes across multiple domains of national armed forces and allied procedures. One of the critical domains directly affecting operational capability is military transport, where tangible needs for the improvement of existing solutions have been identified (Jałowiec, Pietrzyk-Wiszowaty, 2022; USACRC, 2018). Statistical data from NATO and national safety authorities indicate that the majority of accidents occur during logistical operations in peacetime conditions, when personnel vigilance tends to decline and supervisory mechanisms are less stringent. These findings underscore the need for a comprehensive approach that integrates data analysis, enhanced training, and innovative technologies to improve safety within military logistics systems (GAO, 2021).The transportation of combat equipment frequently takes place outside standard road networks, across meadows, forest tracks, mountainous terrain, and muddy surfaces. Such environments require specialized driver competencies and reliable armored vehicles. Nevertheless, statistical evidence points to an increased number of accidents, particularly during tactical exercises and non-combat transport operations (USACRC, 2022). The specific nature of military operations demands a correspondingly tailored safety framework. While civilian transportation systems increasingly rely on automation, monitoring, and regulatory mechanisms, the military sector depends on a high level of training, adaptability, and proper technical preparation, including adequate cargo securing and load stabilization procedures. In this context, growing attention has been directed toward the potential role of simulation-based technologies, such as virtual reality (VR), in risk reduction strategies (USACRC, 2018; Telli Yamamoto, Altun, 2021). The specific nature of military operations demands a tailored safety framework. While civilian transportation systems increasingly rely on automation and monitoring, the military sector depends on a high levels of training, adaptability, and technical preparation, including proper cargo securing procedures. In this context, growing attention has been directed toward simulation-based technologies such as VR as tools for risk reduction (USACRC, 2018; Telli Yamamoto, Altun, 2021). Based on the research objective, the following hypothesis is proposed: the integration of VR-based training into military driver education programs can contribute to reducing accident rates and operational costs while maintaining or enhancing overall operational readiness.

2. ACCIDENTS CAUSED BY MILITARY DRIVER ERRORS

Traffic safety is the outcome of multiple interrelated factors, including human behavior, vehicle characteristics, transport infrastructure, and environmental conditions. Nevertheless, contemporary research consistently confirms that the human factor plays a dominant role in the occurrence of traffic accidents (Zhou et al., 2025). Human error is present in more than 90% of fatal traffic accidents, whereas technical vehicle malfunctions and road-environmental conditions account for a significantly smaller proportion (ERSO, 2024). The mental process underlying driving activities can be divided into three phases: the perceptual phase, the analysis and judgment phase, and the operational phase. Errors occurring in any of these three stages may lead to traffic accidents and are directly linked to the driver's cognitive processing during critical incidents. Although traffic accidents are often attributed to various unlawful or disciplinary violations, an analysis of their root causes reveals that failures in perception, judgment, and reaction within these three stages constitute fundamental contributing factors (Zezhi-Shang, 2013). Accidents caused by perceptual errors account for the largest proportion (48.1%), followed by errors in judgment (36%), and errors in reaction and operation (7.9%). These findings indicate that traffic accidents are highly likely to occur when deficiencies arise in drivers' perceptual, evaluative, or operational capacities (EROS, 2024; Zezhi-Shang, 2013). Factors contributing to perceptual errors among military vehicle

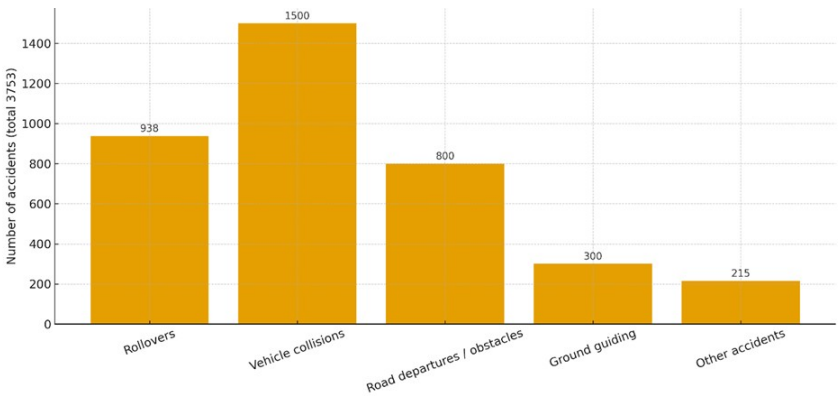
drivers include inadequate nighttime illumination, physical obstacles, and adverse weather conditions that impair the detection of hazards. In addition, drivers of military vehicles may experience psychological strain due to family, professional, or personal stressors, resulting in reduced concentration and delayed reactions. When such challenges are not effectively managed, drivers may fail to recognize hazardous situations in a timely manner, or may not perceive them at all, thereby increasing the likelihood of perceptual error (Zezhi-Shang, 2013). Judgment errors are similarly associated with the physical and psychological condition of military drivers, as well as with their attitudes toward safety. Improper vehicle handling may result in operational mistakes, particularly when training has been insufficient or inadequately standardized. Non-compliance with established operational procedures and deviations from prescribed standards further increase the probability of driving errors (USACRC, 2022).At the core of this issue lies training. Continuous and structured training fosters repetition and skill automatization, enabling drivers to respond reflexively and appropriately to specific operational scenarios. The subsequent sections of this paper define the most common types and principal causes of accidents in military transport operations.

3. STATISTICAL ANALYSIS OF ACCIDENT CAUSES

3.1 Data, Methods, and Limitations

The data analyzed in this study are primarily based on statistics published by the U.S. Government Accountability Office (GAO), an independent federal audit institution of the United States, as well as on research and analytical reports produced by New America. These sources were further supplemented with relevant findings from peer-reviewed academic literature. The objective of the analysis is to identify the most frequent types of accidents, determine their principal causes, and emphasize the need for improved training, supervision, and systematic safety measures aimed at reducing future risk. A total of 3,753 tactical vehicle accidents were recorded during the period 2010–2019. Of these, 938 incidents involved rollovers, representing approximately 25% of all recorded accidents. Other categories included vehicle collisions, roadway departures or impacts with fixed objects, accidents occurring during ground guiding procedures, and additional mechanisms such as injuries sustained while entering or exiting vehicles (GAO, 2021). The data indicate that rollovers accounted for roughly one-quarter of all accidents, while vehicle collisions represented the largest number of total incidents. Roadway departures and ground guiding accidents also comprised a significant proportion of cases. Although rollovers were numerically fewer than collisions, they most frequently resulted in fatal outcomes (GAO, 2021). Between 2012 and 2019, a total of 85 vehicle-related fatalities were recorded (New America, 2024). Based on GAO data, approximately 63% of these fatalities were associated with rollover incidents (GAO, 2021). The remaining fatalities were distributed among vehicle collisions, roadway departures, and other accident mechanisms.

Graph 7. Types of tactical vehicle accidents



Source: GAO (2021)

Between 2012 and 2019, a total of 85 vehicle-related fatalities were recorded (New America, 2024). Based on GAO data, approximately 63% of these fatalities were associated with rollover incidents (GAO, 2021). The remaining fatalities were distributed among vehicle collisions, roadway departures, and other accident mechanisms. From a methodological perspective, the analysis relies on secondary data sources and descriptive statistical interpretation. While the data provide valuable insight into accident distribution and fatality patterns, limitations include potential inconsistencies in reporting standards across institutions, restricted access to detailed micro-level datasets, and the absence of controlled experimental variables. Consequently, the findings should be interpreted as indicative rather than definitive, serving primarily as a foundation for further statistical modeling and simulation-based analysis presented in subsequent sections of this study. It should be emphasized that the statistical model presented in this paper relies partly on simulated assumptions derived from literature-based proportions rather than on primary operational datasets. Consequently, the numerical estimates presented in the following sections should be interpreted as theoretical projections intended for analytical illustration.

3.2 Analysis

Based on the statistical data presented above, a comparative assessment and structured analysis can be conducted.

3.2.1 Initial Data

The baseline dataset used in this analysis indicates that a total of 85 fatal cases were recorded during the period 2012–2019 (New America, 2024). According to data reported by the U.S. Government Accountability Office, approximately 63% of these fatalities were associated with rollover incidents (GAO, 2021). Based on this proportion, the estimated number of rollover-related fatalities amounts to approximately 54 cases, with the remaining 31 fatalities attributed to other accident mechanisms. This initial distribution provides a simplified but analytically consistent representation of fatal accident structures within military transport systems. In the absence of fully disaggregated datasets, the use of proportion-based estimation enables a transparent approximation of accident categories derived from authoritative statistical sources. However, it should be emphasized that such values represent modeled estimates rather than directly observed classifications at the individual case level. The residual 31 fatalities are subsequently interpreted in accordance with classifications established in the relevant literature, which identifies vehicle-to-vehicle collisions and roadway departures as the most prevalent accident mechanisms following rollovers, while other causes, including technical malfunctions and operational factors, constitute a smaller residual category (ERSO, 2024; GAO, 2021; New America, 2024). Overall, this proportional baseline serves as a quantitative foundation for subsequent comparative modeling, scenario analysis, and risk assessment within the broader framework of military transport safety.

3.2.2 Distribution of the Remaining 31 Fatal Cases

Building upon the baseline distribution outlined in the previous section, the remaining 31 fatalities were further categorized into three principal accident mechanisms: vehicle collisions, roadway departures, and other mechanisms. In order to maintain analytical consistency with established accident patterns and ensure comparability with existing statistical findings, a proportional allocation framework was applied. This allocation was derived from the relative frequency distributions reported in the relevant literature and reflects the dominant role of vehicle collisions as the most common accident type following rollover incidents, followed by roadway departures, while other mechanisms represent a comparatively minor share. In this context, the residual fatalities were distributed in a ratio of 20:8:3 across the three categories. Such a proportional allocation approach is methodologically justified in situations where detailed case-level data are not available, as it allows for a structured and transparent approximation of accident distributions based on

aggregated statistical evidence. Nevertheless, it is important to emphasize that the resulting values represent modeled estimates rather than empirically verified classifications, and should therefore be interpreted as indicative rather than definitive. This distribution provides a coherent analytical basis for subsequent quantitative evaluation and supports the development of scenario-based modeling aimed at assessing risk factors and potential mitigation measures within military transport systems.

3.2.3 Verification of Proportional Consistency

The internal consistency of the proposed proportional allocation was verified by confirming that the sum of the distributed values corresponds exactly to the total number of remaining fatal cases. Specifically, the allocation of 20 collision-related fatalities, 8 roadway departure fatalities, and 3 fatalities attributed to other mechanisms yields a total of 31 cases, thereby fully aligning with the previously established residual dataset. When expressed in relative terms, this distribution corresponds to approximately 64.5% for vehicle collisions, 25.8% for roadway departures, and 9.7% for other mechanisms. These proportions are consistent with aggregate accident patterns reported in GAO statistics, which identify vehicle collisions as the most frequent accident type following rollover incidents (GAO, 2021). Although the fatality rate per individual collision event is generally lower than that associated with rollovers, the higher overall frequency of collisions results in their dominance within the residual fatality structure. Roadway departures, while less frequent, are associated with significant accident severity and therefore justify a substantial proportional share. In contrast, other mechanisms, including technical failures and miscellaneous operational factors, occur relatively infrequently and account for a minor proportion of cases (ERSO, 2024; GAO, 2021; New America, 2024). From a methodological perspective, this step serves as a validation of the proportional allocation framework, ensuring both numerical consistency and alignment with empirically observed aggregate trends. Consequently, the 20:8:3 distribution should be interpreted as a structured, literature-supported approximation rather than an exact empirical classification at the individual case level.

3.2.4 Results

The results of the proportional and comparative analysis indicate that rollover incidents represent the dominant cause of fatalities in military transport operations during the observed period from 2012 to 2019, accounting for approximately two-thirds of all recorded fatal cases. This finding is consistent with previously reported statistical patterns, which emphasize the critical severity and high fatality risk associated with rollover accidents. Vehicle collisions constitute the second most significant category, contributing a substantial share of total fatalities. Although individual collision events are generally associated with lower fatality rates compared to rollovers, their higher frequency results in a notable cumulative impact on overall mortality within military transport systems. In contrast, roadway departures and other mechanisms represent less frequent causes of fatal accidents; however, they remain operationally significant due to the severity of outcomes when such incidents occur. These findings highlight the multifactorial nature of accident causation and underscore the importance of addressing both high-risk and high-frequency accident categories in the development of targeted safety interventions. It should be noted that the presented results are derived from proportion-based estimations and should therefore be interpreted as indicative trends rather than precise empirical measurements. Nevertheless, they provide a coherent analytical basis for further scenario modeling and evaluation of risk mitigation strategies within the context of military transport safety. The analysis of accident types and their associated causal factors reveals distinct patterns across the identified categories. Rollovers are primarily linked to operational conditions involving lateral slopes and, most critically, improper load securing, which significantly affects vehicle stability during transport. Vehicle collisions are most frequently associated with reduced visibility conditions and driver fatigue, indicating a strong interaction between environmental constraints and human performance limitations. Roadway departures, on the other hand, are predominantly caused

by loss of vehicle control, often occurring in challenging terrain conditions characterized by slippery or unstable surfaces. In contrast, other accident mechanisms, although less frequent, are typically related to adverse weather conditions as well as technical failures, particularly those involving braking and hydraulic systems. Collectively, these causal patterns highlight the multifactorial nature of accident occurrence in military transport operations and underscore the critical role of both human and technical factors in determining overall safety outcomes.

4. SECURING OF COMBAT EQUIPMENT

The proper securing of armored vehicles represents one of the key determinants of safety in military transport operations, particularly when flatbed transport platforms are used. Such transport assets are designed for the movement of heavy combat vehicles, whether tracked or wheeled. According to available data, more than 30% of rollover-type accidents are associated with improperly secured combat vehicles or incorrectly positioned centers of gravity. This finding clearly indicates that errors occurring during the loading and cargo-securing phase are directly linked to severe operational consequences (GAO, 2021; Liu et al., 2024; Lo et al., 2017; New America, 2024). An additional concern lies in the fact that military drivers often have limited access during training to realistic, hands-on exercises involving proper tie-down and load-securing procedures. This creates a gap between theoretical instruction and practical application (USACRC, 2022). As a result, the likelihood of operational errors under real-world conditions increases, potentially leading to catastrophic outcomes. Contemporary military doctrines emphasize the need for standardized procedures and the integration of simulation-based training methods for load-securing techniques. Such approaches enable drivers and crews to develop competencies in accurately assessing vehicle weight distribution, center-of-gravity positioning, and the appropriate use of tie-down equipment within controlled training environments. This is of particular importance given the increasing complexity of modern combat vehicles and the operational tempo of current military activities (FM 55-30, 1997; Tutton, 2017).

5. VIRTUAL REALITY AND THE NEW PARADIGM OF MILITARY TRAINING

5.1 Technological Foundations and Application of VR Systems

VR enables the realistic simulation of diverse accident scenarios and crisis situations without exposing trainees to physical risk. This technology has already been widely implemented in the transportation industry, medical training, and controlled driving simulations, and is increasingly being integrated into military systems (Xie et al., 2021). A principal advantage of VR technology lies in its capacity for full immersive learning within simulated environments, allowing users to interact dynamically with their surroundings without real-world consequences. This facilitates experiential learning, repeated procedural practice, and enhanced training safety (Peik et al., 2012). Contemporary military simulators and VR systems also support interactive training modules for proper load securing. Within these modules, trainees assess center-of-gravity positioning and apply various tie-down techniques in simulated operational conditions (Xie et al., 2021). Furthermore, the integration of VR platforms with wearable sensor technologies enables monitoring of drivers' psychophysiological states, including fatigue and stress levels. This enhances the realism of training scenarios and provides instructors with objective insight into trainee performance and condition (Meocci et al., 2024; Boboc et al., 2024). Based on experimental findings and recent empirical studies, VR-based training has been reported to improve training outcomes and driver preparedness, which may indirectly contribute to improved safety performance and operational readiness among military vehicle drivers. Research suggests that VR instruction can result in 40–60% greater retention of acquired skills compared to conventional training methods, largely due to its interactive structure and immersive scenario-based learning environment (Xie et al., 2021).

5.2 Operational and Economic Justification

The integration of VR systems into driver and tactical training programs requires an initial capital investment. However, research indicates that such expenditures generate substantial long-term returns through cost optimization, improved safety outcomes, and enhanced operational readiness (Telli Yamamoto, Altun, 2021; Xie et al., 2021). Key advantages include a reduction in extraordinary maintenance costs, as the use of simulators in the early stages of training decreases reliance on actual vehicles. This approach has been associated with 20–30% lower maintenance expenditures due to reduced mechanical wear and operational strain (Meocci et al., 2024). Improved allocation of training resources represents an additional benefit. VR-based instruction allows multiple trainees to participate simultaneously without the logistical constraints associated with limited vehicle availability. This scalability enhances training efficiency and reduces scheduling bottlenecks. Furthermore, VR platforms enable comprehensive after-action review (AAR) analysis, facilitating precise reconstruction of driving sessions and detailed evaluation of procedural and decision-making errors. Such data-driven feedback significantly contributes to the optimization of learning processes and supports improved safety performance in subsequent operations (Meocci et al., 2024; Xie et al., 2021). Cost-projection models suggest that VR systems typically achieve return on investment within two to three years, particularly in larger units characterized by frequent personnel rotations. In this context, VR should not be regarded merely as a technological supplement, but rather as a strategic investment that integrates safety enhancement, operational efficiency, and long-term economic sustainability (Telli Yamamoto, Altun, 2021).

6. ANALYSIS OF THE IMPACT OF VR TRAINING ON MILITARY TRAFFIC ACCIDENTS

6.1 Framework Model

The model presented in this section constitutes a simplified analytical framework intended for exploratory estimation rather than a predictive statistical model validated on operational datasets. It is designed to provide a structured approximation of the potential relationship between key risk factors and the effects of targeted training interventions, based on previously presented data and literature-derived assumptions. Building upon the preceding analysis, several key premises can be established. First, approximately 63% of fatalities in military transport are attributable to rollover incidents (GAO, 2021). Second, the parameter p is introduced to represent the proportion of rollover incidents caused by improper load securing. Third, the parameter X denotes the assumed effectiveness of VR-based training in reducing this specific category of error.

Within this analytical framework, the relative reduction in total fatalities (Δ) can be expressed as a function of these parameters:

$$\Delta = 0.63 \times p \times X$$

Furthermore, if N denotes the total number of fatalities within a given observation period, the expected number of lives saved can be approximated as:

$$\text{Lives saved} \approx N \times 0.63 \times p \times X$$

This formulation isolates a specific causal pathway linking the prevalence of rollover incidents, the share of preventable errors associated with improper load securing, and the potential corrective effect of VR-based training interventions. By focusing exclusively on this direct relationship, the model provides a conservative estimate of potential safety improvements. At the same time, it is important to emphasize that the parameters p and X represent modeled assumptions derived from literature and analytical reasoning, rather than empirically validated coefficients. Consequently, the results generated by this framework should be interpreted as indicative projections rather than precise predictive outcomes.

Moreover, the model does not account for secondary or indirect effects of VR training, such as improvements in situational awareness, decision-making under stress, or overall driving competence, which may further influence accident rates in practice. Despite these limitations, the framework enables scenario-based analysis through systematic variation of parameters p and X, thereby supporting comparative assessment across different effectiveness assumptions and operational contexts. As such, it provides a transparent and analytically tractable basis for evaluating the potential contribution of VR-based training to risk reduction in military transport systems.

6.2 Theoretical Simulation Based on an Empirical Case

For the purpose of illustrative theoretical projection, a set of baseline assumptions was defined based on previously presented data and literature-derived estimates. The total number of fatalities within the observed period is set at N = 85 (New America, 2024). The parameter p, representing the proportion of rollover incidents attributable to improper load securing, is assumed to range between 0.20 and 0.40, reflecting estimates reported in relevant analytical sources. The parameter X, denoting the effectiveness of VR-based training in reducing securing-related errors, is assumed to range between 0.30 and 0.60. This interval is supported by empirical findings on VR effectiveness in procedural skill acquisition, although not directly linked to mortality reduction (Xie et al., 2021).

Applying the previously defined analytical framework:

$$\Delta = 0.63 \times p \times X$$

$$\text{Lives saved} \approx N \times 0.63 \times p \times X$$

a set of scenario-based projections can be derived.

Table 1. Lives Saved by Scenario (N=85)

Scenario	p (Share of rollovers due to securing)	X (VR effectiveness)	0.63×p×X (Relative mortality reduction)	Lives saved (out of 85)
Pessimistic	0,20	0,30	0,0378 (3,78)	≈ 3
Realistic	0,30	0,50	0,0945 (9,45%)	≈ 8-9
Optimistic	0,40	0,60	0,1512 (15,12%)	≈ 13

Source: Authors

The results indicate that, within a system characterized by 85 recorded fatalities, targeted VR-based training focused on load-securing procedures could theoretically contribute to a reduction in fatalities ranging from approximately 3 to 13 lives. The magnitude of this reduction depends on the actual proportion of rollover incidents attributable to securing-related errors, as well as the empirically verifiable effectiveness of VR training in mitigating such errors. When expressed in relative terms, and considering a “realistic” scenario (p = 0.30, X = 0.50), the projected reduction corresponds to approximately 9–10 lives per 100 fatalities, or 9.45%. This result illustrates the potential scale of impact under moderate effectiveness assumptions. It is important to emphasize that the parameters p and X represent modeled assumptions rather than empirically validated coefficients. As such, the presented results should be interpreted as indicative scenario-based projections rather than precise predictive outcomes. The specified parameter ranges constitute analytically reasonable starting points; however, their validation would require access to detailed accident databases, disaggregated operational records, and controlled experimental evaluation of VR training within specific military units. Despite these limitations, the simulation framework provides a transparent and analytically consistent tool for exploring the

potential contribution of VR-based training to accident reduction. It enables comparative assessment across different effectiveness scenarios and supports evidence-informed discussion on the integration of advanced training technologies within military transport safety systems.

7. CONCLUSION

The analysis indicates that military vehicle rollovers represent the most frequent and most severe category of accidents within military transport systems, accounting for approximately 63% of fatalities. Human factors, combined with deficiencies in load securing and vehicle load distribution, emerge as key contributors to accident occurrence.

The findings further suggest that VR-based training may enhance driver preparedness and procedural competence, particularly in relation to load-securing practices and high-risk operational scenarios. In this context, VR should be considered a complementary training tool with potential safety benefits.

The theoretical simulations presented in this study indicate that targeted VR-based training could contribute to a reduction in rollover-related fatalities by approximately 3 to 13 lives (corresponding to approximately 9–10% of total fatalities). However, it is important to emphasize that these projections are based on modeled assumptions and literature-derived parameters, rather than on empirically validated operational data. As such, the results should be interpreted as indicative analytical estimates rather than confirmed outcomes.

Further research based on longitudinal empirical data is required to validate the proposed relationships and to quantify the actual impact of VR training on accident reduction in military transport systems.

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Prethodno priopćenje

UZROCI I RIZICI NESREĆA U PRIJEVOZU BORBENE TEHNIKE: STATISTIČKA ANALIZA, TERENSKI IZAZOVI I DIGITALNA TRANSFORMACIJA VOJNE OBUKE

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SAŽETAK

Prijevoz borbene tehnike predstavlja ključnu komponentu logističke potpore u suvremenim oružanim snagama. No, uvjeti pod kojima se takav prijevoz odvija, uključujući neuređene prometnice, složene terene i stresne operativne okolnosti, rezultiraju visokom stopom nesreća. Istraživanja su pokazala da rollovers (prevrtanja vozila), sudari te izlijetanja s ceste predstavljaju najveće sigurnosne rizike, osobito tijekom vojnih obuka. Cilj ovog znanstvenog rada bio je ispitati najčešće uzroke nesreća primjenom statističkog modela temeljenog na simuliranim podacima i dostupnoj literaturi. Analizom relevantnih čimbenika identificirane su ključne slabosti u postupcima osiguranja tereta te u operativnoj pripremljenosti vozača. Posebna se pažnja posvećuje mogućnosti primjene virtualne stvarnosti (VR) u obuci vojnih vozača, što bi omogućilo uvježbavanje složenih scenarija u sigurnom okruženju. Rezultati upućuju na to da obuka temeljena na VR-u može doprinijeti smanjenju rizika od nesreća i operativnih troškova, uz istodobno održavanje ili poboljšanje ukupne spremnosti. Stoga se preporučuje integracija VR sustava u osnovne i napredne programe obuke vozača unutar vojnih postrojbi.

Ključne riječi: *vojni transport, vojna obuka, rizik od nesreće, virtualna stvarnost, učvršćivanje tereta*

Preliminary Communication

ASSESSMENT OF THE SAFETY LEVEL OF RAILWAY UNDERTAKINGS USING A HYBRID FUCOM–DEA APPROACH

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ABSTRACT

Railway transport safety represents one of the most important elements of modern transportation systems. It directly affects the reliability of railways and the extent to which society accepts them as a safe mode of transport. Traditional safety assessments rely on accident data, but they focus on consequences rather than on the causes and the condition of the system before an accident occurs. In order to overcome these limitations, this paper proposes a hybrid FUCOM–DEA approach for assessing the safety of railway undertakings. The FUCOM method enables the determination of weighting coefficients for safety criteria based on expert evaluations, while preserving the consistency of the weighting process. The DEA method, specifically the BCC model with variable returns to scale, is applied for the quantitative evaluation of the relative efficiency of undertakings in the field of safety. The proposed methodology was tested on four railway undertakings in Bosnia and Herzegovina, using five-year averages of input criteria (workforce, rolling stock age, train-kilometers) and one output criterion (FWSIs – Frequency-Weighted Safety Indicators). The results indicate that passenger undertakings achieve a higher level of safety performance compared to freight undertakings, which, due to a larger volume of operations, exhibit lower relative efficiency in the safety domain. Sensitivity analysis confirms the stability and reliability of the model. The paper provides management with a useful tool for identifying weaknesses in safety management systems and for strategically improving safety performance.

Key words: *railway transport safety; railway undertaking; FUCOM method; DEA;*

1. INTRODUCTION

Modern railway systems face the need to simultaneously improve safety and maintain operational efficiency. This relationship has been further intensified by the processes of globalization and transport market liberalization, in which long-term sustainability is achieved only by those systems capable of establishing synergy between a high level of operational efficiency and robust safety performance. In such an environment, the railway sector in Bosnia and Herzegovina, as well as in much of the Western Balkans, is confronted with a reduced volume of freight and passenger transport compared to the period prior to the global economic crisis. The decline in revenues resulting from decreased industrial production and changes in demand has led to limited investment in the maintenance and modernization of rolling stock, which has a direct and long-term negative impact on system safety. The assessment of railway transport safety has traditionally been based on fragmented and methodologically limited approaches, largely relying on retrospective analyses of accidents and incidents or on subjective expert evaluations. Such reactive models do not provide a comprehensive and quantitatively grounded basis for strategic safety management, nor do they enable the timely identification of systemic weaknesses. Railway transport safety is a multi-criteria problem influenced by technical, organizational, and human factors. Insufficient modernization and increased workload of operational staff significantly raise the risk of errors with serious consequences. Safety accidents and incidents directly affect the perception of the reliability of the railway system, undermine user trust, and weaken the competitive position of rail transport compared to other modes of transportation. Therefore, safety cannot be viewed solely as a technical issue, but rather as a key criterion that integrally reflects the level of organization, technical reliability, and management efficiency of the railway system. The complexity and interdependence of the factors determining safety require the application of methodologically robust, quantitative analytical frameworks capable of integrating heterogeneous input data into a unified, comparable, and objective measure of performance. In this context, this paper proposes the application of a hybrid FUCOM–DEA approach for assessing the safety level of railway undertakings. The proposed methodological framework combines the FUCOM (Full Consistency Method), which enables the consistent and coherent determination of weighting coefficients for safety criteria based on expert evaluations, and DEA (Data Envelopment Analysis), which is used for the objective assessment of the relative efficiency of railway undertakings in the safety domain. By integrating subjective evaluation of criteria with objective efficiency analysis based on real data, the proposed model provides a reliable basis for benchmarking, identifying best practices, and supporting managerial decision-making aimed at the strategic improvement of safety. The aim of the paper is to offer an analytical tool that moves beyond a reactive approach to safety, positioning it as a strategic variable of sustainable development in the railway sector. Based on the defined research objective, the following research question is formulated in the paper: Does the integrated FUCOM–DEA approach enable a methodologically consistent and sufficiently discriminative assessment of the safety level of railway undertakings under conditions of a limited number of decision-making units and heterogeneous safety criteria? Accordingly, the following research hypothesis is proposed: H1: The application of the integrated FUCOM–DEA model enables a more reliable evaluation and ranking of the safety performance of railway undertakings compared to the analysis of individual indicators or the standalone application of the classical DEA model. The scientific contribution of this paper is reflected in the development of an integrated methodological framework for assessing the safety level of railway undertakings, which combines expert-based weighting of criteria using the FUCOM method and an objective evaluation of relative efficiency through the application of the DEA model.

2. REVIEW OF RELATED RESEARCH

The assessment of safety performance in transport systems is increasingly based on the integration of multi-criteria decision-making (MCDM) methods and non-parametric efficiency evaluation techniques. In the railway sector, Data Envelopment Analysis (DEA) has been

widely applied to evaluate operational and technical efficiency (Cooper et al., 2011). Banker, Charnes and Cooper (1984) proposed the BCC model with variable returns to scale, which is particularly suitable for analyzing heterogeneous decision-making units (DMUs), such as railway undertakings of different sizes and activities. To overcome the limitations of classical DEA, namely the assumption that all inputs and outputs are measurable and that weight coefficients are unrestricted, numerous authors have integrated criteria-weighting methods with DEA models. Wang and Luo (2009) proposed combining the AHP and DEA methods to base criteria weights on expert judgments. Blagojević, et al. (2017) integrated Fuzzy AHP and DEA to assess the efficiency of passenger railway undertakings. Similarly, Blagojević, et al. (2020b) combined Fuzzy AHP and DEA to evaluate the efficiency of freight railway undertakings. Blagojević, A. et al. (2020a) proposed a new integrated Entropy–Fuzzy PIPRECIA–DEA model for evaluating railway traffic safety on railway sections in Bosnia and Herzegovina, while Chatterjee et al. (2020) developed a CRITIC–FUCOM–DEA model for assessing the safety of railway sections, thereby introducing the Full Consistency Method (FUCOM) into the context of railway infrastructure. In the broader context of transport systems, Stević et al. (2022) presented an integrated model for evaluating the efficiency of transport companies by combining DEA, PCA, CRITIC, Entropy, and MARCOS methods. The application of integrated MCDM–DEA approaches is also present in related fields. Mitrović Simić et al. (2020) developed a CRITIC–Fuzzy FUCOM–DEA–Fuzzy MARCOS model for assessing road section safety, demonstrating the advantages of fuzzy logic in handling criteria uncertainty. In the field of procurement, Pajić et al. (2025) applied a DEA–FUCOM–CoCoSo approach to optimize supplier selection, while Mishra et al. (2022) improved processes in the automotive industry using the HF–DEA–FUCOM–MABAC technique. Mahmutagić et al. (2021) analyzed forklift efficiency in warehouse systems using a DEA–FUCOM–MARCOS model, and Starčević et al. (2019) compared AHP–DEA, FUCOM–DEA, and BWM–DEA models in the selection of off-road vehicles. The literature review confirms that the integration of DEA and FUCOM methods, along with other MCDM techniques, provides a reliable framework for assessing efficiency and safety in transport systems. However, the integrated application of FUCOM and DEA methods in evaluating the safety performance of railway undertakings, particularly at the level of individual undertakings in Western Balkan countries, remains insufficiently explored. This study aims to fill that gap by adapting the methodology to the specifics of the available data and the context of the railway sector in Bosnia and Herzegovina.

3. METHODOLOGY

The proposed methodological framework integrates the FUCOM and DEA methods to assess the safety level of railway undertakings. The process is carried out in two main phases: (1) determining the weights of the criteria using the FUCOM method based on expert evaluations; and (2) assessing the relative efficiency of undertakings' safety levels using the DEA BCC model, followed by composite ranking.

3.1 FUCOM method

The FUCOM method, developed by Dragan Pamučar et al. (2018), represents a contemporary approach to determining weighting coefficients, based on the principles of full consistency and minimal deviation from expert preferences. Its application in safety analyses enables transparent and mathematically grounded weighting of criteria, thereby reducing the subjectivity often present in traditional MCDM methods. In this study, FUCOM was applied to weight three input criteria (I_1, I_2, I_3) and one output criterion (O_1). The procedure for obtaining weighting coefficients using the FUCOM method is carried out through the following steps:

Step 1 - In the first step, the criteria from a predefined set of evaluation criteria are ranked $C = \{C_1, C_2, \dots, C_n\}$. The criteria are ranked from the highest to the lowest expected weighting coefficient. This results in a ranking of the criteria according to the expected values of the weighting coefficients:

$$C_{j(1)} > C_{j(2)} > \cdots > C_{j(k)} \quad (1)$$

where *k* represents the rank of the considered criterion. If it is assessed that two or more criteria have equal importance, the ">" sign in expression (1) is replaced with an equality sign for those criteria.

Step 2 - In the second step, the ranked criteria are compared pairwise, and the comparative importance ($\varphi_{k/(k+1)}$), $= 1,2, \ldots, n$, is determined, where *k* represents the rank of the evaluation criterion. The comparative importance of an evaluation criterion $\varphi_{k/(k+1)}$ indicates the advantage that the criterion of rank $C_{j(k)}$ has over the criterion of rank $C_{j(k+1)}$. This results in vectors of comparative importance of the evaluation criteria, as expressed in equation (2):

$$\Phi = \left(\varphi_{1/2}, \varphi_{2/3}, \ldots, \varphi_{k/(k+1)}\right) \quad (2)$$

Step 3 - In the third step, the final values of the weighting coefficients of the evaluation criteria $(w_1, w_2, \ldots, w_n)^T$ are calculated. The final weighting coefficients must satisfy two conditions:

1) The ratio of the weighting coefficients must be equal to the comparative importance between the considered criteria $\varphi_{k/(k+1)}$, as defined in Step 2; in other words, the following condition must be satisfied:

$$\frac{w_k}{w_{k+1}} = \varphi_{k/(k+1)} \quad (3)$$

2) The condition of mathematical transitivity, that is $\varphi_{k/(k+1)} \times \varphi_{(k+1)/(k+2)} = \varphi_{k/(k+2)}$. Since $\varphi_{k/(k+1)} = \frac{w_k}{w_{k+1}}$ and $\varphi_{(k+1)/(k+2)} = \frac{w_{k+1}}{w_{k+2}}$ it follows that $\frac{w_k}{w_{k+1}} \times \frac{w_{k+1}}{w_{k+2}} = \frac{w_k}{w_{k+2}}$. Thus, we obtain the second condition that the final weighting coefficients of the evaluation criteria must satisfy:

$$\frac{w_k}{w_{k+2}} = \varphi_{k/(k+1)} \times \varphi_{(k+1)/(k+2)} \quad (4)$$

Maximum consistency (χ) is achieved if transitivity is fully satisfied, that is, when the conditions $\frac{w_k}{w_{k+1}} - \varphi_{\frac{k}{k+1}} \times \varphi_{\frac{k+1}{k+2}} = 0.$ are met. At that point, the condition of maximum consistency is satisfied, meaning that for the obtained weighting coefficients, the consistency value is $\chi = 0$. To satisfy these conditions, it is necessary to determine the values of the weighting coefficients of the evaluation criteria $(w_1, w_2, \ldots, w_n)^T$ that satisfy the condition that $\left|\frac{w_k}{w_{k+1}} - \varphi_{k/(k+1)}\right| = \chi$ i $\left|\frac{w_k}{w_{k+2}} - \varphi_{k/(k+1)} \times \varphi_{(k+1)/(k+2)}\right| = \chi$, while minimizing the value of χ, thereby satisfying the condition of maximum consistency. Based on the defined settings, we can formulate the final model for determining the final values of the weighting coefficients of the evaluation criteria.

$$\begin{aligned}
&min\ \chi \\
&\text{s.t.:} \\
&\left|\frac{w_{j(k)}}{w_{j(k+1)}} - \varphi_{k/(k+1)}\right| = \chi, \forall j \\
&\left|\frac{w_{j(k)}}{w_{j(k+1)}} - \varphi_{k/(k+1)} \times \varphi_{(k+1)/(k+2)}\right| = \chi, \forall j \\
&\sum_{j=1}^{n} w_j = 1, \\
&w_j \geq 0, \forall j
\end{aligned} \quad (5)$$

By solving model (5), we obtain the final values of the evaluation criteria $(w_1, w_2, \dots, w_n)^T$ and the consistency level (χ) of the obtained results (Stević, 2021). For the purpose of applying the FUCOM method, an expert evaluation of the criteria was conducted. Five experts in the field of railway transport and safety participated in the study, with experience in traffic management, transport organization, and railway system safety. Expert assessments were collected through a structured questionnaire, within which the experts first ranked the criteria according to their importance for assessing the safety of railway undertakings. They then determined the comparative significance of adjacent ranked criteria, which represents the basis of the FUCOM method. The final values of comparative significance were obtained as the average values of the experts' assessments and were used to calculate the weight coefficients of the criteria. The obtained value of the consistency degree confirmed the mutual agreement of the expert evaluations.

3.2 DEA model

In the second phase of the proposed methodological framework, the Data Envelopment Analysis (DEA) method was applied. DEA is a non-parametric method based on linear programming that is used to assess the level of relative safety efficiency of decision-making units (DMUs) that use multiple inputs to produce multiple outputs. In this study, the DMUs are four railway undertakings. Considering that the undertakings operate under different conditions and have varying scales of operations, the BCC model (Banker, Charnes, and Cooper, 1984), which assumes variable returns to scale (VRS), was used. This is important because it allows for the comparison of units that are not operating at an optimal scale. Moreover, since the output criterion (FWSIs) is an undesirable output (the smaller, the better), a specific formulation of the model that accounts for undesirable outputs was employed. Two models were applied in the study: the input-oriented BCC model and the output-oriented BCC model with undesirable output.

3.2.1 Input- and output-oriented DEA BCC model

The input-oriented model aims to assess how much inputs can be proportionally reduced in order to reach the efficiency frontier, while maintaining the same level of outputs. In the output-oriented model, the objective is to proportionally reduce the undesirable output while keeping the same level of inputs. The models are formulated as follows:

Input-oriented BCC model	Output-oriented BCC model
$\theta^* = min\theta$, Under the conditions:	$\phi^* = min\phi$, Under the conditions:
$\sum_{j=1}^{n} \lambda_j x_{ij} \le \theta x_{i0}, i = 1, 2, 3, \dots, m;$	$\sum_{j=1}^{n} \lambda_j x_{ij} \le x_{i0}, i = 1, 2, 3, \dots, m;$
$\sum_{j=1}^{n} \lambda_j y_{rj} \ge y_{r0}, r = 1, 2, 3, \dots, s;$ (6)	$\sum_{j=1}^{n} \lambda_j y_{rj} \ge \phi y_{r0}, r = 1, 2, 3, \dots, s;$ (7)
$\sum_{j=1}^{n} \lambda_j = 1$	$\sum_{j=1}^{n} \lambda_j = 1$
$\lambda_j \ge 0, j = 1, 2, 3, \dots, n;$	$\lambda_j \ge 0, j = 1, 2, 3, \dots, n;$
Where: • θ - efficiency coefficient (0≤θ≤1). DMU is efficient if θ = 1. • x_{ij} - value of the i-th input for the j-th DMU. • y_{rj} - value of the r-th output for the j-th DMU. • λ_j - weights (intensity variables)	Where: • φ - factor of proportional reduction of undesirable output. The smaller the value of φ (for efficient units φ=1), the better the safety performance, since the undesirable output can be reduced to a lower level.

3.2.2 Composite ranking

Since the classical DEA model often declares multiple DMUs as efficient (θ = 1), a composite score has been developed for further differentiation. It consists of two parts: 1) the normalized weighted sum of inputs (reflecting the efficiency of resource use) and 2) the normalized output value (reflecting the safety outcome). First, all values are normalized, since all criteria belong to the "cost" group (lower values are more desirable):

$$u_{ij} = \frac{(max(x_j) - x_{ij})}{(max(x_j) - min(x_j))} \tag{8}$$

where x_{ij} is the original value of criterion *j* for DMU_i. Then, the weighted score for inputs (S_i) is calculated using the weights obtained by the FUCOM method (w_j) where the sum of the input criterion weights is normalized to 0.5.

$$S_i = \sum_{j=1}^{3} w_j \times u_{ij} \tag{9}$$

The output criterion (FWSIs) is also normalized on a scale from 0 to 1, where the best (smallest) value receives 1, and the worst (largest) value receives 0:

$$O_i^{norm} = \frac{max(O) - O_i}{max(O) - min(O)} \tag{10}$$

Finally, the composite score (U_i) is calculated as the weighted average of the input score (with weight β) and the normalized output (with weight 1 − β). In the basic model, β = 0.5, giving equal consideration to resource-use efficiency and safety outcome:

$$U_i = \beta \times S_i + (1 - \beta) \times O_i^{norm} \tag{11}$$

3.3 Definition of criteria

In the study, four railway undertakings in Bosnia and Herzegovina were analyzed (decision-making units – DMUs): 1. DMU_1 – ŽFBiH Passenger Transport, 2. DMU_2 – ŽFBiH Freight Transport, 3. DMU_3 – ŽRS Passenger Transport, and 4. DMU_4 – ŽRS Freight Transport. The selection of criteria was carried out in two phases. In the first phase, potential input (I) and output (O) criteria were identified based on a review of relevant literature in the fields of DEA, MCDM, and safety level assessment in railway transport (Cooper et al., 2011; Blagojević et al., 2020b; Blagojević et al., 2017; Chatterjee et al., 2020). In the second phase, the preliminary set of criteria was reviewed by five experts in the field of railway transport and safety, who confirmed their representativeness and practical relevance for the operating conditions of railway undertakings in Bosnia and Herzegovina. Based on this procedure, a final set of criteria was adopted, encompassing human resources, the technical condition of rolling stock, traffic volume, and safety outcomes.

I_1 – Available workforce: The human factor is the dominant link in railway safety – humans are directly or indirectly responsible for the vast majority of accidents and incidents. The number of employees in safety-sensitive positions (train drivers, shunters, dispatchers, wagon inspectors) is crucial. I_2 – Average age of rolling stock: The average age of rolling stock (locomotives, passenger and freight cars) is a key factor in technical reliability. Older rolling stock is more prone to failures and requires more intensive maintenance. Lower average age positively affects safety. I_3 – Train kilometers traveled: This criterion represents the total number of kilometers traveled by vehicles during the year and serves as a measure of exposure to risk. As traffic volume increases, the statistical likelihood of incidents also rises. O_1 – FWSIs (Fatalities and Weighted Serious Injuries): This criterion represents the level of risk in railway transport, defined in accordance with European directives. It is calculated based on accident data, with one serious injury weighted as 0.1 of a fatality.

FWSIs is an undesirable outcome – its value should be as low as possible. The data represent average values over a five-year period (2020–2024), taken from the annual reports of the Railway Regulatory Board of Bosnia and Herzegovina. Using a five-year average helps mitigate the impact of annual fluctuations and provides a more stable picture of railway undertaking performance. Input data are presented in Table 1, and output data in Table 2.

Table 8. Input criterion values per DMU (five-year average)

DMU	I_1 – Available workforce	I_2 - Average age of rolling stock	I_3 - Train kilometers traveled
DMU_1	418	49,63	616728,2
DMU_2	640	47,8	1457822,25
DMU_3	325	52,58	618064,9
DMU_4	420	49,69	640919,9

Source: Annual report of the RRB BiH (2020-2024)

Table 2. Output criterion values per DMU (five-year average)

DMU	O_1 – FWSIs
DMU_1	3
DMU_2	7
DMU_3	2
DMU_4	3

Source: Annual report RRB BiH (2020-2024)

4. RESULTS

The first step was to determine the criterion weights using the FUCOM method. Based on collected expert evaluations, a vector of comparative importance for the input criteria was formed. Experts ranked the criteria according to their importance for safety, assigning the highest importance to the average age of rolling stock (I_2), followed by workforce (I_1), and finally train kilometers traveled (I_3). The average values of comparative significance used in the model were: $\varphi I_2/I_1=1.59$ i $\varphi I_1/I_3=1.08$. The results of applying the FUCOM model are presented in Table 3. For the input criteria, the obtained weights were: $wI_2=0,452$, $wI_1=0,284$, $wI_3=0,264$, with an error value $\chi=0.000$, confirming complete consistency of the expert evaluations. To form the composite score, the weights were normalized. The sum of input criterion weights was set to 0.5, while the output criterion received a weight of 0.5. The final values are presented in Table 3.

Table 3. Criterion weight coefficients

	I_1 - Available workforce	I_2 - Average age of rolling stock	I_3 - Train kilometers traveled	O_1 - FWSIs
FUCOM	0,284	0,452	0,264	1
Final w_j for the composite score	0.142	0.226	0.132	0.5

By applying the input-oriented and output-oriented BCC DEA models, the results obtained are presented in Table 4.

Table 4. Results of the DEA BCC model

DMU	Input-oriented BCC model	Output-oriented BCC model	Safety level
DMU_1	1.000	1.000	Efficient
DMU_2	1.000	1.000	Efficient
DMU_3	1.000	1.000	Efficient
DMU_4	0.999	0.993	Inefficient

The criterion for basic DEA efficiency was that a unit must be efficient in both models ($\theta=1$ and $\varphi=1$). According to this criterion, DMU_1, DMU_2, and DMU_3 are efficient, while DMU_4 falls short of the efficiency boundary. Although the deviation is minimal (0.1% for inputs and 0.7% for outputs), it indicates that DMU_4, with its existing resources and workload, achieves a slightly lower safety level compared to units representing best practice. Since three out of four DMUs are efficient, a more detailed ranking was necessary using the composite score. This procedure was carried out according to the methodology described in Section 3.2.2, with $\beta=0.5$. The results obtained are presented in Table 5.

Table 5. Final results and ranking using the integrated FUCOM-DEA approach

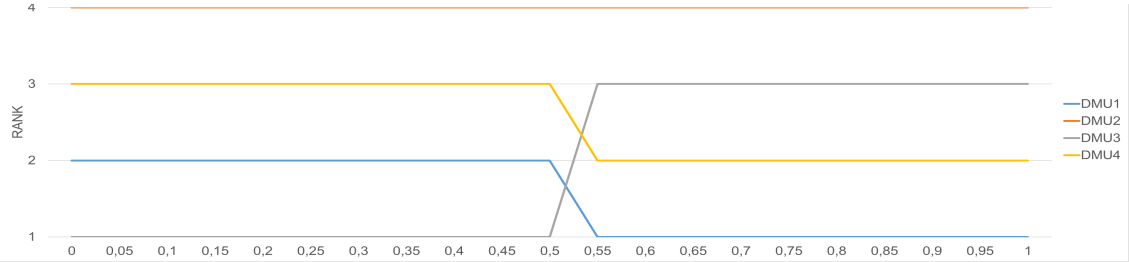
DMU	Input score (Si)	Normalized output (FWSIs)	Composite score (Ui)	Final rank
DMU_1-ŽFBiH Passenger	0.743	0.800	0.772	2
DMU_2-ŽFBiH Freight	0.452	0.000	0.226	4
DMU_3-ŽRS Passenger	0.548	1.000	0.774	1
DMU_4-ŽRS Freight	0.728	0.800	0.764	3

The results of the composite score (Table 5) show that DMU_3 (ŽRS Passenger Transport) achieves the best overall performance. Its advantage over DMU_1 comes primarily from the superior safety outcome (FWSIs = 2), giving it the maximum score of 1.0 in that category. Its input score (0.548) is the lowest among the passenger transport units, indicating that despite having the oldest rolling stock, it still achieves solid resource efficiency. DMU_1 (ŽFBiH Passenger Transport) ranks second, with a very close composite score (0.772). It has an excellent input score (0.743), reflecting a relatively smaller workforce and lower train kilometers relative to resources. Its safety outcome (FWSIs=3) is good, but still slightly worse than DMU_3. DMU_4 (ŽRS Freight Transport) comes in third. Its input score is good (0.728), but its safety outcome is the same as DMU_1 (FWSIs=3). Since DMU_1 performs slightly better in the input score, DMU_4 ranks third. DMU_2 (ŽFBiH Freight Transport) is last, in fourth place. Although the DEA model classified it as efficient, its composite score is drastically lower (0.226). The main reason is the worst safety outcome (FWSIs=7), which completely offsets its input efficiency. This result clearly demonstrates that DEA efficiency does not guarantee the best overall safety profile, especially when dealing with undesirable outputs of high severity.

5. SENSITIVITY ANALYSIS

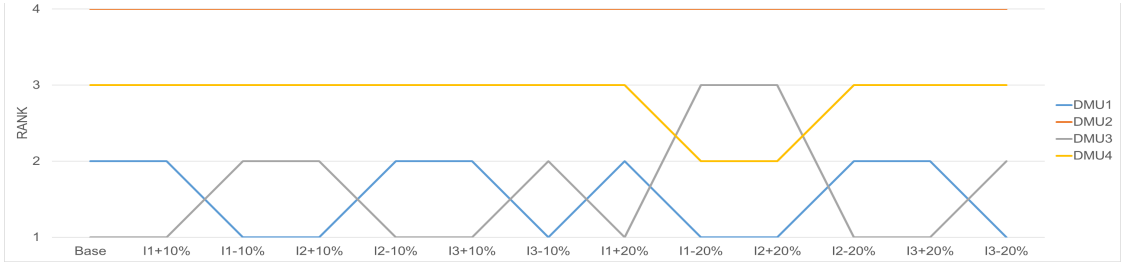
Given the small number of DMUs and the potential impact of subjectivity in determining weights, a sensitivity analysis was conducted to test the stability of the model. The analysis was carried out in two ways: 1) Change in the weighting between input criteria and the safety outcome (β). In the baseline model, the composite score equally weighted the input criteria and the safety outcome ($\beta=0.5$). In the sensitivity analysis, β was varied from 0 to 1, where β represents the weight of the input criteria and $(1-\beta)$ the weight of the safety outcome. The objective was to examine how the ranking of railway undertakings changes depending on whether priority is given to resource-use efficiency or to the final safety outcome (Figure 1).

Figure 1. Sensitivity analysis of the composite score to changes in the balance (β) between input efficiency and the safety outcome



The results shown in Figure 1 indicate that DMU_2 consistently ranks fourth across the entire range of β, due to its markedly unfavorable safety outcome. The first position is shared by DMU_3 and DMU_1: when greater importance is assigned to safety (β≤0.6), DMU_3 dominates, whereas with increasing emphasis on efficiency (β ≥ 0.7), DMU1 takes the leading position. DMU_4 remains stably in third place for most of the interval, with minor deviations at extreme values of β. 2) Perturbation of FUCOM weights (Monte Carlo simulation). The stability of railway undertaking rankings was tested with respect to changes in the weights of the input criteria (I_1–I_3). Multiple iterations were performed with independent weight variations of ±10% and ±20%, followed by renormalization (sum of input weights=0.5). For each iteration, the composite score was recalculated (β=0.5), and the resulting ranking was recorded (Figure 2).

Figure 2. Distribution of DMU rankings after Monte Carlo simulation with perturbation of FUCOM input weights (±10% and ±20%).



The results of the Monte Carlo simulation (Figure 2) confirm the stability of the model. DMU_2 retained fourth place in 100% of the simulations, indicating that its position is a consequence of its fundamental performance rather than the choice of weights. DMU_4 remained in third place in over 95% of cases, with occasional swaps with DMU_1 or DMU_3 under extreme weight combinations, but without ever dropping to the last position. The first position is distributed between DMU_3 (≈55% of simulations) and DMU_1 (≈45%), confirming that their performances are very close and that the final ranking depends on the weight structure. No other DMU attained first place.

6. DISCUSSION OF RESULTS AND CONCLUSION

The paper develops and applies an integrated FUCOM–DEA methodological framework for assessing the safety level of railway undertakings in Bosnia and Herzegovina. The key contribution of the research lies in linking the subjective determination of criteria weights (FUCOM) with the objective assessment of relative efficiency (DEA), thereby forming a composite measure of safety performance that overcomes the limitations of traditional, predominantly reactive approaches based solely on individual indicators. The results confirm the research hypothesis (H1) that the integrated FUCOM–DEA approach enables a more reliable differentiation of the safety performance of railway undertakings compared with the use of individual indicators or the classical DEA model. The integrated approach provides a

clearer picture of safety performance than when each method is used separately. The results indicate that the application of the classical DEA model, due to the limited number of decision-making units, leads to a high frequency of efficient DMUs, thereby reducing the discriminatory power of the analysis. In the specific case, three out of four railway undertakings were evaluated as efficient, which is a consequence of the relationship between the number of units and the number of variables. Specifically, the number of DMUs (n = 4) relative to the number of variables (m=3, s=1) does not fully satisfy the standard DEA discrimination condition $n \geq max\{m \times s, 3(m+s)\}$, which methodologically increases the likelihood of obtaining a larger number of efficient units. This characteristic represents one of the limitations of the study and is typical for research involving small samples of railway undertakings. For this reason, the composite ranking based on the integration of FUCOM weights and the normalized safety outcome allowed for additional differentiation of performance, while the sensitivity analysis confirmed the stability of the final ranking of the decision-making units. The empirical analysis, conducted on a sample of four railway undertakings using five-year average data, showed that the highest overall safety performance was achieved by the passenger railway undertaking ŽRS (DMU_3), thanks to the most favorable safety outcome (lowest FWSI indicator values). The passenger railway undertaking ŽFBiH (DMU_1) ranks second, with efficient resource use and a satisfactory safety result, while the freight railway undertaking ŽRS (DMU_4) is ranked third, with performance close to the leading units.

The least favorable profile is shown by the freight railway undertaking ŽFBiH (DMU_2), which, despite being formally DEA-efficient, ranks last due to its markedly high FWSI indicator values. The results clearly demonstrate that DEA efficiency does not guarantee safety - DMU_2 achieves operational volume at increased risk, while DMU_3 and DMU_1 attain a better balance between resource use and safety outcome. The sensitivity analysis confirmed the high robustness of the model, particularly regarding the stability of DMU_2's last-place position. At the same time, the shift in the leading position between DMU_3 and DMU_1 depends on whether priority is given to the safety outcome or to the efficiency of input resources. This finding has significant implications for regulatory authorities, as it highlights the need to clearly define strategic priorities when evaluating railway undertaking performance and helps decision-makers align priorities with system objectives. The limitations of the study primarily relate to the small number of DMUs analyzed relative to the number of variables, which is typical for DEA studies and may reduce the discriminatory power of the model. Additionally, FWSI is an aggregated indicator that does not differentiate between fatal outcomes and serious injuries, resulting in some loss of analytical precision. Future research should include a larger number of railway undertakings, including regional railway undertakings, or apply a panel DEA approach using annual data to increase the reliability and discriminatory power of the results. It is also recommended to separate the components of the FWSI indicator and to incorporate additional qualitative measures, such as safety management system (SMS) audit results and staff training levels. Despite these limitations, the proposed model represents a relevant and reliable analytical tool for regulatory authorities and railway undertaking management to identify weaknesses and improve safety systems.

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Prethodno priopćenje

PROCJENA RAZINE SIGURNOSTI ŽELJEZNIČKIH PRIJEVOZNIKA PRIMJENOM HIBRIDNOG FUCOM–DEA PRISTUPA

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SAŽETAK

Sigurnost željezničkog prometa predstavlja jedan od najvažnijih elemenata suvremenih transportnih sustava. Ona izravno utječe na to koliko je željeznica pouzdana i koliko je društvo prihvaća kao siguran način prijevoza. Tradicionalne procjene sigurnosti oslanjaju se na podatke o nesrećama, ali se bave posljedicama, a ne uzrocima i stanjem sustava prije nego do nesreće dođe. S ciljem prevladavanja ovih ograničenja, u radu je predložen hibridni FUCOM–DEA pristup za procjenu sigurnosti željezničkih prijevoznika. FUCOM metoda omogućuje određivanje težinskih koeficijenata sigurnosnih kriterija na temelju ekspertskih ocjena, uz očuvanje konzistentnosti ponderiranja. DEA metoda, odnosno BCC model s varijabilnim prinosima, primijenjena je za kvantitativnu ocjenu relativne učinkovitosti prijevoznika u području sigurnosti. Predložena metodologija testirana je na četiri željeznička prijevoznika u Bosni i Hercegovini, koristeći petogodišnje prosjeke ulaznih kriterija (radna snaga, starost vozila, vozni kilometri) i izlaznog kriterija (FWSIs - ponderirani indikator nesreća). Rezultati pokazuju da putnički prijevoznici ostvaruju višu razinu sigurnosnih performansi od teretnih, koji zbog većeg opsega operacija imaju nižu relativnu učinkovitost u domenu sigurnosti. Analiza osjetljivosti potvrđuje stabilnost i pouzdanost modela. Rad menadžmentu nudi koristan alat za identifikaciju slabosti u sustavima upravljanja sigurnošću i strateško unapređenje sigurnosnih performansi.

Ključne riječi: *sigurnost željezničkog prometa; željeznički prijevoznik; FUCOM metoda; DEA*

Professional paper

THE ROLE OF MARKETING IN SHAPING USER PERCEPTIONS OF SAFETY IN RAIL AND ROAD TRANSPORT: COMMUNICATION STRATEGIES AND TRUST FACTORS

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ABSTRACT

The perception of safety is one of the key factors that influence the choice of means of transport and user trust in transport systems. In modern conditions, marketing and communication strategies play a significant role in shaping users' attitudes about the safety and reliability of rail and road traffic. The aim of the paper is to examine how users perceive the safety of these two modes of transportation and to what extent marketing communications influence the feeling of trust and safety. The research was conducted using a survey questionnaire. The questionnaire included respondents' views on safety, trust, information and communication of transport companies towards users. The data were processed with the MS Excel program, where the t-test for independent samples was applied to determine the differences in the perception of safety between rail and road traffic users. The scientific contribution of the work is reflected in the connection of marketing and the perception of safety in the field of traffic, while the practical contribution can serve as a basis for improving the communication strategies of transport companies.

Key words: *Marketing, Communication strategies, Railway traffic, Road traffic.*

1. INTRODUCTION

Traffic safety is one of the basic prerequisites for the functioning of modern society. The development of infrastructure, the modernization of rolling stock and the improvement of technical and technological systems have contributed to the increase of objective safety, but at the same time they have opened up the issue of the subjective perception of safety of users. Namely, it is not enough that the traffic is statistically safe, it is also important how the users perceive it.

In conditions of intense competition between different modes of transport, the perception of safety becomes a significant factor when choosing a means of transport. Users often make decisions not only on the basis of realistic risk indicators, but also on the basis of their personal sense of security, trust in the system and information they receive through the media and communication channels. This is precisely where marketing takes on a new and expanded role, because it is not only an instrument for service promotion, but also a mechanism for building trust and a stable perception of security.

Rail and road transport are the two dominant forms of land passenger transport. Although statistical data often indicate differences in the level of security between these two systems, user perception may not always be consistent with these indicators (Stegnjajić, Vesković, 2024). The formation of attitudes is influenced by various factors: media coverage of accidents, personal experiences, recommendations of other users, but also the way transport

companies communicate their safety standards, procedures and responsibility towards passengers.

Traffic marketing has traditionally focused on price, availability, speed and comfort of service. However, modern trends show that safety is becoming one of the central brand values in the transport industry (Jusufranić, 2014). Communication strategies that emphasize the technical correctness of vehicles, staff training, compliance with safety standards, and transparency in user information have the potential to directly influence the perception of system reliability. In this sense, marketing moves from the sphere of classic promotion to the area of strategic management of reputation and trust.

The question of trust is also very important. The user's trust in the transport system implies the belief that the service will be provided safely, responsibly and professionally. It is not only built through long-term practice and experience, but also through consistent, clear and timely communication. In crisis situations, such as traffic accidents or technical problems, the method of communication can have a decisive influence on maintaining or losing the trust of users.

In the modern digital environment, communication between transport companies and users becomes interactive and continuous. Social networks, mobile applications, websites and passenger information systems enable rapid information exchange, but at the same time increase user expectations in terms of transparency and accountability. Insufficient or inadequate communication can lead to the creation of uncertainty, even when objective safety indicators do not indicate an increased risk.

Precisely because of this, the research of the relationship between marketing and the perception of security takes on special importance. It is necessary to see to what extent communication strategies influence the formation of users' attitudes and whether there are differences in the perception of safety between rail and road traffic. Also, it is important to determine whether users' information and their trust in transport companies are mediating factors in this relationship.

The subject of this paper is the analysis of the role of marketing in shaping the perception of user safety in rail and road traffic. The aim of the research is to identify factors that contribute to building trust in rail and road transport. Special emphasis was placed on identifying factors that contribute to building trust, as well as on determining any statistically significant differences in the perception of safety between users of different modes of transportation.

It is based on the assumption that the perception of safety is not exclusively the result of objective safety indicators, but also a consequence of strategic communication and marketing activities of transport systems. In this context, marketing is seen as an integral part of the management of transport organizations, and not only as a promotional function.

The scientific contribution of the work is reflected in the interdisciplinary approach that connects marketing and traffic safety, two areas that are often considered separately in practice. The practical importance is reflected in the possibility of applying the research results in improving the communication strategies of transport companies, with the aim of strengthening trust and a positive perception of safety among users.

2. THEORETICAL FRAMEWORK AND PREVIOUS RESEARCH

2.1. Teoretical framework

Marketing is defined in contemporary literature as a business function and management process aimed at identifying, creating and delivering value to customers. According to the literature, marketing is not just a sales or advertising activity, but an integrated customer relationship management system aimed at satisfaction, loyalty and long-term trust (Đorđević, Ćoćkalo, 2010).

Contemporary marketing is based on customer orientation and perceived value. The value of a service does not depend solely on technical characteristics, but on the way the customer experiences the service. In the context of transport, this means that safety is not only a technical category (standards, regulations, infrastructure), but also a marketing category, as it affects the perception of the value of a transport service. Service marketing is particularly important, given that services are intangible, variable and dependent on interaction with the customer. The perception of quality depends on the trust and security that the user feels.

Communication strategies represent a systematically designed process of planning, shaping and transmitting messages to a target group with the aim of informing, persuading and encouraging a certain behavior. In modern marketing, communication is no longer a one-way activity, but an interactive process that involves the exchange of information and continuous building of relationships with users (Milenović, Ratković, 2012: 223). According to domestic marketing theory, communication includes:

- advertising
- public relations
- direct marketing
- digital communication
- brand management (Vukmirović, 2021).

The development of marketing is a very intensive process, so the field of marketing is now the focus of study in both education and practice. Marketing has several aspects of interpretation, such as: a business concept, a business function, a scientific discipline, and an economic process (Marković, 2025: 351). Consistent communication reduces uncertainty and builds a stable brand perception (Joksimović, 2013).

In the transport sector, communication strategies are of particular importance because:

- users often do not have direct insight into technical aspects of safety,
- they rely on information provided by the company,
- media reporting on accidents can erode trust.

Traffic safety is a system of measures and activities aimed at reducing the risk of traffic accidents and their consequences. What should be emphasized is that public perception is often not entirely consistent with statistical data when it comes to traffic safety (Živković et al., 2025). Based on the studied literature, security can be viewed as:

- objective category (statistical indicators, number of accidents, injuries),
- subjective category (user's sense of security).

Human factors and participant behavior have a significant impact on safety, but also on the way the public perceives risk. Safety in rail and road transport is regulated by strict standards, but the communication of those standards to the public can affect the level of trust (Vilke et al., 2024).

Perception is the process by which individuals interpret information and form attitudes. In marketing, perception is often more important than objective reality, as it is what influences consumer behavior. Perceived risk directly influences the decision to purchase or choose a service. The greater the risk, the greater the need for trust (Maričić, 2011).

Trust is a central element of a long-term relationship between a user and an organization. The perception of security in this case is formed based on a combination of:

- personal experience,
- media information,

- company communication,
- general image of the system (Borisavljević, 2016).

2.2. Previous research

According to research, perceived safety and quality of service are key determinants of the perception of availability and acceptance of public transport systems. A study from Northern Europe shows that the perception of service quality can significantly improve the perceived accessibility of a system and that security is a mediating factor in that respective chain (Friman et al., 2020).

A study conducted in the public transport system in Belgrade showed that service quality, employee behavior, adequate information, and other marketing factors significantly influence passenger satisfaction and that such factors represent the basis for improving service and marketing interventions in transport (Radnović et al., 2015).

When comparing different demographic groups, it was found that gender and socio-demographic factors can influence feelings of safety, which means that tailored communication strategies for different user segments should be considered (Bihi Ouali et al., 2020).

Assessing the perception of safety at railway stations shows that not only infrastructure but also social factors (e.g. theft, harassment) influence the feeling of insecurity, which is important for the development of marketing communication and increasing user trust in the service (Coppola, Silvestri, 2020).

3. RESEARCH METHODOLOGY

This chapter presents the research procedure and data analysis methods. The aim of the research was to examine the differences in the perception of safety between road and rail transport users. The research was conducted using a quantitative method, using a questionnaire as the main instrument for data collection. The questionnaire was created online and distributed to respondents via digital channels, with respondents completing it independently.

The questionnaire is structured in two parts. The first part includes general (demographic) data on the respondents, including gender, age structure and most frequently used mode of transport (rail or road). The second part of the questionnaire refers to the attitudes of the respondents and contains a total of 10 statements, which are grouped into three thematic units.

The first unit refers to perceived safety and includes attitudes about how safe the transport they use is, to what extent they trust the safety measures of the transport operator, as well as whether they feel safe during the trip.

The second part refers to the role of marketing and communications, and includes an assessment of the carrier's clear communication regarding safety, the impact of marketing messages on the feeling of safety, as well as the impact of advertising and notifications on user trust, including the perception of the professionalism of communication.

The third part refers to the carrier's trust and image, and includes attitudes about the carrier's perceived image in the public, the impact of trust on the choice of means of transport, as well as the willingness of users to use the services of a carrier that actively communicates about safety.

All statements in the second part of the questionnaire were rated using a Likert scale from 1 to 5, where 1 indicates "I completely disagree" and 5 indicates "I completely agree". Data collection was carried out during January and February 2026, and respondents of different age groups who use public transport services participated in the survey.

In order to determine the existence of differences in the attitudes of the respondents in relation to the type of transport, a T-test for independent samples was applied. The analysis was conducted at the level of statistical significance α = 0.05. The data were processed and analyzed in the Microsoft Excel program, using the Data Analysis tool and the t-Test option: Two-Sample Assuming Unequal Variances. Based on the research objective, the following hypotheses were formulated:

- **H_0**: It is assumed that there are no statistically significant differences in the overall perception of safety between road and rail transport users
- **H_1**: The differences in the overall perception of safety between road and rail transport users are statistically significant.

4. RESEARSH RESULTS

The research was conducted on a sample of 100 respondents with different socio-demographic characteristics. In terms of gender, the sample consisted of 56% female respondents and 44% male respondents, indicating a relatively even representation.

When it comes to age structure, the largest number of respondents belongs to the age group from 26 to 35 years (28%), followed by the groups up to 25 years (21%) and from 36 to 45 years (21%). The share of respondents aged 46 to 55 is 17%, while the smallest number of respondents is in the category older than 56 years (13%). This structure indicates a good representation of different age groups.

In terms of the most frequently used mode of transport, road transport (bus) dominates, which is used by 76% of respondents, while rail transport is used by 24% of respondents. This data indicates a greater prevalence of road transport in the respondents' daily trips. Table 1 shows descriptive statistics.

Table 1. Descriptive statistics (Mean and SD)

Type of transport	M (Mean)	SD (Standard Deviation)
Road transport	3,186	1,208
Rail transport	4,121	0,967

Source: Author's research

Based on the results obtained, it can be determined that rail transport users perceive transport as safer (M = 4.12) compared to road transport users (M = 3.19). Also, the standard deviation is higher for road transport (1.208) and it indicates a greater diversity of responses, while the smaller SD for rail transport (0.967) shows more consistent attitudes of the respondents.

Table 2. T-test table view

Question	t-value	p-value	Significance (α=0,05)
1	-6,444	2,064	0,01
2	-5,774	3,355	0,01
3	-6,647	8,729	0,01
4	-4,219	0,000	0,01
5	-6,476	1,533	0,01

6	-5,366	1,271	0,01
7	-4,313	0,000	0,01
8	-0,708	0,484	Not statistically significant
9	-2,223	0,031	0,05
10	-3.254	0,002	0,01

Source: Author's research

The results presented in Table 1. show that for nine out of ten analyzed questions there is a statistically significant difference between rail and road transport users ($p < 0.05$). The exception is question number 8, for which no statistically significant difference was determined ($p = 0.484$), which indicates that the respondents have similar attitudes regarding this aspect.

The extremely low p-values for most questions ($p < 0.001$) indicate a strong statistical difference between the observed groups. This means that the probability that the observed differences occurred by chance is extremely low. The results obtained indicate that the type of transport is a significant factor that influences the perception and attitudes of users regarding the analyzed elements (safety, reliability, organization, quality of service, etc.).

Since the obtained p-value is significantly lower than the significance level $\alpha = 0.05$, the null hypothesis (H_0), which predicts that there are no statistically significant differences in the perception of safety between road and rail transport users, must be rejected. By rejecting H_0, the alternative hypothesis (H_1), which indicates that there are statistically significant differences between the two groups, is accepted.

This means that the mode of transport has a measurable and significant impact on the way in which respondents perceive transport safety. Higher average results among rail transport users indicate that this group perceives transport as safer, while the greater dispersion of responses among road transport users indicates greater diversity of attitudes and possible variability in perceived safety. In this way, the results not only confirm the existence of differences, but also provide insight into the directions of those differences, which is useful for further analysis and possible applications in improving transport safety and informing users.

5. CONCLUSION

The results of the conducted research clearly indicate the existence of statistically significant differences in the perception of safety between users of road and rail traffic. The obtained data confirm that the users of railway transport to a greater extent perceive this mode of transport as safer compared to road transport, which is confirmed by higher average scores, as well as a smaller dispersion of answers. Based on the applied t-test for independent samples, the null hypothesis is rejected and the alternative hypothesis is accepted, thus confirming that the type of transportation has a significant impact on the subjective perception of user safety.

The research showed that the perception of safety is not solely the result of objective indicators (number of accidents, technical standards and regulatory frameworks), but that it is significantly influenced by communication, information and the level of trust in transport organizations. It is in this context that marketing and communication strategies gain strategic importance. Transparent information, consistent communication about security standards, professional behavior of employees and adequate management of crisis situations contribute to building trust and a stable perception of security.

The practical implications of the work are reflected in the need for transport companies to position safety as one of the key values of their brand. Special attention should be paid to the development of integrated communication strategies that, in addition to promotion, will emphasize responsibility, reliability and customer care. What still needs attention is the importance of market segmentation and adapting communication to different target groups, bearing in mind that risk perception can vary depending on individual and sociodemographic factors.

The scientific contribution of the work is reflected in the interdisciplinary linking of marketing and traffic safety, which indicates the need to consider safety as a technical-regulatory category, but also through the communication dimension of transport system management. Although there are certain limitations, primarily in terms of sample size and structure, it represents a basis for future research that could include a wider number of respondents, different geographic regions, and additional variables. Effective marketing and communication activities have the potential to significantly influence the building of trust, image improvement and long-term strengthening of the position of transport companies on the market.

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Stručni rad

ULOGA MARKETINGA U OBLIKOVANJU PERCEPCIJE KORISNIKA O SIGURNOSTI U ŽELJEZNIČKOM I CESTOVNOM PROMETU: KOMUNIKACIJSKE STRATEGIJE I FAKTORI POVJERENJA

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SAŽETAK
Percepcija sigurnosti jedan je od ključnih čimbenika koji utječu na izbor prijevoznog sredstva i povjerenje korisnika u prometne sustave. U suvremenim uvjetima marketinške i komunikacijske strategije imaju značajnu ulogu u oblikovanju stavova korisnika o sigurnosti i pouzdanosti željezničkog i cestovnog prometa. Cilj rada je ispitati kako korisnici percipiraju sigurnost ova dva oblika prijevoza te u kojoj mjeri marketinške komunikacije utječu na osjećaj povjerenja i sigurnosti. Istraživanje je provedeno primjenom anketnog upitnika. Upitnik je obuhvatio stavove ispitanika o sigurnosti, povjerenju, informiranju i komunikaciji prijevozničkih poduzeća prema korisnicima. Podaci su obrađeni u programu MS Excel, pri čemu je primijenjen t-test za nezavisne uzorke radi utvrđivanja razlika u percepciji sigurnosti između korisnika željezničkog i cestovnog prometa. Znanstveni doprinos rada ogleda se u povezivanju marketinga i percepcije sigurnosti u području prometa, dok praktični doprinos može poslužiti kao osnova za unaprjeđenje komunikacijskih strategija prijevozničkih poduzeća.

Ključne riječi: *marketing, komunikacijske strategije, željeznički promet, cestovni promet.*

Original Scientific Paper

A VISION ZERO-BASED RISK FRAMEWORK FOR REGIONAL ROAD SAFETY ASSESSMENT: A COMPARATIVE STUDY OF THREE COUNTIES IN NORTHERN CROATIA

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ABSTRACT

This paper addresses the persistent problem of fatal and serious road traffic injuries through the application of the Vision Zero concept at the regional level. The objective of the research is to develop and apply a structured analytical framework for assessing and comparing systemic road safety risk across regions, focusing on outcome-based indicators rather than individual responsibility. The study is based on official police road traffic accident data for Varaždin County, Međimurje County, and Koprivnica-Križevci County over the period 2020-2024. A Vision Zero Risk Framework is proposed, integrating key safety indicators related to fatalities and serious injuries (KSI), including magnitude, severity structure, and temporal development. To ensure comparability, indicators are normalized using a min-max method and aggregated into a composite Vision Zero Risk Index through a transparent weighting procedure aligned with Vision Zero priorities. The results reveal distinct regional risk profiles, highlighting structural differences in severe crash outcomes. Additional structural risk profiling, including analysis of vulnerable road users and selected crash characteristics where data are available, provides further contextual interpretation of regional disparities. The findings demonstrate that road traffic mortality is not randomly distributed but reflects structural characteristics of the transport system at the regional level. The main contribution of the paper lies in the development of a transparent, reproducible, and policy-relevant assessment framework that supports evidence-based prioritization of Vision Zero measures. The proposed approach can be replicated in other regions and serves as a practical tool for integrating Vision Zero principles into regional road safety management.

Key words: *Vision Zero, road safety, traffic fatalities, risk assessment, regional analysis*

1. INTRODUCTION

Road traffic injuries remain one of the most persistent public health and transport system challenges globally. According to the Global Status Report on Road Safety 2023, approximately 1.19 million people die each year in road crashes, while tens of millions sustain non-fatal injuries that often result in long-term disability and profound socio-economic consequences. Road trauma disproportionately affects children, adolescents, and economically active populations, generating measurable impacts on productivity, health systems, and regional development (WHO, 2023, p. 4). Despite decades of intervention efforts, global progress has slowed in recent years, and substantial disparities persist across

and within countries (WHO, 2023, pp. 8-9, 14-15). These disparities indicate that road traffic mortality and serious injury are not randomly distributed phenomena. Instead, they reflect structural characteristics of transport systems, such as infrastructure design, traffic composition, speed management regimes, exposure patterns, and institutional safety governance capacity. The OECD/International Transport Forum has argued that traditional approaches centred primarily on individual behaviour modification have reached diminishing returns and that further substantial safety gains require systemic reform rooted in a Safe System philosophy (OECD/ITF, 2008, pp. 21-22). This shift marks a transition from reactive crash reduction strategies toward proactive, performance-based road safety management embedded within transport planning and design processes (OECD/ITF, 2008, pp. 195-197).

At the European policy level, this systemic perspective has been reinforced through research and innovation frameworks that emphasize integrated mobility governance and long-term safety targets. Horizon 2020 initiatives and subsequent EU road safety strategies highlight the need for data-driven safety management tools capable of supporting the EU's ambition toward zero fatalities (CINEA, 2022).

Such frameworks underscore that achieving "Vision Zero" requires not only technological and infrastructural improvements but also analytical instruments enabling benchmarking, monitoring, and accountability across governance levels.

In response to the limitations of conventional road safety paradigms, the Vision Zero concept emerged in Sweden in the late 1990s as a transformative policy innovation. Vision Zero is grounded in the ethical principle that human life and health are non-negotiable and that no level of fatal or serious road trauma is acceptable as a trade-off for mobility (Björnberg, 2022). Rather than treating crashes as inevitable consequences of human error, Vision Zero reframes fatalities and serious injuries as preventable system failures and redistributes responsibility between road users and system designers (OECD/ITF, 2008, pp. 111-113). This normative repositioning has since diffused internationally and increasingly shapes global and regional road safety governance (Kristianssen, 2022).

Building upon the Vision Zero philosophy, the Safe System approach operationalizes these ethical commitments through engineering and governance principles designed to ensure that crash forces do not exceed human biomechanical tolerance limits (OECD/ITF, 2008, p. 113). Core pillars include safe speeds, safe roads and infrastructure, safe vehicles, safe road use, and effective post-crash response, supported by measurable performance targets and institutional accountability mechanisms (OECD/ITF, 2008, pp. 25-27, 195-197).

Empirical research suggests that the adoption of Safe System-oriented management structures is associated with sustained improvements in fatal and serious injury trends, although causal attribution remains inherently complex in dynamic policy environments (Elvik and Nævestad, 2023). Nevertheless, Vision Zero has not been without critique. Philosophical and operational debates question its realism, prioritization logic, and implementation feasibility (Abebe, Hansson and Björnberg, 2022). Such critiques highlight the importance of translating normative ambition into measurable and transparent policy instruments capable of supporting rational decision-making and performance evaluation.

Despite the conceptual maturity of Vision Zero and Safe System thinking, implementation and monitoring at the regional (subnational) level remain methodologically fragmented. Many assessments rely on single indicators, such as fatalities per capita, without integrating fatal and serious injury outcomes into a structured comparative framework. Yet regional disparities in land use patterns, road network characteristics, traffic exposure, and enforcement practices may generate distinct systemic risk profiles even within the same national governance context. This creates a need for transparent, reproducible analytical tools capable of supporting inter-regional benchmarking and evidence-based prioritization.

This study addresses that gap by developing and empirically applying a Vision Zero, based regional risk framework grounded in established composite indicator methodology. The framework integrates outcome-based indicators of fatal and serious road trauma into a

composite index designed to enable structured comparison across regions while maintaining methodological transparency in indicator selection, normalization, weighting, and aggregation. The objective of this paper is therefore to develop and apply a transparent and reproducible Vision Zero Risk Framework that quantifies systemic road safety risk across regions and enables benchmarking through a composite index approach. The empirical application focuses on three counties in Northern Croatia: Varaždin County, Međimurje County, and Koprivnica-Križevci County, over the period 2020-2024.

The central hypothesis of the study is:

H_1: Systemic road safety risk differs structurally across regions and can be quantified and ranked through a composite Vision Zero–based index integrating fatal and serious injury outcomes using transparent normalization and weighting procedures.

By operationalizing Vision Zero principles into a measurable regional index, this research contributes to bridging the gap between normative road safety philosophy and data-driven regional safety management, supporting targeted interventions and continuous monitoring toward the reduction of fatal and serious injuries.

2. METHODOLOGY

2.1 Conceptual Foundation: Vision Zero and Systemic Risk

The methodological framework of this study is grounded in the conceptual integration of the Vision Zero philosophy, the Safe System approach, and contemporary theories of road safety governance. These approaches redefine fatal and serious road traffic injuries as the result of systemic deficiencies rather than isolated behavioural failures (OECD/ITF, 2008, pp. 21-22). Such a reinterpretation represents a shift from the traditional “road user blame” model toward a systemic accountability and risk management paradigm.

Public health literature further supports the understanding of road safety as a complex system in which outcomes arise from the interaction of infrastructure design, vehicle standards, regulatory frameworks, mobility patterns, and institutional coordination capacity (WHO, 2004; WHO, 2023, p. 4). The Safe System approach is built upon the premise that human error is inevitable, but death and serious injury are not, provided that the transport system is designed so that crash forces remain within human biomechanical tolerance thresholds (OECD/ITF, 2008, p. 113). In this sense, safety is conceptualised as a property of the system rather than an attribute of individual competence.

The normative core of Vision Zero rests on the ethical principle that human life and health take absolute priority over mobility and efficiency (Björnberg, 2022). This ethical stance implies a redistribution of responsibility between system users and system designers, integrating safety considerations into transport planning and governance structures. Kristianssen (2022) characterises Vision Zero as a potential paradigm shift in global road safety policy, as it demands long-term, institutionally embedded, objective-driven management supported by measurable performance indicators.

Empirical research indicates that countries adopting Safe System principles and performance-based management structures tend to achieve sustained reductions in fatalities and serious injuries, although precise causal attribution remains methodologically complex in dynamic policy environments (Elvik and Nævestad, 2023). At the same time, critical scholarship questions the normative realism and operational feasibility of the “zero” target, as well as its implications for prioritisation and resource allocation (Abebe, Hansson and Björnberg, 2022). These debates underscore the necessity of analytical instruments capable of translating normative ambition into measurable and transparent performance metrics.

The institutional dimension of road safety management has been further elaborated in the literature on road safety management systems, which emphasises the importance of clearly defined responsibilities, systematic data collection, and hierarchical target structures linking institutional outputs to measurable outcomes (Bliss and Breen, 2009). OECD/ITF (2008, pp.

195-197) highlight the importance of results-focused management, in which targets, indicators, and institutional accountability mechanisms are embedded within long-term strategic frameworks.

Within this conceptual context, systemic road safety risk can be defined as a multidimensional construct reflecting both the magnitude and structural composition of severe crash outcomes. Since fatalities and serious injuries represent the most critical performance indicators within the Vision Zero philosophy, they form the empirical foundation of the analytical model developed in this study.

To enable structured comparison across territorial units, systemic risk must be expressed through a composite indicator integrating multiple outcome dimensions into a single, interpretable metric. The OECD Handbook on Constructing Composite Indicators emphasises that such an approach requires transparent procedures for indicator selection, normalization, weighting, and aggregation to ensure methodological robustness and replicability (OECD, 2008). Accordingly, this study develops a Vision Zero Risk Index (VZRI) designed to quantify and rank systemic road safety risk at the regional level using a transparent composite indicator methodology.

2.2 Selection of Indicators

The selection of indicators was guided by conceptual alignment with the Vision Zero philosophy, empirical reliability, institutional data availability, and methodological coherence with composite indicator construction principles. Within the Vision Zero and Safe System framework, the primary objective of road safety policy is the elimination of fatal and serious injuries (OECD/ITF, 2008, pp. 25-27; WHO, 2023, p. 4). Accordingly, outcome-based indicators constitute the most direct and policy-relevant measures of systemic road safety performance.

The empirical dataset used in this study is derived from official crash statistics published by the Croatian Ministry of the Interior (MUP) for the period 2020-2024. The available variables include total crashes, crashes involving fatalities, number of fatalities, number of seriously injured persons, number of slightly injured persons, and total casualties. These administrative records ensure institutional consistency and comparability across the three observed counties.

Based on these data, four core indicators were selected to represent distinct dimensions of systemic road safety risk. The first indicator is the average annual number of fatalities over the five-year period. Fatalities represent the most severe outcome and remain the principal benchmark of road safety performance internationally (WHO, 2023, p. 4). Averaging over multiple years reduces stochastic volatility typical of smaller territorial units and enhances comparative stability.

The second indicator is the average annual number of KSI (Killed or Seriously Injured), integrating fatalities and serious injuries into a consolidated severity measure widely used in European road safety monitoring systems. As emphasised in the Safe System literature, reliance on fatalities alone may obscure structural deficiencies where survival outcomes are influenced by post-crash medical response (Elvik and Nævestad, 2023). Including KSI therefore strengthens the severity sensitivity of the framework.

The third indicator captures structural severity composition through the proportion of KSI within total casualties. While absolute numbers reflect magnitude, proportional indicators provide insight into qualitative injury structure. Regions with similar total casualty counts may exhibit substantially different shares of severe outcomes, indicating structural differences in crash dynamics and exposure to high-energy events.

The fourth indicator incorporates a temporal dimension by measuring the trend of KSI over the observation period. Results-focused road safety management requires monitoring not only static outcome levels but also directional development over time (OECD/ITF, 2008, pp.

195-197). The inclusion of a trend variable allows differentiation between regions demonstrating improvement and those experiencing stagnation or deterioration in severe injury outcomes.

Although additional structural indicators, such as crash-type characteristics and vulnerable road user involvement, are relevant within the Vision Zero framework, these variables were not consistently available across all three counties in a harmonised format. To preserve full inter-regional comparability and avoid methodological asymmetry, such variables were excluded from the composite index construction. However, they are examined separately in the empirical results section to provide contextual interpretation of regional risk profiles.

In line with the OECD Handbook on Constructing Composite Indicators (OECD, 2008), the selected indicators satisfy three methodological criteria: conceptual relevance, statistical availability across the entire observation period, and non-redundancy in capturing complementary dimensions of systemic risk. Together, the four indicators represent magnitude (fatalities), aggregate severity (KSI), structural injury composition (KSI proportion), and dynamic evolution (trend), forming a coherent multidimensional basis for the construction of the Vision Zero Risk Index.

Although additional indicators, such as traffic exposure measures, infrastructure characteristics, or behavioural factors, were considered during the conceptual design phase, their inclusion was constrained by the lack of harmonised and comparable data across all observed regions. Therefore, the final selection was limited to four core outcome-based indicators that ensure full comparability and methodological consistency within the composite framework.

2.3 Data Sources and Variable Construction

The empirical implementation of the Vision Zero Risk Framework required the operationalisation of outcome-based indicators using administrative data. The analytical focus of this study is the systemic performance of regional transport systems. Consistent with results-oriented road safety management approaches, the emphasis is placed on severe outcome indicators as the most direct expression of system-level safety performance (OECD/ITF, 2008, pp. 195-197; Bliss and Breen, 2009). The index therefore evaluates the structural burden of fatal and serious injuries within each territorial system rather than individual exposure-adjusted risk.

Four variables were operationalised. The first variable represents the average annual number of fatalities over the five-year observation period. The use of multi-year averaging mitigates random annual volatility and enhances the stability of inter-regional comparison. The second variable is the average annual number of Killed or Seriously Injured persons (KSI). The KSI indicator integrates fatalities and serious injuries into a consolidated severity measure widely applied in European road safety monitoring practice (OECD/ITF, 2008, pp. 25-27; WHO, 2023, p. 4). Its inclusion strengthens the outcome sensitivity of the framework beyond fatality counts alone.

The third variable captures injury structure through the proportion of KSI within total casualties:

$$KSI\ Share = \frac{KSI}{Total\ Casualties} \tag{1}$$

Temporal development was estimated using ordinary least squares (OLS) linear regression. Time was coded sequentially (t = 1 for 2020 through t = 5 for 2024). The slope coefficient (β) was calculated as:

$$\beta = \frac{\sum(t_i - \bar{t})(Y_i - \bar{Y})}{\sum(t_i - \bar{t})^2} \tag{2}$$

where Y_i denotes annual KSI values. The coefficient β represents the average annual change in KSI and operationalises the dynamic component of systemic risk, consistent with

longitudinal performance monitoring procedures (OECD, 2008, pp. 87-89). To ensure dimensional comparability, all indicators were normalised using min-max transformation:

$$x_{norm} = \frac{x - x_{min}}{x_{max} - x_{min}} \quad (3)$$

This transformation rescales indicators into the bounded interval [0,1], preserving relative inter-regional differences (OECD, 2008, pp. 84-88). The Vision Zero Risk Index (VZRI) was calculated using linear aggregation with equal weights:

$$VZRI = \frac{1}{4}\sum_{i=1}^{4} Ii \quad (4)$$

where I_i denotes each normalised indicator. Equal weighting and linear aggregation were applied in accordance with OECD composite indicator guidelines (OECD, 2008, pp. 31-34, 118-121).

3 RESULTS

Table 1 presents the constructed indicators, their normalised values, and the resulting Vision Zero Risk Index (VZRI) for the three observed counties over the period 2020-2024.

Table 1. Constructed, Normalised Indicators and Vision Zero Risk Index (2020-2024)

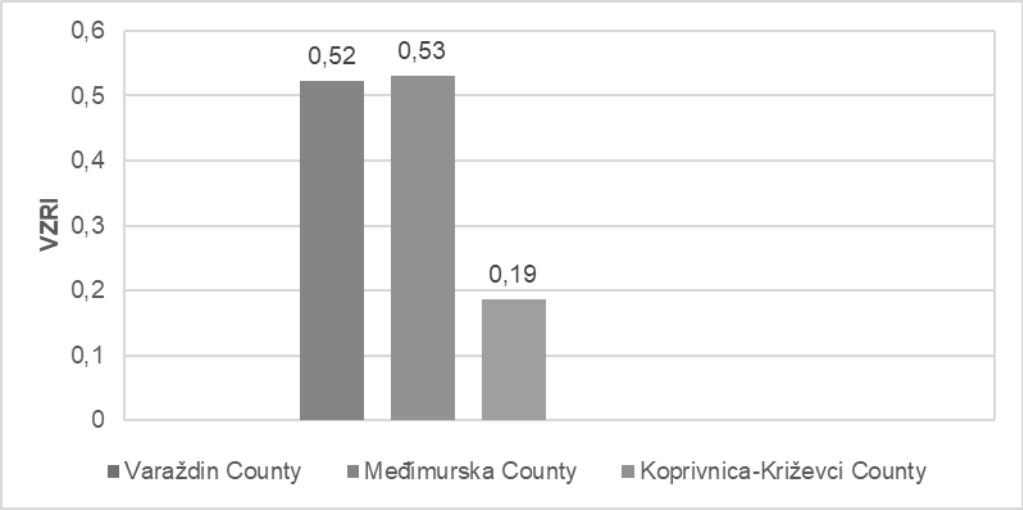
County	Avg. Fatalities	Avg. KSI	KSI share (%)	KSI trend (β)	Norm. fatalities	Norm. KSI	Norm. KSI share	Norm. (β)	VZRI
Varaždin County	10,8	94.0	22.07	6,10	1.00	1.00	0.09	0.00	0.52
Međimurje County	6,4	62.2	25.42	9,10	0.12	0.00	1.00	1.00	0.53
Koprivnica-Križevci County	5,8	72.2	21.74	7,40	0.00	0.31	0.00	0.43	0.19

Source: Own calculation based on MUP data (2020-2024)

Note: Avg. = average annual value; Norm. = min–max normalised value; β = OLS slope coefficient; VZRI = Vision Zero Risk Index.

Varaždin County records the highest average number of fatalities (Avg. fatalities = 10.8) and the highest average KSI value (Avg. KSI = 94.0), indicating the largest absolute severity burden among the analysed regions. Međimurje County, although characterised by lower absolute outcome levels (Avg. fatalities = 6.4; Avg. KSI = 62.2), exhibits the highest structural severity share (KSI share = 25.42%) and the strongest upward dynamic trend (β = 9.10). Koprivnica-Križevci County demonstrates intermediate KSI levels (72.2) and a moderate positive trend (β = 7.40), but the lowest structural severity proportion (21.74%). After min-max normalisation and equal-weight aggregation, the composite index reveals nearly equivalent systemic risk levels for Međimurje County (VZRI = 0.53) and Varaždin County (VZRI = 0.52), albeit driven by different structural components. Koprivnica-Križevci County records a substantially lower composite value (VZRI = 0.19). These findings confirm that systemic road safety risk is multidimensional. Absolute fatality levels alone do not determine composite positioning. To facilitate visual comparison of composite regional risk levels, the final Vision Zero Risk Index values are also presented graphically in Figure 1.

Figure 1. Vision Zero Risk Index (VZRI) by county (2020-2024)



Source: Own calculation based on MUP data (2020-2024)

The graphical representation confirms the numerical findings reported in Table 1. Although Varaždin County records the highest absolute severity burden in terms of average fatalities and average KSI, the composite index reveals a nearly equivalent systemic risk level in Međimurje County.

This positioning is primarily driven by Međimurje's higher structural severity share and the strongest positive KSI trend, indicating a dynamic deterioration in severe outcomes despite lower absolute counts. By contrast, Koprivnica-Križevci County exhibits a substantially lower composite value, reflecting comparatively moderate KSI levels, a lower structural severity proportion, and a less pronounced upward trend. The graphical comparison highlights that systemic road safety risk is not determined solely by absolute fatality magnitude but emerges from the interaction between outcome level, structural composition, and temporal development. These results empirically support Hypothesis H_1, demonstrating that systemic road safety risk differs structurally across regions and can be quantified and ranked using a composite Vision Zero-based index.

4 DISCUSSION

4.1 Empirical Interpretation and Systemic Differentiation

The comparative results of the Vision Zero Risk Index (VZRI) reveal differentiated systemic safety configurations rather than a simple hierarchical ranking of counties. Although Međimurje and Varaždin County exhibit almost identical composite scores, the internal composition of their risk differs substantially, while Koprivnica-Križevci County demonstrates a markedly lower systemic burden. This differentiation confirms the Safe System proposition that road trauma is an emergent property of interacting structural variables, speed regimes, infrastructure configuration, exposure patterns, and governance performance, rather than merely crash frequency (Tingvall and Haworth, 1999, pp. 1-6; OECD/ITF, 2008, pp. 21-23).

Vision Zero conceptualises fatalities and serious injuries as failures of system design, occurring when crash forces exceed biomechanical tolerance limits (OECD/ITF, 2008, pp. 104-113). Elevated average KSI values therefore signal structural exposure to high-energy crash environments rather than random variation. Varaždin's index position is primarily magnitude-driven, as its multi-year average of fatalities and KSI remains comparatively high despite recent improvement. This pattern indicates historical exposure to severe crash configurations that continue to influence composite positioning.

In contrast, Međimurje's profile is shaped by a higher proportional severity component (KSI share) and a positive KSI trend (β). The trend element is analytically significant because

performance monitoring must incorporate directional development rather than static levels alone (Bliss and Breen, 2009, pp. 15-16, 43-47; ITF, 2016, pp. 18-24). A positive β may indicate insufficient systemic adaptation or exposure growth not matched by compensatory safety design.

Koprivnica-Križevci's lower VZRI reflects comparatively favourable magnitude, structural severity, and trend components. However, Safe System governance literature cautions that sustained performance depends on continuous monitoring and proactive hazard treatment rather than reliance on historically low fatality levels (ITF, 2016, pp. 20-23).

4.2 International Evidence and Policy Implications

The structural differentiation identified in the VZRI findings aligns with international empirical evidence from jurisdictions implementing Vision Zero and Sustainable Safety principles. Johansson (2009, pp. 827-829) documents Sweden's long-term fatality decline following Vision Zero adoption, attributing reductions primarily to infrastructure transformation and systematic speed management. Evaluations of Swedish 2+1 roads with median barriers demonstrate reductions in killed and seriously injured casualties between 50% and 80% on treated corridors (Carlsson, 2009, pp. 375-377; Vadeby and Anund, 2013, pp. 4-7). These interventions physically eliminate high-energy head-on collisions and directly address magnitude-driven severity profiles such as those observed in Varaždin. Speed remains the central systemic regulator of crash severity. Nilsson's power model, subsequently refined by Elvik (2009, pp. 2-5; 2019, pp. 116-119), demonstrates a non-linear elasticity between mean speed and injury outcomes. Fatal crash risk approximates a fourth-power relationship to speed, while serious injuries follow a third-power relationship.

This exponential sensitivity explains why counties with similar crash volumes may display divergent KSI shares. Elevated proportional severity, as observed in Međimurje County, may therefore reflect systemic speed-conflict interaction rather than simple exposure magnitude.

Intersection redesign evidence further supports this interpretation. Meta-analyses show that converting traditional intersections to roundabouts significantly reduces fatal and serious injury crashes due to lower impact speeds and simplified conflict angles (Elvik, 2017, pp. 366-369; SWOV, 2018, pp. 22-29). Where right-of-way violations and inappropriate speed are prominent contributing factors, structural intersection modification aligned with Safe System principles provides stronger long-term severity reduction potential than isolated enforcement.

Taken together, international experience confirms that structural interventions, median separation, speed environment redesign, forgiving roadsides, and intersection transformation, yield more sustained KSI reductions than reactive or purely behavioural measures. The differentiated VZRI profiles therefore support territorially tailored intervention strategies consistent with Safe System logic.

4.3 Theoretical and Methodological Implications

The findings also contribute to ongoing theoretical debate regarding Vision Zero's normative foundation. While widely recognised as transformative, Vision Zero has been criticised for the perceived impracticality of an absolute "zero fatalities" target (Abebe, Hansson and Björnberg, 2022, pp. 246-250; Fahlquist, 2006, pp. 1114-1116). Critics argue that ethical absolutism may conflict with resource constraints and competing policy objectives. However, the present study does not operationalise zero as a binary benchmark. Instead, the VZRI translates Vision Zero's ethical directionality into a comparative performance continuum, consistent with Johansson's interpretation of Vision Zero as a long-term systemic transition (Johansson, 2009, pp. 827-828).

Methodologically, the index adheres to established composite indicator principles. The separation of magnitude, structural severity, and temporal trend enables multidimensional diagnosis consistent with OECD composite methodology (OECD, 2008, pp. 84-88, 118-121;

Nardo et al., 2005, pp. 16-19, 30-35). Equal weighting ensures transparency but introduces partial compensability between components. Improvement in one dimension may offset deterioration in another, reflecting real-world trade-offs rather than analytical distortion (OECD, 2008, pp. 76-79). Although equal weighting was adopted to ensure transparency and methodological neutrality, the sensitivity of composite indices to alternative weighting schemes is well recognised in the literature. Variations in weighting could potentially influence the relative ranking of regions, particularly where indicator values are closely aligned. Future research could therefore include sensitivity analysis to assess the robustness of the index under different weighting scenarios.

Min-max normalisation ensures comparability across heterogeneous indicators while preserving relative inter-regional distances (OECD, 2008, pp. 84-88). However, such bounded scaling introduces sample dependency, meaning that index values remain relative to the observed territorial set. The temporal component (β), estimated via ordinary least squares across a five-year series, captures linear directional change but does not account for non-linear dynamics or structural breaks. Nonetheless, within the constraints of regional data availability, it provides a transparent and replicable approximation of systemic progression.

Despite the analytical robustness of the proposed framework, several methodological limitations should be acknowledged. First, the empirical application is based on a relatively small territorial sample of three counties, which limits the generalizability of the findings beyond the analysed regions. Second, the constructed index relies exclusively on outcome-based indicators, without incorporating exposure-related variables such as traffic volumes, vehicle-kilometres travelled, or network characteristics. While this approach is consistent with Vision Zero principles that prioritise severe outcomes, it does not fully capture differences in underlying exposure conditions between regions. Third, the application of min-max normalisation introduces sample dependency, meaning that index values are relative to the observed dataset and may change with the inclusion of additional regions. Finally, the use of equal weighting ensures transparency and avoids normative bias in indicator prioritisation; however, it implies partial compensability between components and may influence the relative positioning of regions. These limitations should be considered when interpreting the results and provide a basis for future methodological refinement.

Overall, the VZRI demonstrates that similar composite values may arise from fundamentally different systemic conditions. Varaždin's profile is burden-driven, Međimurje's is structure and trend-driven, and Koprivnica-Križevci represents comparatively stable performance with lower severity exposure. By integrating magnitude, structural composition, and temporal development, the index operationalises Vision Zero principles within a transparent analytical framework capable of supporting territorially differentiated governance decisions.

From a practical policy perspective, the proposed framework provides a structured tool that can support regional transport authorities and road safety agencies in prioritising interventions. By identifying whether systemic risk is driven primarily by magnitude, structural severity, or adverse trends, decision-makers can tailor measures accordingly. For example, regions with high magnitude indicators may prioritise infrastructure redesign and speed management, while regions with increasing trends may require targeted enforcement, monitoring, and early intervention strategies. In this sense, the Vision Zero Risk Index can serve not only as a benchmarking instrument but also as a decision-support tool for evidence-based allocation of resources and strategic planning in regional road safety management.

5 CONCLUSION

This study developed and applied a composite Vision Zero Risk Index (VZRI) for the comparative assessment of systemic road safety risk across three counties in Northern Croatia for the period 2020-2024.

By integrating average fatalities, average KSI, proportional severity (KSI share), and temporal development (β trend), the index provides a multidimensional representation of regional safety performance that extends beyond single-indicator benchmarking.

The empirical analysis demonstrates that similar composite index values may emerge from fundamentally different structural configurations of risk. Although Međimurje and Varaždin County record nearly identical VZRI scores, the underlying mechanisms differ. Varaždin's position is predominantly influenced by a sustained multi-year severity burden, whereas Međimurje's profile reflects a higher proportional concentration of severe outcomes combined with an unfavourable trend in KSI development. Koprivnica-Križevci County exhibits comparatively lower systemic risk across all components, yet the presence of measurable dynamics underscores the need for continued monitoring and proactive safety management.

The results confirm that outcome-based benchmarking consistent with Vision Zero principles requires simultaneous consideration of severity magnitude, structural injury composition, and temporal progression. The inclusion of a trend component strengthens the analytical framework by capturing systemic directionality and governance responsiveness, thereby moving beyond static performance comparison.

Methodologically, the VZRI illustrates the applicability of transparent composite indicator construction procedures in regional road safety analysis. Min–max normalisation ensures comparability of heterogeneous indicators, while equal weighting preserves methodological neutrality. Although linear aggregation introduces partial compensability between components and normalisation implies sample dependency, these characteristics reflect recognised properties of composite measurement rather than analytical shortcomings.

Substantively, the findings reinforce the Safe System premise that sustained reductions in fatalities and serious injuries depend primarily on structural interventions that manage kinetic energy, regulate speed environments, and redesign infrastructure configurations. The differentiated regional profiles identified in this study support territorially specific prioritisation rather than uniform policy responses.

By translating Vision Zero from an ethical aspiration into a measurable continuum of systemic risk exposure, the proposed index contributes to bridging the gap between normative ambition and performance-based regional road safety governance. Future research may expand the framework through the inclusion of exposure indicators, robustness testing of weighting schemes, and broader territorial application to enhance generalisability and policy relevance.

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Izvorni znanstveni rad

VISION ZERO-UTEMELJEN OKVIR PROCJENE RIZIKA ZA REGIONALNU ANALIZU SIGURNOSTI CESTOVNOG PROMETA: KOMPARATIVNA STUDIJA TRIJU ŽUPANIJA SJEVERNE HRVATSKE

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SAŽETAK

Rad se bavi trajnim problemom smrtnih i teških ozljeda u cestovnom prometu primjenom koncepta Vision Zero na regionalnoj razini. Cilj istraživanja je razviti i primijeniti strukturirani analitički okvir za procjenu i usporedbu sistemskog rizika sigurnosti cestovnog prometa među regijama, s naglaskom na pokazatelje ishoda, a ne na individualnu odgovornost sudionika u prometu. Istraživanje se temelji na službenim policijskim podacima o prometnim nesrećama za Varaždinsku županiju, Međimursku županiju i Koprivničko-križevačku županiju u razdoblju 2020.-2024. godine. Predložen je Vision Zero okvir procjene rizika koji integrira ključne sigurnosne pokazatelje povezane sa smrtno stradalim i teško ozlijeđenim osobama (KSI), uključujući razinu, strukturu težine ozljeda i vremenski razvoj. Radi osiguravanja usporedivosti, pokazatelji su normalizirani metodom min-max te agregirani u kompozitni Vision Zero indeks rizika primjenom transparentnog postupka ponderiranja usklađenog s prioritetima filozofije Vision Zero. Rezultati ukazuju na postojanje različitih regionalnih profila rizika, pri čemu su identificirane strukturne razlike u teškim ishodima prometnih nesreća. Dodatna analiza strukturnih obilježja rizika, uključujući sudjelovanje ranjivih skupina sudionika u prometu i odabrane karakteristike prometnih nesreća tamo gdje su podaci dostupni, pruža dodatni kontekst za tumačenje regionalnih razlika. Dobiveni nalazi potvrđuju da smrtnost u cestovnom prometu nije nasumično raspoređena, već odražava strukturne karakteristike prometnog sustava na regionalnoj razini. Glavni doprinos rada ogleda se u razvoju transparentnog, replikabilnog i za javne politike relevantnog okvira procjene koji omogućuje prioritizaciju mjera u skladu s načelima Vision Zero na temelju empirijskih dokaza. Predloženi pristup moguće je primijeniti i u drugim regijama te predstavlja praktičan alat za integraciju principa Vision Zero u regionalno upravljanje sigurnošću cestovnog prometa.

Ključne riječi: *Vision Zero, sigurnost cestovnog prometa, smrtni ishodi, procjena rizika, regionalna analiza*

Professional Paper

ANALYSIS OF HALF-BARRIER/BARRIER BREAKAGES AT RAILWAY-ROAD CROSSINGS IN THE REPUBLIC OF CROATIA

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ABSTRACT

Railway-road crossings (RRCs) represent one of the most critical points in the transport system due to the potential conflict between road and rail traffic. Despite the installation of modern active protection systems, a significant number of extraordinary events continue to be recorded at RRCs. This study analyzes incidents involving half-barrier and barrier breakages at RRCs in the Republic of Croatia during the period 2018–2024. The aim of the research is to analyze the occurrence of half-barrier and barrier breakages at RRCs and to determine the extent to which the human factor contributes to these incidents. The working hypothesis is based on the assumption that most half-barrier and barrier breakages result from unsafe and unlawful behaviour by road users. The analysis is based on official data provided by HŽ Infrastruktura Ltd. The research results were obtained through the application of methods of analysis and synthesis, the comparative method, and descriptive statistics. The results show that more than 55% of all extraordinary events on railway lines managed by HŽ Infrastruktura in the Republic of Croatia occur at RRCs, while more than 92% of extraordinary events at RRCs involve half-barrier and barrier breakages. In approximately 95% of cases, responsibility lies with RRC users, namely drivers of road vehicles. Each recorded breakage represents a high-risk "near-miss" event with considerable potential for an accident.

Key words: *railway–road crossing, human factor, near-miss, half-barrier breakage, traffic safety*

1. INTRODUCTION

Railway-road crossing (RRC) is a location where a railway line or industrial track crosses a road at the same level, posing a high-risk point for all traffic participants. It can also involve the crossing of a railway with pedestrian and bicycle paths or other routes intended for the crossing of people, animals, vehicles or machinery. The crossing of a railway line and another roadway must be constructed in a way that ensures safe traffic flow on both the railway and the roadway, guaranteeing the safety of all traffic participants. Within the railway network managed by HŽ Infrastructure Ltd. in Croatia, all railway-road crossings (RRCs) are equipped with the prescribed level of protection in accordance with applicable regulations. The safety level of protection is in accordance with national plans for the development and maintenance of railway-road crossings (RRCs), and is determined by legal regulations specifying the exact safety level required at each RRC. (Fonverne, 2018)

In case of inadequate safety measures at railway-road crossings (RRCs), the danger significantly increases, as evidenced by the number of incidents occurring there. Accidents in traffic generally occur due to human or technical errors. Technical advancement has resulted in accidents reduction caused by technical factors, while the number caused by human factors has proportionally increased. The modernization of railway-road crossing protection systems does not guarantee the prevention of accidents, as evidenced by the occurrence of barrier breakages at even the most advanced railway-road crossings. In 2024 alone, there were 462 extraordinary events at railway-road crossings (RRCs), of which 426 involved half-barrier/barrier breakages, indicating that drivers attempted to cross the railway while the half-barriers/barriers were lowered (HŽ Infrastruktura d.o.o., 2025). Therefore, each half-barrier/barrier breakage represents a potential accident.

One of the most challenging tasks facing railway transportation regarding safety is undoubtedly preventing conflict situations, both within the railway system itself and with other forms of transportation sharing the same environment.

2. THEORETICAL FRAMEWORK AND RESEARCH PROBLEM

Railway-road crossings (RRCs) in Croatia are secured in the same way as in most countries around the world, using two basic methods: passive protection and active protection. Passive protection measures involve marking the railway-road crossings (RRCs) with traffic signs (TS) - St. Andrew's Cross and STOP sign with the prescribed visibility triangle, and at pedestrian crossings (PC) TS (MO) + visibility triangle - road traffic signs, passing barriers and visibility triangle. Active protection measures are implemented by physically preventing road vehicles from crossing railway tracks using barriers or half-barriers alongside light and sound signals, or solely light and sound signals, complemented by appropriate road traffic signs.

The installation of half-barriers/barriers, i.e., their operation and control, can be achieved through mechanical, electromechanical, or electronic devices. In addition to mechanical protection, the most common supplementary measures include flashing lights and audible signals. Activation and deactivation may occur automatically as the train approaches predefined track contacts, remotely from an official control location by railway staff, or manually by on-site personnel operating the level crossing barrier.

Since the half-barriers/barriers at railway-road crossings are often broken just before the passage of the train for which they were lowered, each breakage of a half-barrier/barrier can lead to an accident (cf. Figure 1).

Figure 1. Occurrence of half-barrier/barrier breakage

Source: Made by authors.

In the Republic of Croatia, railway infrastructure is managed by HŽ Infrastruktura Ltd., the national railway infrastructure manager. The company manages a railway network with a

total length of 2,617 km, of which 38.7% is electrified and 10.5% is double-tracked. The network comprises 547 official locations, 548 bridges, 113 tunnels, records 20.4 million train-kilometres annually, employs more than 5,194 staff, and includes 1,437 level crossings and pedestrian crossings.

Of the total 1,437 level crossings (LCs) and pedestrian crossings (PCs), 490 level crossings are protected by light and sound signalling, either alone or in combination with half-barriers or barriers. This group includes 23 manually operated mechanical barriers and 467 crossings equipped with signalling equipment, light and audible warning devices, and half-barriers. In total, 604 level crossings and pedestrian crossings are protected by automatic or mechanical devices, meaning that 42% of all level crossings and pedestrian crossings are actively protected. In relation to the total length of the railway network, this means that, on average, there is one level crossing or pedestrian crossing every 1.82 kilometres of railway line (HŽ Infrastruktura d.o.o., 2025, p. 4).

Table 1. Protection of RRCs and PCs in Croatia

RRCs and PCs secured by traffic signs and visibility triangles	Mechanical barriers with manual operation	Light-sound signalling and half-barriers	Pedestrian crossings with light-sound signalling and channelling barriers	TOTAL RRCs and PCs
833	23	467	114	1437

Source: HŽ Infrastruktura d.o.o. (2025), Annual Safety Report 2024.

Mostly, on lower-category railways, railway-road crossings (RRCs) and pedestrian crossings (PCs) are secured with road traffic signs and visibility triangles, while on main corridor railways, RRCs and PCs are predominantly secured by light and sound signals and half-barriers (Knežević and Belančić, 2018).

3. RESEARCH RESULTS AND DISCUSSION

For analyzing incidents involving half-barriers/barriers at railway-road crossings (RRCs) in Croatia, a graphical representation is provided comparing the total number of extraordinary events on railway lines in Croatia with those occurring at RRCs, as well as the number of incidents involving half-barriers/barriers in the period from 2018 to 2024. In addition, the tables present liability for half-barrier/barrier breakages, the level of material damage, the percentage of known perpetrators, and an analytical representation of the relationship between these variables (Tables 2, 3, 4 and 5).

During the analyzed period, a total of 5,880 extraordinary events occurred on railways, of which 55% (3,249) took place at railway-road crossings. Of these 3,249 extraordinary events at RRCs, 92% (2,980) involved half-barrier/barrier breakages. Users of railway-road crossings were responsible for 95% (2,820) of all recorded half-barrier/barrier breakages. Among all recorded extraordinary events on railways, half-barrier/barrier breakages constituted the largest individual category, accounting for more than 50% of all incidents (Graph 1).

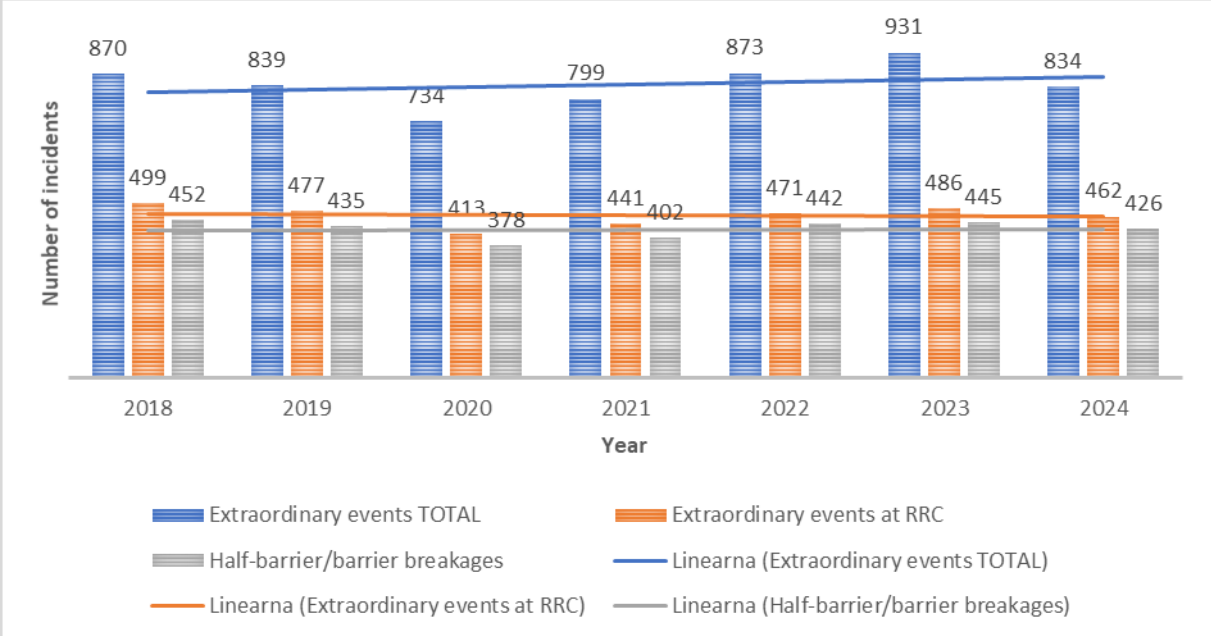
Table 2. Comparative overview of extraordinary events in Croatia, extraordinary events at railway-road crossings (RRCs) and half-barrier/barrier breakages from 2018 to 2024

Year	2018	2019	2020	2021	2022	2023	2024	Avg. 2018-2023	Index (2024/ avg. x100)	Index (2024/ 2023 x100)
Extraordinary events TOTAL	870	839	734	799	873	931	834	823,00	101,34	95,53
Extraordinary events at RRC	499	477	413	441	471	486	462	460,20	100,39	98,09
Half-barrier/barrier breakages	452	435	378	402	442	445	426	421,80	101,00	96,38

Source: Author's compilation based on data provided by HŽ Infrastruktura Ltd. for the period 2018–2024.

Based on the data from Graph 1, in 2024 there were a total of 426 half-barrier/barrier breakages, which is 3.6% fewer than in 2023, but 1.0% above the 2018–2023 average. The trend line for half-barrier/barrier breakages shows a mild decline over the observed period. At the same time, the trend line for extraordinary events at railway-road crossings remained relatively stable, while the overall trend line for extraordinary railway events in Croatia showed a slight increase.

Graph 1. The relationship between extraordinary events in Croatia, extraordinary events at railway-road crossings (RRCs) and half-barrier/barrier breakages from 2018 to 2024

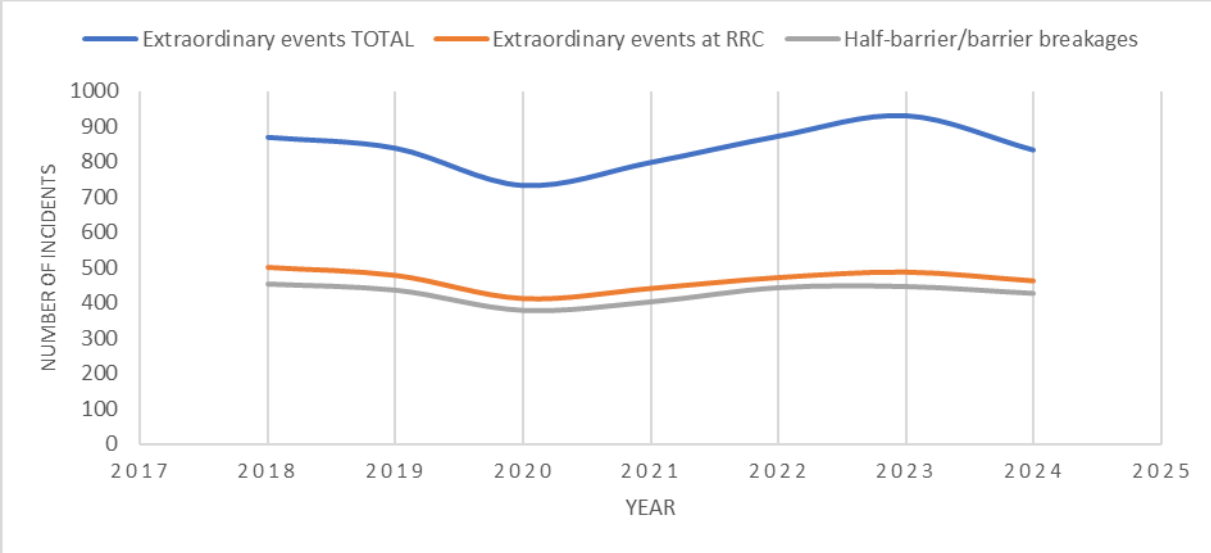


Source: Author's compilation based on data provided by HŽ Infrastruktura Ltd. for the period 2018–2024.

Graph 2 indicates that extraordinary events at railway-road crossings and half-barrier/barrier breakages account for a substantial share of all extraordinary railway events in Croatia during the observed period.

This is not a favorable indicator, since a higher number of half-barrier/barrier breakages may contribute to an increased risk of traffic accidents. Therefore, each half-barrier/barrier breakage can be considered as a potential risk factor for an accident.

Graph 2. Graphical representation of the relationship between the total number of extraordinary events in the Republic of Croatia and extraordinary events at railway-road crossings involving half-barrier/barrier breakages from 2018 to 2024



Source: Author's compilation based on data provided by HŽ Infrastruktura Ltd. for the period 2018–2024.

During the observed period there was a very high number of cases in which vehicles collide with lowered half-barriers/barriers. There were 2,980 breakages of these barriers, with users of railway-road crossings responsible for 2,820 of them, i.e., 95%, while the remaining incidents were attributed to adverse weather conditions, unauthorized people, and third parties (Table 3).

It is evident that the behavior of road users is the dominant identified cause of half-barrier/barrier breakages, while a smaller share of incidents is associated with adverse weather and other causes.

Table 3. Liability for breakages of half-barriers/barriers in Croatia from 2018 to 2024

Responsibility	2018	2019	2020	2021	2022	2023	2024	TOTAL
RRC user	432	419	346	385	427	400	411	2820
Unauthorized people	1	0	0	0	1	0	0	2
Third party	0	0	0	0	1	0	0	1
Adverse weather	19	16	32	17	13	45	15	157
TOTAL:	452	435	378	402	442	445	426	**2980**

Source: Author's compilation based on data provided by HŽ Infrastruktura Ltd. for the period 2018–2024.

If the material damage resulting from the breakage of a half-barrier/barrier is considered, the total damage during the observed period amounted to EUR 539,000. The highest annual damage was recorded in 2023 (EUR 104,000), while in 2024 it amounted to EUR 89,000 (Table 4 and Graph 3).

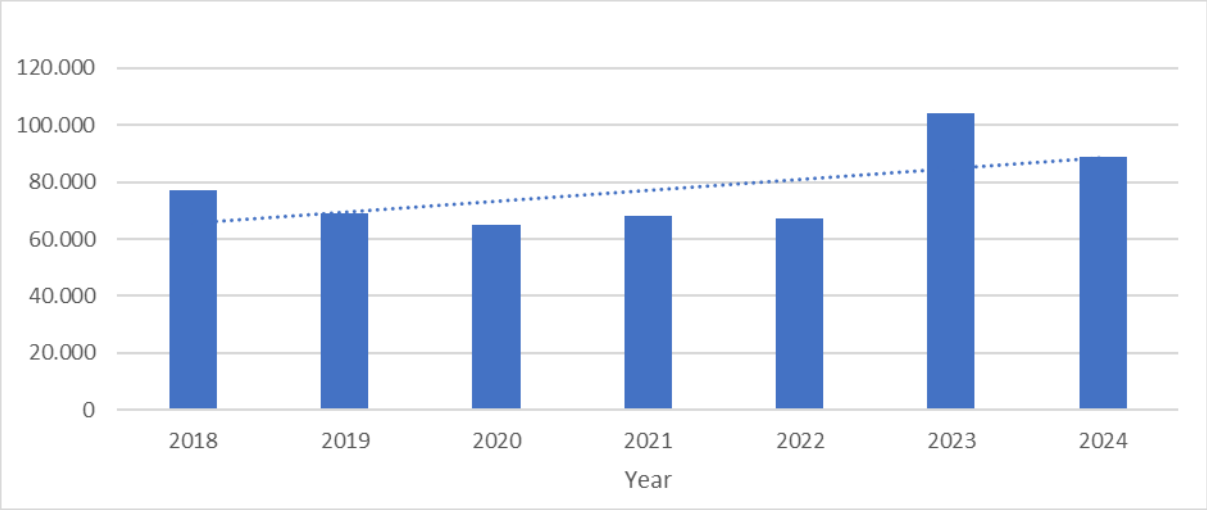
Table 4. Material damage at railway–road crossings in the Republic of Croatia, 2018–2024

Year	2018	2019	2020	2021	2022	2023	2024	TOTAL
Damage (EUR)	77.000	69.000	65.000	68.000	67.000	104.000	89.000	**539.000**

Source: Author's compilation based on data provided by HŽ Infrastruktura Ltd. for the period 2018–2024.

Graph 3 presents the annual amount of material damage caused by half-barrier/barrier breakages at railway-road crossings in the Republic of Croatia during the period 2018–2024 and shows that the highest value was recorded in 2023, while the level of damage remained comparatively high in 2024.

Graph 3. Material Damage at Railway–Road Crossings in the Republic of Croatia in the Period 2018–2024



Source: Author's compilation based on data provided by HŽ Infrastruktura Ltd. for the period 2018–2024.

Table 5 shows the percentage of cases in which the perpetrator is known. On average, the identity of the perpetrator in half-barrier/barrier breakages is not established in approximately 28,6% of cases.

Table 5. Known perpetrators for the breaking of half-barriers/barriers in Croatia from 2018 to 2024

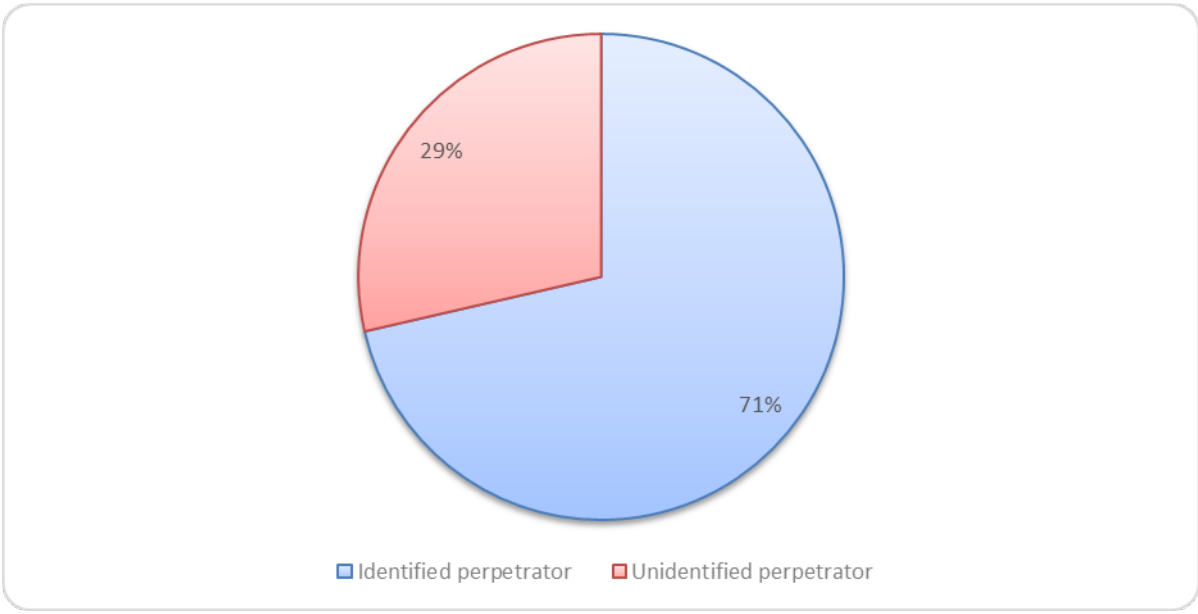
Year	2018	2019	2020	2021	2022	2023	2024	AVERAGE
Perpetrator known (%)	75	83	60	66	85	61	70	**71,4**

Source: Author's compilation based on data provided by HŽ Infrastruktura Ltd. for the period 2018–2024.

The fact that approximately 28,6% of users who break the half-barrier/barrier remain unpunished due to the inability to establish their identity after leaving the place of accident is worrying.

Graph 4 provides a graphical presentation of the average percentage share of identified and unidentified perpetrators in cases of half-barrier/barrier breakages during the observed period.

Graph 4. Average Percentage Share of Identified and Unidentified Perpetrators at Railway–Road Crossings in the Republic of Croatia in the Period 2018–2024



Source: Author's compilation based on data provided by HŽ Infrastruktura Ltd. for the period 2018–2024.

4. SAFETY IMPROVEMENT RECOMMENDATIONS

Based on the results obtained, the following measures are recommended:

1. Installation of video surveillance systems with automatic vehicle identification to reduce the number of unidentified perpetrators and enhance deterrence.
2. Implementation of energy-absorbing or flexible half-barriers to reduce material damage and system downtime.
3. Targeted traffic enforcement and sanctioning at high-risk crossings.
4. Continuous public education campaigns emphasizing the dangers of railway-road crossings, train approach speed and braking distance.
5. Risk-based adaptation of closure times at crossings with a high frequency of incidents.

5. CONCLUSION

Analyses of half-barrier/barrier breakages at railway-road crossings (RRCs) in the Republic of Croatia indicate that approximately 95% of breakages were caused by road traffic participants who did not adhere to traffic regulations. These findings indicate that such incidents are predominantly associated with unsafe or non-compliant behavior by road users.

Unfortunately, data from Croatia confirm that more than 55% of all extraordinary railway events in the observed period occurred at railway-road crossings, while more than 92% of

extraordinary events at railway-road crossings involved half-barrier/barrier breakages. However, the high number of half-barrier/barrier breakages at railway-road crossings should not lead to the mistaken conclusion that investing in modern equipment is not cost-effective. It must be considered that the level of danger at individual crossings varies depending on:

- the number of traffic participants and traffic frequency,
- the way the crossing is secured,
- the meteorological conditions,
- the conditions for driving road and railway vehicles.

The authors point out the importance of this study because extraordinary events at railway-road crossings (RRCs) account for more than 55% of all extraordinary events on railway lines in Croatia, while the share of half-barrier/barrier breakages within this group is very high and the influence of human factors on their occurrence is approximately 95%. The results suggest that a considerable number of road users either underestimate or disregard the risks associated with crossing railway tracks at the same level.

Road users often underestimate train speed and braking distance. It is concerning that approximately 17% of irresponsible users who break half-barriers/barriers remain unpunished because their identity cannot be determined, as they leave the place of accident.

Therefore, the main finding of this study is that human error accounts for approximately 95% of half-barrier/barrier breakages, while about 92% of extraordinary events at railway-road crossings involve half-barrier/barrier breakages, which supports the working hypothesis.

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Stručni rad

ANALIZA LOMA POLUBRANIKA/BRANIKA NA ŽELJEZNIČKO-CESTOVNIM PRIJELAZIMA U REPUBLICI HRVATSKOJ

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SAŽETAK

Željezničko-cestovni prijelazi (ŽCP) predstavljaju jednu od najkritičnijih točaka prometnog sustava zbog mogućnosti konflikta između cestovnog i željezničkog prometa. Unatoč ugradnji suvremenih aktivnih sustava zaštite, na ŽCP-ovima se i dalje bilježi značajan broj izvanrednih događaja. Ova studija analizira incidente lomova polubranika i branika na ŽCP-ovima u Republici Hrvatskoj u razdoblju 2018.–2024. Cilj istraživanja je analizirati pojavnost lomova polubranika i branika na ŽCP-ovima te utvrditi u kojoj mjeri ljudski čimbenik doprinosi nastanku ovih incidenata. Radna hipoteza polazi od pretpostavke da je većina lomova polubranika i branika posljedica nesigurnog i nepropisnog ponašanja sudionika cestovnog prometa. Analiza se temelji na službenim podacima koje je dostavila HŽ Infrastruktura d.o.o. Rezultati istraživanja dobiveni su primjenom metoda analize i sinteze, komparativne metode te deskriptivne statistike. Rezultati pokazuju da se više od 55 % svih izvanrednih događaja na prugama kojima upravlja HŽ Infrastruktura u Republici Hrvatskoj događa na ŽCP-ovima, dok više od 92 % izvanrednih događaja na ŽCP-ovima uključuje upravo lomove polubranika i branika. U približno 95 % slučajeva odgovornost snose korisnici ŽCP-a, odnosno vozači cestovnih vozila. Svaki zabilježeni lom predstavlja visokorizičan „near-miss" događaj s velikim potencijalom za nastanak nesreće.

Ključne riječi: *željezničko-cestovni prijelaz, ljudski čimbenik, izbjegnuta nesreća, lom polubranika, sigurnost prometa*

Pregledni rad

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SAŽETAK

Proces upravljanja sigurnošću prometom bio je prioritet u tradicionalnom željezničkom sustavu što je bilo propisano zakonskim aktom. Uspostavom sustava upravljanja sigurnošću s preventivnim pristupom došlo je do sve veće odgovornosti donositelja odluka, bez obzira što su najveći broj teških nesreća prouzročile „treće osobe“, sudionici u prometu koji su izravno vezani za željeznički promet. Takav pristup zahtjeva od menadžera sigurnosti da se upoznaju s „trećim osobama“ kako bi upoznali njihova ponašanja u prometu te ponudili prometna rješenja koja će minimizirati mogućnost pogreške sa štetnim posljedicama. U radu je predstavljeno nekoliko projektnih aktivnosti povezivanja s trećim osobama, osobito aktivnim sudionicima u prometu, odnosno ranjivim skupinama. U primjerima su prezentirani rizični željezničko cestovni prijelazi, križanja cestovnih prometnica s industrijskim kolosijecima i industrijskim matičnjacima te divlji prijelazi preko pruge. Dodatno su istaknute opasnosti rizičnih ponašanja na željezničkim mostovima. Postizanje ciljeva Vizije Nula zahtjeva novi pristup procesu upravljanja sigurnošću prometom. „Slobodan ZA sigurnost“ je jedan od takvih pristupa.

Ključne riječi: *siguran tijek prometa, ranjive skupine, upravljanje poslovnom sigurnošću, sustav upravljanja sigurnošću*

1. UVOD

Transformacija tradicionalnog u suvremeni željeznički sustav značajno utječe na područje sigurnosti prometa. U tradicionalnom sustavu naglasak je bio na unutarnjoj kontroli, koja je nadzirala provedbu tehnološkog procesa stvaranja prijevozne usluge. Sredinom prošlog stoljeća radnici unutarnje kontrole imali su činove, pa čak i oružje, zbog čega se i danas u neformalnom govoru kontrole sigurnosti ponekad nazivaju „pištoljaši“. Tradicionalni sustav bio je dizajniran polazeći od pretpostavke da radnici i sudionici u prometu ne griješe. Kada bi do pogreške došlo, odgovornost je bila individualna i sankcionirana. Suvremeni sustav upravljanja sigurnošću donosi bitno drugačiji pristup. Naglasak se premješta na preventivne aktivnosti, upravljanje rizicima, sustavno prepoznavanje izvora opasnosti i analizu uzroka. Takva transformacija zahtijeva tehnološke i psihološke promjene od redizajna procesa upravljanja sigurnošću do primjene novih metoda procjene i analize stanja sigurnosti. Kao i kod svake velike promjene, treba vremena da se novi pristup prihvati, pa se i danas može čuti kako je „nekad bilo bolje“. Sve snažnije mjesto u prometnom sustavu zauzimaju koncepti

Dizajniranje sigurnog sustava, Vizija nula i Kultura pravednosti (engl. *Safety System Design, Vision Zero, Just Culture Learning*). Dizajniranje sigurnosti sustava uključuje prepoznavanje organizacije kao uzroka pogreške, a ne prebacivanje na individualnu odgovornost. Cilj Vizije nula je nula smrtno stradalih i teško ozlijeđenih u prometu. Takav pristup podrazumijeva dizajniranje prometnog sustava koji prepoznaje i minimizira ljudske nesavršenosti. Prometna rješenja moraju biti oblikovana tako da ljudska pogreška ne rezultira najtežim posljedicama. Kultura pravednosti ide korak dalje - ona ne traži samo individualnu odgovornost, već analizira sustavne uzroke pogreške. Ključno pitanje više nije samo „Tko je pogriješio?“, nego i „Je li sustav doveo radnika ili sudionika u situaciju u kojoj je pogreška bila vjerojatna?“ Posljednjih 25 godina u željezničkom sustavu naglasak je bio na modernizaciji zapuštene infrastrukture i prijevoznih sredstva. Međutim, pri tome je često zanemarena potreba održavanja visoke razine: stručne osposobljenosti izvršnih radnika, kontinuirane edukacije i zdravstvene sposobnosti ključnog osoblja. Prometna rješenja u strateškim vizijama željezničkih poduzeća ostajala su u drugom planu. Posljedice su: nedostatak kvalitetnih izvršnih radnika, manjak stručnih planera i slabije prepoznavanje izvora opasnosti u prometnim rješenjima.

Suvremene organizacije sve više uvode procese upravljanja poslovnom sigurnošću. Sigurnost se promatra i kroz financijsku prizmu uz sve prisutnije pitanje: „Koliko sigurnost košta?“ Povezivanjem ciljeva Dizajniranja sigurnog sustava, Vizije Nula, Kulture pravednosti i poslovne sigurnosti, uloga prometnih planera postaje strateška. Oni više nisu samo tehnički projektanti, već ključni dionici u dizajniranju sigurnog i održivog prometnog sustava.

Analize izvanrednih događaja u željezničkom prometu pokazuju da su u središtu pažnje često nesreće koje uzrokuju tzv. „treće osobe“. To su osobe koje nisu izravno uključene u željeznički promet i o njemu imaju ograničena znanja. Najčešće se radi o: vozačima cestovnih vozila na željezničkom-cestovnim prijelazima, pješacima i biciklistima (ranjivim skupinama) i osobama koje željezničku infrastrukturu doživljavaju kao izazov ili prepreku. Poseban sigurnosni izazov predstavljaju: divlji prijelazi, rizični željezničko-cestovni prijelazi i križanja cestovnih prometnica s industrijskim kolosijecima i matičnjacima. Rezultati analiza jasno pokazuju potrebu za zajedničkim željezničko-cestovnim rješenjima koja integriraju infrastrukturu, edukaciju i preventivne mjere.

Kako bi se podigla razina svijesti o promjenama u procesima sustava upravljanja sigurnošću prometa te istaknula nova, proaktivna uloga prometnih planera u dizajniranju sigurnijih rješenja za aktivne sudionike u prometu, članovi neprofitne organizacije safety.guru INSTITUT proveli su niz projektnih aktivnosti. Željeznički mostovi, zbog svoje arhitektonske atraktivnosti i vizualne snage, često postaju mjesta rizičnih ponašanja i adrenalinskih aktivnosti. Umjesto isključivo restriktivnog pristupa, sve se češće primjenjuju umjetničke intervencije, sportski i rekreativni sadržaji te usmjeravanje ponašanja kroz dizajn prostora. Time se rizik preusmjerava u kontrolirane i sigurnije oblike korištenja prostora. Sloboda za odgovornost prometnih planera prema sigurnim rješenjima u prometu obrađena je i primjenom metode generiranja hipotenuze više kvadranata kao analitičkog alata za procjenu sigurnosnih rješenja, te pregledom rezultata ankete profesionalnih vozača o stanju stručnog obrazovanja. Kao rezultat konferencije i provedenih aktivnosti, izrađen je vodič za učenike osnovnih škola pod nazivom „Moja pažnja u prometu“, koji na jednostavan i ilustrativan način upoznaje djecu s pravilima sigurnog ponašanja u prometu te potiče razvoj preventivne svijesti.

Rezultati tih aktivnosti predstavljeni su na više međunarodnih konferencija ILCAD (*International Level Crossing Awareness Day*) diljem svijeta, kao i na konferencijama o održivosti održanima u Zagrebu. Na taj je način otvoren stručni dijalog o potrebi sustavnog, preventivnog i interdisciplinarnog pristupa sigurnosti prometa, s posebnim naglaskom na odgovornost prometnih planera u oblikovanju sigurnog prometnog okruženja.

2. KAKO NASTAJU RANJIVE GRUPE U PROMETU (ILCAD Denver, Colorado)

U analizama o izvanrednim događajima u željezničkom prometu posebno se ističu nesreće koje su prouzročile treće osobe, odnosno sudionici u prometu koji nisu izravno uključeni u željeznički promet i nemaju odgovarajuća znanja o ponašanju u njegovoj blizini. To uključuje vozače cestovnih vozila na željezničko-cestovnim prijelazima, aktivne sudionike u prometu poput pješaka, biciklista i ranjive skupine čija je vjerojatnost nastanka nesreće povećana upravo zbog dizajna komunikacijskih mjesta (prijelaza i križanja). Takvo stanje predstavlja izazov za prometne planere te se može raščlaniti na sljedeće razine:

• prometna dijagnoza – sigurnost cestovnog i željezničkog prometa promatrana je odvojeno, regulirana kroz zasebne zakonske akte.

• prometna prognoza – naglasak je na integraciji cestovnog i željezničkog sustava unutar kopnenog prometa.

• prometna terapija – fokus se prebacuje na integrirano upravljanje sigurnošću cestovnog i željezničkog prometa kroz zajednička rješenja i mjere.

Vizija nula je međunarodna strategija sigurnosti prometa s temeljnim ciljem da ne smije biti smrtno stradalih ili teško ozlijeđenih osoba u prometu te da je takav ishod neprihvatljiv s etičkog, društvenog i inženjerskog gledišta. Vizija nula napušta tradicionalni model koji pripisuje većinu odgovornosti sudionicima u prometu. Umjesto toga, naglašava da sustav mora biti takav da njegove slabosti ne dovode do tragičnih posljedica.

Svoje projektne aktivnosti članovi neprofitne organizacije safety.guru INSTITUT usklađuju s principima i zahtjevima Vizija nula. U okviru tih aktivnosti analizirano je kako se ranjive skupine formiraju na željezničko-cestovnim prijelazima i pješačkim prijelazima te kako promjena dizajna i promišljanja prometnih rješenja može dovesti do sigurnijeg tijeka prometa. Pojam siguran tijek prometa zakonski je definiran (Zakon o sigurnosti željezničkog prometa, 2007) kao uvjet i način za sigurno, uredno, redovito i neometano obavljanje željezničkog prometa. Ta definicija naglašava sustavni pristup sigurnosti, uključujući planiranje, organizaciju i nadzor, umjesto uske kontrole ponašanja pojedinaca.

2.1 Neometan i ometan tijek prometa

Neometan tijek prometa odnosi se na osiguranje visoke razine sigurnosti željezničkog prometa čak i u uvjetima izvođenja različitih aktivnosti na infrastrukturi, bilo da je riječ o osuvremenjivanju i modernizaciji pruga, redovitom održavanju, ili izvanrednim situacijama. U takvim okolnostima primjenjuju se posebne regulacije prometa kako bi planirani vozni red mogao biti izvršen. Zatvori pruga mogu biti predviđeni ili nepredviđeni, a njihovo upravljanje i regulacija definirani su Prometnim pravilnikom HŽI-2 (Pravilnik HŽI-2). Istim aktom propisani su i zatvori u slučaju izvanrednih događaja.

Razvoj i širenje urbanih područja dovelo je do izgradnje novih naselja uz obje strane željezničkih pruga, čime pruga često postaje prepreka za neometane tokove cestovnog, biciklističkog i pješačkog prometa. S obzirom na visok intenzitet vlakova i aktivnog cestovnog i pješačkog prometa, najpraktičnija i dugoročno održiva rješenja uključuju dvostruku razinu prometa, gdje se željeznički i cestovni tokovi odvajaju radi sigurnosti i efikasnosti svih sudionika.

Slika 1. Strme stepenice na Oranicama, Zagreb

Budući da uključivanje lokalne zajednice i osiguranje značajnijih ulaganja često zahtijeva vrijeme i resurse, često se pribjegava polovičnim rješenjima (npr. stepenice na Oranicama – Slika 1) ili se rješenja odgađaju, što dovodi do pojave divljih prijelaza (npr. Vrapče).

Slika 2. Pješaci na divljem prijelazu uz potok Vrapčak, Zagreb

Odredbe pravila o nedopuštenim prijelazima preko željezničke pruge regulirane su jedino Unutarnjim redom (Zakona o sigurnosti i interoperabilnosti željezničkog sustava, 2020). Tijekom 2019. godine prebrojeno je više od 30 divljih prijelaza na relaciji od Podsused Stajališta do Sesveta, pri čemu su divlji prijelazi uz potok Vrapčak posebno istaknuti zbog velikog broja pješaka i biciklista koji ih svakodnevno koriste. Uz taj divlji prijelaz provedena je preventivna akcija, koja je medijski popraćena i pohvaljena od strane menadžera sigurnosti. Ipak, do danas na tom prijelazu nisu provedene trajne sigurnosne mjere.

Slična situacija prisutna je i kod divljih prijelaza u blizini kolodvora Zagreb Borongaj, koje najčešće koriste studenti na putu prema Studentskom kampusu Borongaj i natrag. Na tom području, tijekom samo jednog mjeseca 2023. godine, smrtno su stradale četiri mlade osobe: dva studenta na vagonima, djevojka kod stajališta Čulinec te mladić na željezničko-cestovnom prijelazu Osječka.

Slika 3. Divlji prijelaz kolodvor Zagreb Borongaj

Ovi tragični događaji dodatno naglašavaju potrebu za hitnim i trajnim rješenjima te integriranim pristupom sigurnosti pješaka i biciklista na željezničkoj infrastrukturi.

2.2 Redovit i neredovit tijek prometa

Redovnost, odnosno redovitost vlakova u prometu regulirana je člankom 14. Prometnog pravilnika HŽI-2, a vlak može biti redovan ili izvanredan. Redovan vlak je svaki vlak koji vozi svakodnevno ili za koji je voznim redom utvrđeno kalendarsko vrijeme vožnje (kalendar prometa). Izvanredan vlak su svi vlakovi koji ne zadovoljavaju kriterije redovnog vlaka.

Redovitost vlakova pozitivno utječe na uhodanost i predvidljivost u realizaciji prijevozne usluge. S druge strane, izvanredni vlakovi zahtijevaju dodatne aktivnosti u planiranju i sigurnom upravljanju prometom. Kad su u pitanju manevarski sastavi koji se kreću po industrijskim matičnjacima i kolosijecima još više do izražaja dolazi redovnost sigurnog tijeka prometa zbog sljedećih razloga:

- industrijski matičnjaci i kolosijeci su zapušteni te se izvanredno koriste za manevarske vožnje
- pri križanju industrijskog matičnjaka i kolosijeka sa cestovnom prometnicom način posluživanja kolosijeka regulira se Poslovnim redovima kolodvora te je obavezno zaustavljanje manevarskog sastava dok se ne osigura prolaznost preko ceste
- prometni znakovi na križanjima industrijskim matičnjaka i kolosijeka sa cestovnim prometnicama su nepravilni i zapušteni.

Slika 4. Industrijski matičnjak Podsused, Zagreb

Redovitost u ovakvim uvjetima ne samo da povećava sigurnost prometa, već i omogućava učinkovitije upravljanje ljudskim i tehničkim resursima u željezničkom sustavu.

Slika 5. Industrijski kolosijek kod trgovačkog centra *City Center One East*, Zagreb

Loše stanje ovakvih križanja dovodi do nepravilnog ponašanja sudionika cestovnog prometa. Naviknuti na to da manevarski sastavi (vlakovi) rijetko prolaze, vozači često prelaze preko kolosijeka bez zaustavljanja, zanemarujući prometni znak „STOP“. Takva svakodnevna praksa stvara lošu naviku, koja povećava rizik na mjestima gdje vlakovi redovito prometuju. S ciljem rješavanja ovog problema, na području grada Zagreba organiziran je radni sastanak sa svim relevantnim dionicima. Međutim, do danas još uvijek nije provedeno sustavno i dugoročno rješenje za sigurnost ovih križanja.

2.3 Uredan i neuredan tijek prometa

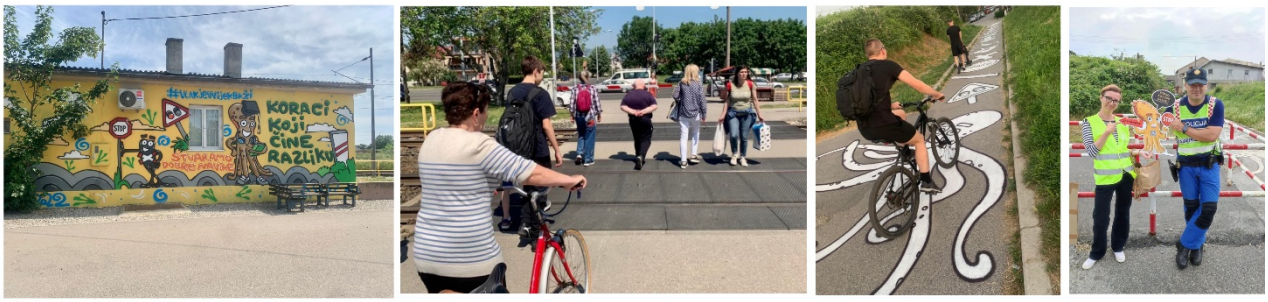
Pojam urednost prometa formalno nije definiran u zakonodavstvu, iako se u članku 6. Prometnog pravilnika HŽI-2 spominje neometano odvijanje prometa, a kasnije se u praksi koristi i pojam urednosti prometa. Urednost prometa najčešće se odnosi na točnost, a neurednost na kašnjenje vlakova, što je potvrđeno i Prilogom 5. Zakona o željeznici: „Kod izračuna plaćanja prema sustavu pokazatelja kvalitete uzima se u obzir prosječno kašnjenje vlakova za koje vrijede slični zahtjevi za točnošću.“ Na željezničko-cestovnim prijelazima, uredan tijek prometa znači da vlakovi dolaze i prolaze prema planiranom voznom redu. Cestovni korisnici u tim trenucima planiraju svoje kretanje upravo prema očekivanoj točnosti vlakova. Problemi nastaju na prugama gdje se prijelazi nalaze u blizini kolodvora, jer organizacija prometa dodatno otežava duže čekanje vozila i pješaka na prolazak vlakova. Nakon dužeg čekanja, korisnici cesta često prelaze prugu unatoč upaljenim semaforima i signalizaciji, što stvara visok rizik od nesreća. Klasičan primjer ovakvog neurednog ponašanja vidljiv je na željezničko-cestovnom prijelazu Osječka, gdje dugotrajna čekanja i svakodnevna navika ignoriranja signalizacije dovode do rizičnih situacija.

Slika 6. ŽCP Osječka, Zagreb

Osim klasičnih željezničko-cestovnih prijelaza, vrijedi istaknuti primjer ŽCP Trnava, koji se također nalazi na području kolodvora Zagreb Borongaj. S južne strane tog prijelaza nalazi se mimoilazna ograda na pješačkom prijelazu preko nekadašnje pruge Zagreb Istočni kolodvor – Zagreb Borongaj.

Međutim, pješaci, koji čine najčešće korisnike, zatim prelaze preko samog ŽCP-a Trnava, koji nema mimoilaznu ogradu. Nakon kraćeg čekanja, mnogi pješaci prelaze prugu pored spuštenih polubranika, čime nastaje ozbiljan sigurnosni rizik.

Slika 7. ŽCP Trnava, Zagreb



2.4 Siguran i nesiguran tijek prometa

Siguran tijek prometa sastoji se od pet osnovnih elemenata: prometnice, vozila, čovjeka i prometa na prometnici i incidentnog čimbenika. U kontekstu željezničke infrastrukture, promet na prometnici nužno uključuje sudjelovanje cestovnih korisnika (vozača, pješaka, biciklista) na području željezničke infrastrukture. Sudionici cestovnog prometa često nisu upoznati s pravilima i odredbama koje se odnose na sigurnost željezničkog prometa. Stoga je važno promatrati njihovo ponašanje već prije nego što pristupe željezničkoj infrastrukturi, kako bi se identificirali potencijalni rizici. Nepravilno ponašanje cestovnih sudionika potrebno je minimizirati, a to je moguće kroz integraciju sigurnosti cestovnog i željezničkog prometa, osobito na:

- željezničko-cestovnim i pješačkim prijelazima
- križanjima cestovnih prometnica s industrijskim kolosijecima i matičnjacima
- mjestima mogućeg neovlaštenog pristupa, koja se često koriste kao divlji prijelazi.

Takav integrirani pristup osigurava da svi sudionici, bez obzira na njihovo predznanje i iskustvo, imaju veći stupanj sigurnosti prilikom kretanja u blizini željezničke infrastrukture.

2.5 Profesionalni vozači i sigurnost

Polaganje vozačkog ispita jednom u životu ne osigurava trajno poznavanje svih prometnih pravila. S ciljem procjene stvarnog znanja, provedeno je istraživanje o poznavanju prometnih pravila među profesionalnim vozačima u cestovnom (vozači kamiona i autobusa) i željezničkom (strojovođe) prometu. Ukupno je ispitano 91 sudionik: 36 strojovođa iz Hrvatske i Slovenije,14 vozača kamiona i

41 vozač autobusa. Svi ispitanici pokazali su veliko iskustvo u unutarnjem i međunarodnom prijevozu putnika i tereta te dobro poznavanje stanja prometnica. Međutim, primijećeno je nedovoljno poznavanje specifičnih križanja cestovnih prometnica s industrijskim kolosijecima i matičnjacima. Preporuke za unaprjeđenje sigurnosti odnosile su se odnosilo se na poboljšanje osiguranja željezničko-cestovnih prijelaza. Cestovni vozači preferirali su rješenja poput horizontalne signalizacije i navigacijskih upozorenja. Strojovođe su više naglašavali potrebu za primjenom kamera i video nadzorom. Kako strojovođe imaju učestalija redovita poučavanja od vozača u cestovnom prometu, preporuke za poboljšanje sigurnosti uključuju

integraciju prometne edukacije već od osnovne škole, povećanje medijskog prostora posvećenog sigurnosti na ŽCP-ima i poticanje cjeloživotnog obrazovanja svih profesionalnih vozača, kako cestovnih tako i željezničkih.

Slika 8. Strojovođa i vozač kamiona

Ovo istraživanje naglašava da iskustvo i praksa same profesionalne vozače ne čine automatski sigurnima te da kontinuirana edukacija i modernizacija sigurnosnih sustava imaju ključnu ulogu u smanjenju rizika.

3. „PRIČA O HENDRIXU“

Hendrixov most, službeno poznat kao Zeleni željeznički most, izgrađen je 1939. godine kao dvokolosiječni željeznički most preko Save u Zagrebu. Nosiva konstrukcija je čelična, s četiri otvora i najvećim rasponom od oko 135 metara, izvedena kao kontinuirani punostijeni nosač s lučnim ojačanjima. Mostovi u željezničkom sustavu propisani su Uputom o postupku kategorizacije nosivosti postojećih metalnih i betonskih željezničkih mostova (Uputa HŽI-326) koja daje smjernice za realno ocjenjivanje nosivosti metalnih i betonskih željezničkih mostova, čime se osigurava sigurno korištenje Hendrixovog mosta u okviru pružnog donjeg ustroja, i Pravilnikom o tehničkim specifikacijama i uvjetima za pružni donji ustroj željezničkih pruga kao dijela građevinskog infrastrukturnog podsustava (Pravilnik HŽI-315).

Neslužbeni naziv „Hendrixov most“ nastao je zbog grafita legendarnog gitarista Jimi Hendrixa, koji je postao prepoznatljiv gradski simbol. Most privlači ljude na kulturne i sportske aktivnosti, ali i rizična ponašanja poput hodanja po konstrukciji izvan sigurnosnih zona. Zbog toga je kombinacija estetske privlačnosti i sigurnosnih izazova stalna tema u upravljanju prometom i zaštiti pješaka.

Slika 9. Hendrix kao motiv

3.1 Kuća slavnog Hendrixa

Hendrixov most, osim po svojoj ljepoti, dugi niz godina privlači pažnju i zbog grafita „Hendrix“ koji potječe iz 1980-ih. Legendarni gitarist Jimi Hendrix ostavio je značajan glazbeni trag, ali i niz inspirativnih izjava, koje su poslužile kao motiv za primjenu metode *Kuća slavnih* (Korkut, Kopal, 2018). Metoda Kuća slavnih temelji se na traženju savjeta i inspiracije od uspješnih osoba kroz tri koraka:

1. Napraviti popis najdražih citata i koristiti ih nasumično.
2. Nabaviti knjigu citata ili izraditi vlastitu „Kuću slavnih“.
3. Birati citate koji se mogu povezati s konkretnim izazovom.

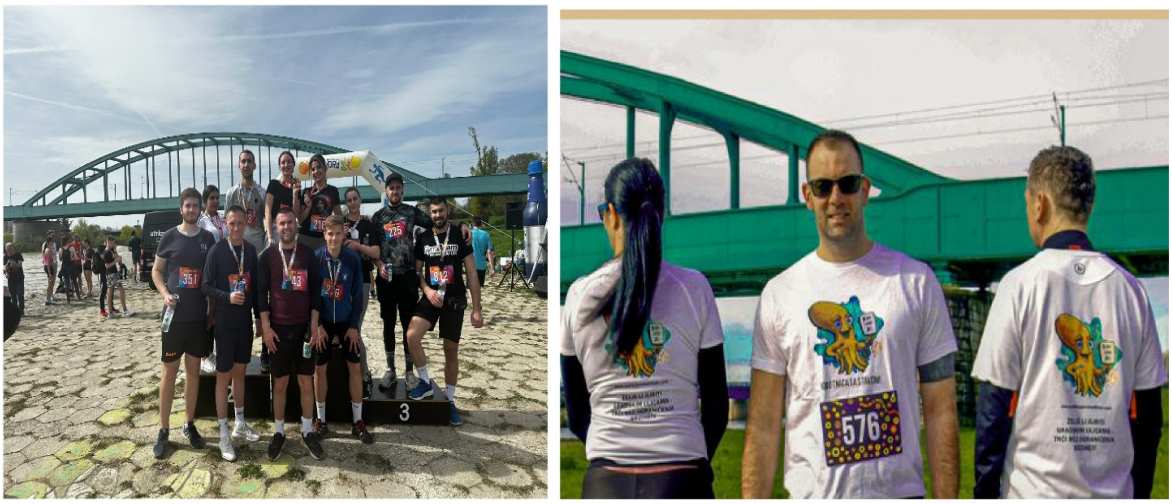
Slika 10. Edukativna kartica Kuća slavnog Hendrixa

Na temelju ovih citata izrađene su privlačne i edukativne kartice, koje se mogu primijeniti u svakodnevnom radu i učenju, potičući kreativnost i motivaciju.

3.2 Hendrix Half

Ispod Hendrixova mosta svake godine se održava utrka Hendrix Half, koja uključuje dvije discipline: 5 km i polumaraton, po kojem utrka i nosi ime. Na izdanju utrke 2023. godine sudjelovali su i studenti studija Menadžment poslovne sigurnosti s Libertas međunarodnog sveučilišta. Osim što je utrka aktivnost korisna za zdravlje, studenti su kroz sudjelovanje imali priliku promatrati i razumjeti aktivne sudionike u prometu, prepoznajući ih kao rizične skupine u prometnom okruženju.

Slika 11. Studenti i „Hobotnica sa stavom“ na Hendrix Halfu 2023.



Utrka Hendrix Half bila je dio cjelogodišnjeg projekta „Diši“ koji provodi safety.guru INSTITUT. Tijekom projekta sudjelovalo se na više od 40 utrka, pri čemu je za svaku utrku obrađena po jedna priča iz prometa, a posebna pažnja posvećivala se i lokaciji na kojoj se utrka održavala. Takav pristup omogućava sudionicima ne samo tjelesnu aktivnost, već i edukaciju o sigurnosti prometa u kontekstu stvarnih mjesta i situacija.

Koliko je sigurnost života i zdravlja povezana u sportu i prometu, dobro pokazuje primjer Split Marathon 2026. Na 26. izdanju sudjelovalo je 4.500 natjecatelja iz 65 zemalja, a program je započeo već u petak edukativnim predavanjima o pravilnom treniranju i očuvanju zdravlja sportaša. Organizator Kristijan Sindik detaljno je predstavio staze, naglasio atrakcije uz koje natjecatelji prolaze, ali i upozorio na kritične točke svake dionice. Sama utrka obuhvatila je pet disciplina: u subotu 2 km i 5 km, te u nedjelju 10 km, polumaraton (21,1 km) i maraton (42,2 km).

Unatoč temeljitoj pripremi, dogodila se nepredviđena situacija – naglo skretanje pod kutom od 90° s asfaltirane ceste na stari kameni pločnik koji je zbog kiše bio izrazito sklizak. Takvi primjeri jasno pokazuju koliko su prevencija, edukacija i jasna signalizacija važni u svakom sustavu – bilo u sportu ili u prometu. Dodatnu sigurnost osiguravali su stotine volontera raspoređenih duž staze, koji su pomagali natjecateljima i pravodobno ih upozoravali na potencijalno opasne dijelove trase.

Split Marathon pokazuje kako profesionalna organizacija, planiranje i upravljanje rizicima smanjuju potencijalne ozljede. Na isti se način, primjenom načela Vizije nula i Kulture pravednosti, može unaprijediti i sigurnost u prometu – jer sigurnost nije slučajnost, nego rezultat znanja, pripreme i zajedničke brige.

Slika 12. Split Marathon

4. ODGOVORNOST ZVANA SLOBODA ZA SIGURNOST (ILCAD Buenos Aires, Argentina)

Svaka sloboda ima dvije dimenzije: „od“ i „za“. Sloboda „od“ označava oslobođenje od unutarnjih nagnuća i pritisaka ega – ono što čovjeku dopušta da ne bude rob svojih impulsa. Sloboda „za“ odnosi se na sposobnost biti odgovoran – za svoje odluke, postupke i savjest. Drugim riječima, prava sloboda ljudske volje znači biti oslobođen od nagnuća, ali u isto vrijeme preuzeti odgovornost za vlastite postupke i sigurnost drugih. U kontekstu prometa i sporta, to znači da sloboda sudionika dolazi s obvezom da svojim odlukama i ponašanjem doprinosi sigurnosti svih sudionika. (Frankl, 2023)

4.1 Generiranje hipotenuze više kvadranata

Primjena smjera „slobodan za sigurnost“ u prometu temelji se na ideji da sloboda dolazi s odgovornošću i sviješću. Za ilustraciju ovog pristupa primijenjena je metoda Generiranje hipotenuze više kvadranata, koja analizira scenarije nesreća i odgovornosti u prometu. U prva tri scenarija razmatraju se sljedeće mogućnosti:

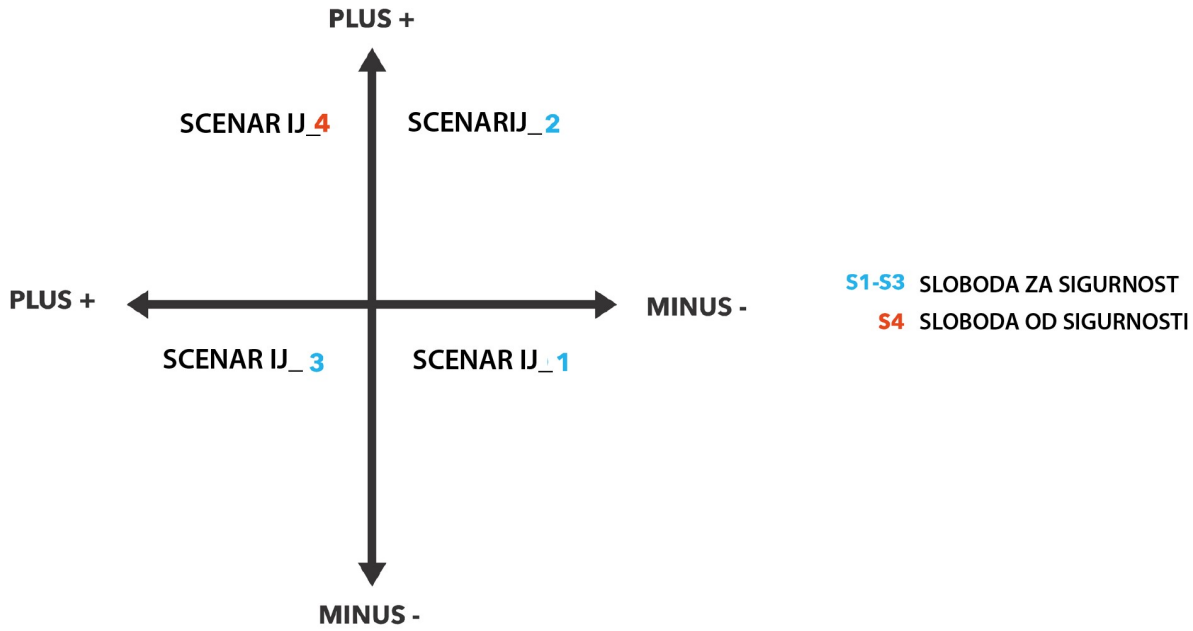
S1 – Prepoznavanje uzroka i odgovornosti: identificirani su uzroci nesreća na željezničko-cestovnim prijelazima (ŽCP-ima) i odgovornost sudionika u prometu. Statistika pokazuje 5–10 smrtnih slučajeva i do 20 teško ozlijeđenih osoba godišnje. U posljednjih 25 godina, željeznice su provele preventivno-edukativne akcije u preko 300 škola s 40.000 učenika te na preko 150 ŽCP-a s 10.000 sudionika u prometu. Unatoč uloženom trudu, napredak u smanjenju nesreća je minimalan.

S2 – Dugoročni planovi modernizacije: planira se modernizacija ŽCP-a, ali odgovornost se i dalje prebacuje na sudionike u prometu. Nesreće se i dalje događaju.

S3 – Povremene kontrole: povremene provjere ŽCP-a provodi policija, dok odgovornost ostaje na željezničkim tvrtkama. Nesreće se i dalje događaju.

Ovi scenariji pokazuju da sam trud i nadzor nisu dovoljni; potrebna je integracija preventivnog pristupa, edukacije i odgovornosti svih sudionika kako bi se postigao stvarni napredak u sigurnosti.

Slika 13. Slobodan za sigurnost

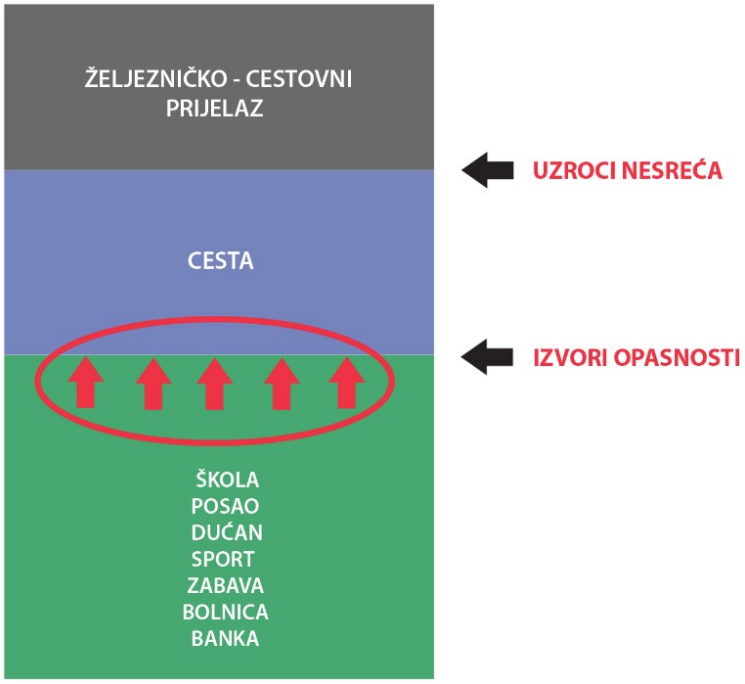


S4 – „Slobodan za sigurnost“ prepoznaje da Zakon o sigurnosti i interoperabilnosti željezničkog sustava regulira željezničko-cestovne prijelaze, ali istovremeno naglašava ulogu sudionika u cestovnom prometu koji dolaze na područje željezničke infrastrukture putem različitih tokova:

- prometni tokovi: cestovna vozila na ŽCP-ima
- pješački i biciklistički tokovi: na pješačkim prijelazima (PP) i divljim prijelazima
- pješački tokovi – neovlašteni ulazak: individualni pristup pješaka zbog atraktivnosti željezničke infrastrukture – hodanje po pruzi i avanturističke aktivnosti na infrastrukturi i vozilima.

Zbog toga je nužno prepoznati cestovni promet kao polazište istraživanja i izvor potencijalne opasnosti, što omogućuje preventivni i odgovoran pristup u dizajniranju sigurnih prometnih rješenja.

Slika 14. Cestovni promet kao izvor opasnosti na ŽCP-ima



4.2 Moja pažnja u prometu

Tijekom 2023. godine, na Veleučilištu u Rijeci održana je „Konferencija o zaštiti prava djece u prometu-gdje smo i što još moramo učiniti?“ Konferencija je važna iz dva razloga:

1. usmjerava aktivnosti iz posljedičnog djelovanja u preventivno, kroz provedbu ciljeva strategije Vizija nula, koja teži nula smrtno stradalih i teško ozlijeđenih u prometu;

2. prepoznaje djecu do 14 godina kao posebnu kategoriju sudionika u prometu s vlastitim pravima, u skladu s Konvencijom o pravima djeteta.

Konferencija je ukazala na dvije važne činjenice:

1. „Sigurnost djece u prometu“ još nije prepoznata kao posebno područje u Nacionalnom planu sigurnosti cestovnog prometa

2. Odgovornost za sigurnost djece leži na organizacijama koje planiraju i grade prometnu infrastrukturu, no te se organizacije rijetko prepoznaju među uzrocima prometnih nesreća.

S ciljem podizanja svijesti o opasnostima kojima su djeca izložena u prometu izrađen je vodič „Moja pažnja u prometu – Otkrij svijet prometa kroz igru“. Vodič je namijenjen učenicima nižih razreda osnovne škole i izravno je povezana s UNICEF-ovim programom „Djeca su naš najvažniji posao“. Nastala je iz potrebe da se prometna edukacija djece sagleda drugačije – ne kroz nametanje odgovornosti, nego kroz razumijevanje dječje perspektive. Jer djeca su – samo djeca. Na putu do škole i natrag oni su radoznali, razigrani i spontani, a sustav sigurnosti mora biti prilagođen njima, a ne obrnuto. Ovaj vodič zato otvara novo poglavlje u pristupu sigurnosti prometa. Umjesto da teret odgovornosti stavlja prvenstveno na najmlađe sudionike, potiče razvoj svijesti kroz igru, istraživanje i razumijevanje okruženja. Kroz zanimljive priče, interaktivne zadatke i razigrane ilustracije djeca otkrivaju promet na njima blizak i razumljiv način. Ne uče samo pravila – uče prepoznati skrivene izvore opasnosti koji često prethode nepravilnom ponašanju. U vremenu sve većeg broja vozila i sve manjeg prostora za slobodno kretanje i igru, sigurnost djece postaje izazov za cijelo društvo – roditelje, škole, prometne stručnjake i donositelje odluka.

Taj je izazov prepoznat i na nacionalnoj razini, a knjiga predstavlja konkretan doprinos preventivnom djelovanju. Sadržajno, knjiga obuhvaća deset poglavlja: Uvod & Hobotnica sa stavom, Sigurnost doma, Put do škole, Vozila, Šareni svijet znakova, Pravila, Sigurnost, Željeznica, Tvoja pažnja u prometu te Zaključak.

Slika 15. Knjiga „Moja pažnja u prometu“

Posebna vrijednost leži u naglašavanju povezanosti sigurnosti doma i sigurnosti u prometu, međusobne povezanosti cestovnog i željezničkog prometa te širem razumijevanju pojma sigurnosti kao zajedničke odgovornosti. Jezik i terminologija usklađeni su s važećom prometnom regulativom, ali oblikovani tako da budu jasni, pristupačni i zanimljivi djeci. Profesionalno izrađene, vedre i istraživački usmjerene ilustracije dodatno potiču aktivno sudjelovanje, čineći učenje sigurnosti prirodnim i poticajnim iskustvom.

4.3 Nastupi na konferencijama

Obrađene teme u radu usmjerene su na podizanje svijesti o važnosti ciljeva Vizije Nula te su prezentirane na domaćim konferencijama o društveno odgovornom poslovanju i održivom razvoju, kao i na međunarodnim ILCAD konferencijama posvećenima podizanju svijesti o opasnostima u željezničkom prometu.

Na konferencijama o društveno odgovornom poslovanju i održivom razvoju prezentirane su sljedeće teme:

- **Konferencija o društveno odgovornom poslovanju 2018.**: Osuvremenjivanje signalizacije na prijelazima cesta preko industrijskih kolosijeka
- **Konferencija o društveno odgovornom poslovanju 2019.**: Analiza rezultata istraživanja iskustava profesionalnih vozača na željezničko-cestovnim prijelazima
- **Konferencija o društveno odgovornom poslovanju 2020.**: „Mjerenje Zagreba” kao turističko-sportska atrakcija tijekom pandemije korona virusa
- **Konferencija o održivom razvoju 2021.**: Društveno odgovorno djelovanje u funkciji smanjenja broja nelegalnih (divljih) prijelaza preko željezničke pruge
- **Konferencija o održivom razvoju 2022.**: Provedba projekta „Koraci koji čine razliku“ s ciljem smanjenja nelegalnih prijelaza na području kolodvora Zagreb Borongaj
- **Konferencija o održivom razvoju 2023.: Priča o Hendrixu.**

Na međunarodnim ILCAD konferencijama (International Level Crossing Awareness Day), posvećenima podizanju svijesti o opasnostima na željezničko-cestovnim prijelazima, teme su prezentirane prema sljedećem rasporedu:

- **ILCAD 2019 (Amersfoort, Nizozemska)**: Budi profesionalni vozač
- **ILCAD 2022 (Denver, SAD)**: Hobotnica sa stavom – Kako nastaju ranjive skupine u prometu
- **ILCAD 2023 (Varšava, Poljska)**: Priča o Hendrixu
- **ILCAD 2024 (Buenos Aires, Argentina)**: Slobodni ZA sigurnost
- **ILCAD 2024 (York, Ujedinjeno Kraljevstvo)**: Prezentacija vodiča „Moja pažnja u prometu“.

4.4 Dizajniranje sigurnog sustava i kultura pravednosti

Uz Viziju Nula, u suvremenom upravljanju sigurnošću sve više dolaze do izražaja koncepti dizajniranja sigurnog sustava (Safety System Design) i kulture pravednosti (Just Culture).

Dizajniranje sigurnog sustava definira se kao sveobuhvatna metodologija usmjerena na stvaranje i provedbu zaštitnih mjera, protokola i mehanizama za sprječavanje nesreća, minimiziranje rizika te zaštitu ljudskih života, imovine i okoliša. Ovo specijalizirano područje dizajna integrira principe iz inženjerstva, ergonomije, psihologije i upravljanja rizicima kako bi se razvili sustavni pristupi za sprječavanje i ublažavanje opasnosti. (Design+Encyclopedia, 2026)

Takav pristup sve se više prepoznaje i u željezničkom prometu, gdje uključuje sustavno prepoznavanje izvora opasnosti odnosno hazarda (npr. primjenom metode „Drvo hazarda“) te upravljanje sigurnosnim rizicima. Time se preventivni model djelovanja postavlja ispred tradicionalnog, reaktivnog pristupa temeljenog na analizi posljedica.

Kultura pravednosti najčešće se primjenjuje u civilnom zrakoplovstvu i zdravstvu. Postupanje s izvješćima provodi se na način da se spriječi korištenje informacija za druge svrhe osim u svrhu sigurnosti te da se na odgovarajući način zaštiti povjerljivost identiteta izvjestitelja i osoba spomenutih u izvješćima o događajima, s ciljem promicanja kulture pravednosti („Just Culture“). Kultura pravednosti podrazumijeva nekažnjavanje djelatnika na terenu ili drugih osoba za njihove postupke, propuste ili odluke koji su u skladu s njihovim iskustvom i izobrazbom, ali u kojoj se ne toleriraju krajnja nepažnja, voljne povrede i destruktivni postupci. (Hrvatska agencija za civilno zrakoplovstvo, 2026)

Kultura pravednosti prepoznaje se i u željezničkom prometu kroz Uredbu komisije (EU) 2018/762 o utvrđivanju zajedničkih sigurnosnih metoda u vezi sa zahtjevima za sustav upravljanja sigurnošću. Njome se prema vodstvu željezničkih poduzeća postavlja zahtjev za promicanjem pozitivne kulture sigurnosti, dok se kontinuirano poboljšanje sustava upravljanja sigurnošću u željezničkom prometu temelji na kontrolama, unutarnjim revizijama, preispitivanjima koje provodi uprava te učenju na nesrećama i nezgodama. (Europska komisija, 2018)

5. ZAKLJUČAK

Tradicionalni željeznički sustav naglasak stavlja na stroga pravila, unutarnju kontrolu sigurnosti i posljedične (reaktivne) aktivnosti. Takav pristup duboko je ukorijenjen u zakonima i podzakonskim aktima, radnim procesima, organizacijskoj kulturi, pa čak i u obrazovnim programima i udžbenicima. Stoga su zahtjevi za uspostavom sustava upravljanja sigurnošću temeljenog na preventivnom pristupu često teško prihvatljivi i zahtijevaju promjenu paradigme.

U radu je uspostavljena poveznica između određenih pojmova definiranih u važećim propisima, koncepta *Vision Zero* te preventivno-edukativnih aktivnosti. Analizom terminologije u propisima utvrđeno je da su pojedini pojmovi iz postojećih procesa upravljanja sigurnošću nestali, neki se koriste neujednačeno ili se različito interpretiraju, dok određeni pojmovi nisu jasno definirani. Takva situacija omogućuje različita tumačenja pravila i otežava dosljednu primjenu sigurnosnih mjera. Također, u važećim zakonskim i podzakonskim aktima ne spominju se koncepti poput *Vision Zero*, Dizajniranja sigurnog sustava (*Safe System Design*) ili Kulture pravednosti (*Just Culture*).

Posvećenost postizanju ciljeva *Vision Zero* zahtijeva promjenu pristupa kod donositelja odluka odgovornih za sigurnost prometa. To podrazumijeva preuzimanje aktivne odgovornosti za oblikovanje sustavnih sigurnosnih rješenja koja će minimizirati mogućnost pogreške sudionika u prometu te ublažiti posljedice kada do pogreške dođe. Osim teorijskog i normativnog znanja, nužno je kontinuirano terensko djelovanje, izravna prisutnost među sudionicima u prometu te praćenje njihovih navika i obrazaca ponašanja.

U radu je prikazan pregled projektnih aktivnosti usmjerenih na aktivne sudionike u prometu, osobito ranjive skupine, s ciljem predstavljanja različitih modela komunikacije i suradnje u kreiranju sigurnijih rješenja. Također je izrađen pregled konferencija na kojima su te aktivnosti predstavljene, kako bi se istaknula važnost podizanja svijesti među donositeljima odluka o njihovoj proširenoj i proaktivnoj ulozi u sustavu upravljanja sigurnošću.

Menadžeri sigurnosti, kao nositelji poslovne sigurnosti, dužni su provesti analizu postojećeg stanja radi dijagnosticiranja učinkovitosti aktualnog sustava upravljanja sigurnošću. Slijedeći ciljeve *Vision Zero*, potrebno je definirati odgovarajuće „prometne terapije“, odnosno skup strateških i operativnih mjera, kako bi se do 2050. godine ostvario cilj nula smrtno stradalih i teško ozlijeđenih u prometu.

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Review

THE ROLE OF SAFETY MANAGERS IN IMPLEMENTING THE GOALS OF "VISION ZERO"

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SUMMARY

Railway traffic safety management has traditionally been regulated through a legally prescribed system. However, the implementation of a preventive Safety Management System (SMS) has shifted responsibility toward proactive risk management and increased the accountability of decision-makers. Despite established control mechanisms, most serious railway accidents occur due to the actions of third parties — primarily road users at railway-road crossings and other contact points between railway and road infrastructure. Achieving the goals of Vision Zero requires safety managers to move beyond traditional system supervision and actively engage with traffic participants, particularly vulnerable groups. Understanding behavioural patterns of third parties is essential for designing targeted preventive measures that reduce the likelihood of human error and its severe consequences.This paper presents practical project activities aimed at improving safe traffic flow at high-risk railway-road crossings, intersections with industrial sidings, locations affected by trespassing, and railway bridges where unsafe behaviour has been identified. The paper introduces the concept "Free FOR Safety" as a proactive and field-oriented approach that integrates behavioural insight, risk assessment, and stakeholder cooperation. The presented approach contributes to the development of a more dynamic and preventive traffic safety management model aligned with Vision Zero principles.

Keywords*: safe traffic flow, vulnerable groups, business security management, safety management system*

Review

INCREASING STUDENT SAFETY IN SCHOOL ZONES

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ABSTRACT

Children are extremely vulnerable in traffic due to their physical, cognitive, and social limitations compared to adults. Their short stature hinders their ability to perceive traffic situations and makes them less visible to drivers. It is crucial to change the mindset to ensure that roads not only serve their purpose but also provide safety for everyone, including children, pedestrians, cyclists, and motorcyclists. Research focuses on traffic signs and signals in school zones to mitigate risks and safeguard children. Analyzing data on sign presence across Croatia will assess their effectiveness and visibility. Challenges such as insufficient signage, poor environmental management, and inappropriate speed on Croatian roads must be addressed to improve children's safety. In addition to the analysis, the article also provides suggestions for increasing security in school zones. Traffic safety education is critical, along with adopting legislative measures and pilot projects for child-friendly school routes.

***Key words**: traffic safety, school children's safety, road infrastructure*

1. INTRODUCTION

Road safety presents a multidimensional issue involving technological, behavioral, sociological, and value-based dimensions. Despite causing more fatalities than HIV/AIDS or many other diseases, road safety still lacks the necessary attention. According to PAHO (2022), more than half of all traffic fatalities involve vulnerable road users: pedestrians, cyclists, and motorcyclists. Due to their physical, cognitive, and social limitations, children are particularly vulnerable in traffic compared to adults. Their short stature makes it harder for them to perceive traffic situations, and they are less visible to drivers and other road users. Additionally, their softer head structure makes them more susceptible to serious head injuries in accidents compared to adults. Younger children may also struggle with interpreting images and sounds, affecting their ability to judge distances, directions, and vehicle speeds. Their impulsiveness and limited attention span further increase the risk of traffic accidents.

Child road safety is compromised not only by their behaviour but also due to driver negligence, often speeding near schools, disregarding traffic laws, or driving under the influence of alcohol. Besides physical injuries and disabilities resulting from accidents, road safety significantly impacts broader public health issues. Road safety systems that fail to include safe walking areas, cycling lanes, or integration with public transport can lead to increased reliance on motor vehicles, reducing motivation for walking, cycling, or using public transport, thereby decreasing alternative transport usage. Children of all ages are susceptible

to the risks and dangers posed by traffic accidents. Every four minutes, one child loses their lives, and many others suffer severe injuries, causing immense grief and draining societal resources, including economic and healthcare aspects, by WHO (2015).

In developed countries, roads are often built without adequate integration with the communities they serve. Changing approaches is essential to ensure roads not only fulfil their purpose but also provide safety for all road users, including children and other vulnerable groups like pedestrians, cyclists, and motorcyclists.

This approach requires integrating advanced technological solutions, changing driver and pedestrian behaviours, and carefully planning urban and rural roadways to enhance safety for all road users. A holistic approach and collaboration across various sectors are crucial for achieving significant progress in reducing accidents and increasing road safety.

2. PROBLEM STATEMENT, OBJECT AND RESEARCH METHODS

Research Subject: The subject of this research is the issue of inadequate regulation and (non)marking of school zones and streets in the Republic of Croatia. The focus is on traffic signs and road equipment in front of or near educational institutions, which warn drivers of the possible presence of children. The problem lies in the lack of traffic signage, poor infrastructure, and traffic organization, which reduces the safety of school children. The aim of the research is to collect and analyse data to prove that a significant number of streets around primary schools in Croatia are not adequately regulated with traffic signs or road markings, negatively affecting children's safety.

Object of research: In collaboration with HERE and the Croatia - Safe2School campaign, the goal was to verify the correctness of speed limits around primary schools in Croatia. During the verification process, data and information were collected using Google Maps, the Croatian Roads Geoportal, and on-site inspections.

Collected Data: The data pertains to the following aspects:

- Traffic signs placed on roads near primary schools
- Road classification (state, county, local, unclassified road)
- Presence of other road equipment (speed bumps, raised surfaces, road markings)

The collected data and information are crucial for the analysis and assessment of the adequacy of regulation and marking of school zones, with the aim of improving the safety of children in traffic.

Research Methods: In this study were used scientific research methods. Part of the research was conducted in collaboration with Here Technologies, while the other part was carried out using Google Maps and the Geoportal of Croatian Roads. The compilation method was applied to review existing statistical data from the Ministry of the Interior on traffic accidents, along with the use of inductive and deductive methods, the method of proving, and the counting method.

3. SCHOOL STREETS AND SCHOOL ZONES

3.1 School zones

To enhance the safety of children on roadways surrounding primary schools, the concepts of "school zones" and "school streets" have been defined. A school zone refers to the network of roads around a school where there is a high probability of children pedestrians. During specific hours, typically around the beginning and end of school sessions, these zones enforce reduced speed limits. They are often marked with traffic signs, flashing lights, road markings, and sometimes include traffic-calming measures like speed bumps (Goldenbeld et al., 2017)

School zones are crucial around primary schools because younger children may not be fully aware of traffic situations and potential dangers, increasing the risk of accidents. Implementing school zones enhances safety by lowering vehicle speeds and increasing driver awareness of children's presence. Additional measures may be necessary due to drivers not adhering to reduced speed limits, including police enforcement, widened curbs, raised pedestrian crossings, and crossings painted in distinct colors.

Factors influencing vehicle speeds in school zones include the type of school (primary or secondary), number of lanes, one-way or two-way streets, length of the school zone, presence of fences and protective bollards, and visible presence of children. An effective measure to reduce vehicle speed is installing speed indicators alongside roads. In rural areas, these devices are often linked with traffic lights that use radar to detect vehicle speeds and turn red if a driver exceeds the speed limit (50 km/h or higher), prompting them to slow down or stop.

Such measures significantly contribute to improving child safety in traffic and reducing the number of accidents.

Figure 1. School zone in Novi Sad, Serbia.

Source: P. Brlek

3.2 School streets

The School Street initiative is implemented to increase children's safety on their way to school. This measure involves closing certain streets to motorized traffic during school arrival and departure times, creating a safe environment exclusively for pedestrians and cyclists. The first example of such an initiative in Croatia was successfully implemented in collaboration with the City of Zagreb, where it was introduced in several elementary schools.

This initiative, which has already been successfully implemented in other European countries such as Italy, Belgium, and the Netherlands has shown significant positive effects in reducing traffic congestion, improving air quality, and promoting active lifestyles among students. Motor vehicles can enter the school street only with special permission, typically granted to residents or organizations within the zone, as well as emergency services providing essential assistance (Varma, 2021).

Closing the school street to motor vehicles is usually done using physical barriers such as bollards, barriers, or automatic number plate recognition (ANPR) cameras. These measures ensure that the school street is used exclusively for the safe passage of children, aiming to

reduce the risk of traffic accidents and create a peaceful environment for all participants (ETSC, 2019).

Introducing the school street as a measure to improve safety proves to be an effective way to promote a healthy and safe school environment, contributing to positive change in the local community.

3.2.1 Example of School Streets in the City of Zagreb

The School Streets initiative in Zagreb involves a program where certain streets are closed to motorized traffic during school drop-off and pick-up times. The aim of this measure is to create a safer environment for pedestrians and cyclists, especially children traveling to school.

In Zagreb, several primary schools have successfully implemented this initiative to reduce traffic congestion, improve air quality, and promote active transportation for students. Examples of such schools include "Vladimir Nazor Elementary School," "August Šenoa Elementary School," "Miroslav Krleža Elementary School," among others.

These school streets are typically marked with traffic signs and physical barriers such as stairs or temporary barriers that prevent motor vehicles from entering. Residents and emergency services providing essential assistance are usually granted special permission to enter this zone during school hours (Šimunović et al., 2018)

Zagreb schools participating in the School Streets initiative often collaborate with the City Office for Education, Culture and Sports and other relevant municipal services to ensure the safety and effectiveness of these measures.

Building on the successful implementation of the School Streets initiative, the “Greener and Safer School Streets” project took a step further by involving the school communities directly in the design process. Participatory workshops were held in three Zagreb elementary schools, Petar Zrinski Elementary School”, “Ivan Gundulić Elementary School” and “Josip Juraj Strossmayer Elementary School”, where parents and students collaboratively envisioned how their school streets could look and function.

These workshops revealed a shared recognition of the need not only for safer streets but also for more welcoming, calming, and stimulating environments. Children expressed a desire for spaces that are enjoyable and encourage movement, not just areas that protect them from traffic dangers.

Proposals for improvements covered key areas such as traffic equipment and infrastructure, alongside enhancements to the physical environment with a focus on greening and better spatial organization. Additionally, suggestions included organizing behaviors and activities, as well as integrating creative and educational content into the streetscape.

Interestingly, while children often showed a weakened emotional connection to the daily routes they take, their creative ideas reflected a strong and clear demand for positive change. This participatory approach underscores the importance of involving the community to develop school streets that are not only safer but also more engaging and supportive of children’s well-being.

3.3 Lack of legislative regulation as a fundamental issue

In developed countries across Europe, there is a notable issue of lacking legal regulations, provisions, acts, and rules that adequately govern traffic conditions around schools. Only a few European countries include specific legal provisions that precisely define how traffic should be regulated in the vicinity of educational institutions.

In Europe, the regulation of streets around educational institutions varies between different countries and is often part of national traffic safety laws or regulations.

Here are a few examples:

- Germany: In Germany, school zones (Schulzone) are defined by law and marked with special traffic signs. The speed limit in school zones is usually restricted to 30 km/h during specific hours (Kidical Mass Koln, 2025)
- France: In France, there is a similar regulation where school zones are clearly marked with traffic signals. Vehicles must reduce speed in these zones to ensure the safety of children. (Day, P., 2023)
- Italy: In Italy, school zones are defined by law and regulated by specific traffic safety regulations. These zones typically have reduced speed limits and additional precautions for drivers. (Fundaro, A. 2024)
- Spain: School zones in Spain are also regulated by law, which dictates reduced speed limits near schools during school hours. (trenty.com, 2023)
- Belgium: As mentioned earlier, Belgium has specific regulations for school streets that govern vehicle access and speed limits near schools. (trafficrules.be, 2025)
- Serbia: In Serbia, school zones are defined by law and marked with specific traffic signs. The speed limit in school zones is typically restricted to 30 km/h during specific hours, aimed at ensuring the safety of children. (Law on road traffic safety of the Republic of Serbia, 2025)

Each of these countries has its own specific laws and regulations regarding traffic regulations in school zones or streets to ensure the safety of children traveling to school. Details about these regulations can be found in national traffic safety laws or road traffic regulations.

4. ANALYSIS OF TRAFFIC SAFETY AROUND SCHOOLS IN CROATIA

Collaboration with HERE Technologies and the Croatia – Safe2School campaign provided a thorough insight and analysis of traffic conditions around Croatian educational institutions. Using Google Maps and the Geo portal of Croatian Roads, a total of 788 locations around primary schools, across the Republic of Croatia were verified. Given that, according to statistical data, the number of all primary schools is 891, this number is considered relevant for that research. (dzs.hr, 2025)

The analysis revealed that the existing traffic regulations at a significant number of these locations are inadequate, potentially compromising the safety of children during their commute to and from school. During the analysis, particular attention was given to the classification of roads, the presence of traffic signs alerting drivers to the possible presence of children, other road markings or equipment, speed limit restrictions, and whether the street is two-way or one-way. It's important to note that the analyzed streets include not only those directly in front of schools but also those in proximity that could constitute potential school zones, through which children travel on foot to educational institutions.

The results of the analysis were organized and presented in tables with graphical representations, providing a basis for further identification of areas requiring improved traffic safety measures around educational institutions in Croatia.

4.1 Research results

An analysis of traffic safety around Croatian educational institutions has been conducted, categorized by various criteria such as groups of traffic signs, road equipment, and types of roads. Table 1. illustrate the distribution of schools according to categorization of roads. The results indicate that out of 788 inspected locations, 546 are situated on unclassified roads, 67 on state roads, 108 on county roads, 51 on local roads, and 4 locations are shared between county and local roads. In this context, unclassified roads are most often city streets, where school entrances are located.

Table 1. Categorization of roads

Road category	Number of schools
Unclassified road	546
State road	67
County road	108
Local road	51
County/local road	4
Pedestrian zone	12

Source: Authors

Further analysis determined the type of streets in terms of traffic flow, specifically whether it is one-way or two-way. The results show that most locations, 675 in total, are situated on two-way streets, while 93 locations are on one-way streets.

Table 2. Street types

Street types	Number of schools
Two-way street	675
One-way street	93
Two-way/one-way street	8
Pedestrian zone	12

Source: Authors

Special attention is dedicated to speed limit signs, given their significant impact on the safety of school children. Lower speed limits directly enhance children's safety when crossing roads. However, since some drivers do not adhere to prescribed speed limits, there is a need to legislate minimum speed limits in front of educational institutions. In cases where speed limits are not clearly defined by traffic signs, there is a higher likelihood that drivers will exceed the speed limit, potentially disregarding the possibility of children crossing the road. Higher speeds increase stopping distances, thereby increasing the risk of accidents.

Analysis has revealed the following: 11 locations have a speed limit of 20 km/h, 103 locations are regulated by a speed limit sign of 30 km/h or designated as 30 km/h zones, and an additional 103 locations have a speed limit of 40 km/h. Nine locations are marked with a speed limit sign of 50 km/h, while a staggering 562 locations near schools or in front of them lack speed limit signs.

Considering that most schools are in urban areas, it is assumed that in these cases, the speed limit according to the Road Traffic Safety Law is 50 km/h. According to Road Traffic Safety Law (2024), Article 53, paragraph 1., unless a sign prescribes a different value, the speed limit in all settlements in the Republic of Croatia is 50 km/h.

Therefore, it can be concluded that in over 70% of cases, vehicle speeds are limited to 50 km/h or higher, negatively impacting the safety of children and other traffic participants.

Table 3. Speed limits

Speed limits	Number of schools
Speed limit 20 km/h	11
Speed limit 30 km/h	103
Speed limit 40 km/h	103
Speed limit 50 km/h	9
No speed limit sign	562

Source: Authors

The categorized and analyzed are other traffic signs installed along the roads near educational institutions. Most locations, 377 of them, feature the "Children on Road" sign, while the marked pedestrian crossing sign is present at 323 locations. Signs indicating road bumps are visible at 117 locations, whereas school zone signs are placed at only 29 locations. Although a good number of schools are marked with multiple signs, there are no additional traffic signs at 188 locations and data for 22 locations were unavailable on Google Maps. These results are comprehensively presented in the following table.

Table 4. Other traffic signs

Signs	Number of schools
Pedestrian crossing	323
Children on road	377
Road bumps	117
School	29
No signs	188

Source: Authors

Based on a detailed analysis conducted in school zones, various infrastructure measures have been implemented to ensure greater safety for children.

A total of 396 locations has been equipped with road markings that alert drivers to the presence of schools. In addition, vibration strips to calm traffic have been installed at 40 locations to further encourage drivers to slow down near schools. Elevated platforms or traffic-calming measures have been placed at 126 locations, physically limiting vehicle speed.

These measures are aimed at reducing the risk of traffic accidents and ensuring a safe environment for school children and pedestrians. The integration of various infrastructure solutions plays a crucial role in promoting safety in urban areas with high traffic density.

Table 5. Road equipment

Road equipment	Number of schools
Road markings	396
Rumble strips	40
Raised platforms	126

Source: Authors

5. RESEARCH CONCLUSIONS

Children must be provided with safety during their travels to and from school and other educational institutions, as well as the freedom to play and explore their surroundings. Traffic safety is becoming a critical issue due to concerns for children's personal safety, as well as changes in economic and social conditions influencing children's travel behaviors. Many parents increasingly opt to drive their children to school and other activities in private cars, perceiving children's pedestrian travel as inherently unsafe. Consequently, car travel now constitutes a significant portion of the distances children cover between the ages of 10 and 14. Restricting children's mobility may be a deliberate attempt by parents to protect them from potential dangers, but it may unintentionally limit their physical activity and social development.

Traffic safety results from a combination of traffic participant behavior and the implementation of safety measures, which can be categorized into three main groups:

- **Education** (e.g., traffic safety education in schools)
- **Engineering** (e.g., changes in road infrastructure, including vehicle safety features like seat belts)

- **Enforcement** (e.g., legal regulations, regular speed enforcement near schools)

Various factors affect traffic safety around educational institutions, including road conditions, roadside equipment, and technical characteristics of the road itself. For instance, poor road conditions such as potholes or inadequate signage can impact vehicle speeds and increase the risk of accidents, especially in areas with children present. Analysis has shown deficiencies in additional traffic signage at many locations near schools in Croatia, as well as a lack of physical barriers such as protective fences that could enhance children's safety in traffic. Technical aspects of roads, such as lane width and the presence of edge markings, also play a crucial role in traffic safety, influencing vehicle speeds and improving visibility and safety for road users, particularly in low visibility conditions like nighttime or fog. (Ptiček, L., 2023)

Ensuring children's safety in traffic requires fundamental changes in approaches to make roads safer for all users, especially children and other vulnerable participants such as pedestrians, cyclists, and motorcyclists. Analysis of relevant factors underscores the need for greater attention and care for children's safety, particularly in proximity to elementary schools. Children are often exposed to risks during their journeys to and from school, reacting impulsively due to their playfulness and quick mobility on the road. Therefore, one of the major traffic concerns is the safety of children in school zones.

The times of arrival and departure from school often coincide with peak traffic, resulting in very busy roads directly adjacent to schools. This intense mix of vehicles, pedestrians, and cyclists causes congestion and often leads to frustration among drivers and residents, exacerbating traffic chaos caused by parents and children during school commutes. Frustrated drivers pose an additional threat to children near schools, as their unpredictable reactions can lead to reckless driving, potentially causing serious consequences for children.

Issues identified on Croatian roads include a lack of traffic signage, poor environmental design, insufficient road markings, and inappropriate vehicle speeds. Addressing or mitigating these issues and improving children's safety necessitates implementing a series of measures and infrastructure improvements. In addition to physical changes, it is crucial to increase police traffic surveillance, especially in school zones, and penalize drivers who do not adhere to speed limits.

Improving pedestrian and cycling infrastructure would also significantly contribute to children's safety and encourage sustainable transportation from an early age, positively impacting their physical and mental health, as well as reducing traffic congestion during morning and afternoon peaks when fewer parents drive their children to school.

Furthermore, enacting laws that regulate school zones and streets, similar to practices in other European countries, would enhance road safety. Implementing pilot projects and programs in Croatia focusing on children's safety and marking safe school routes would be a step forward. These measures validate the main hypothesis of this study, suggesting that organizing traffic around educational institutions would significantly enhance the safety of children and other traffic participants.

In smaller communities interconnected with each other, it is important to involve children and parents in projects promoting safety and responsible behavior in traffic. The second hypothesis of this study, regarding factors influencing traffic safety and awareness among parents and drivers, is also partially confirmed. Therefore, regular workshops and age-appropriate education would be highly beneficial to instill traffic culture in children from a young age and promote responsible behavior in traffic. In addition to lectures, children should be involved in projects, as in other countries, which allow them to develop good traffic habits from a young age and feel like active members of the community who contribute to not only their own safety, but also that of others.

This conclusion can be further structured:

5.1 Education (e.g., traffic safety education in schools)

One of the most sustainable long-term solutions for improving children's safety in traffic is the introduction of structured and continuous traffic safety education from an early age. Currently, traffic safety education within the Croatian educational system is implemented in a fragmented and sporadic manner, often depending on individual practices and initiatives rather than a structured system-wide approach. Traffic workshops, preventive school activities, and projects have been introduced in recent years to strengthen the continuity and quality of traffic safety education for children and to support the development of a sustainable traffic safety culture.

A key step toward systematization has been the introduction of school-level coordinators responsible for organizing preventive activities and supporting teachers in delivering traffic-related content.

In parallel, efforts are underway to move from isolated educational activities toward a more sustainable and structured approach through planned curriculum updates. Proposed changes to the Technology Education curriculum for grades 5 and 6 aim to embed essential traffic safety knowledge into the educational system, marking an important step toward continuous and structured traffic safety education for children.

These developments indicate a shift from scattered initiatives toward a coordinated model based on educator training and curriculum integration, representing an important foundation for long-term improvement in children's traffic safety education.

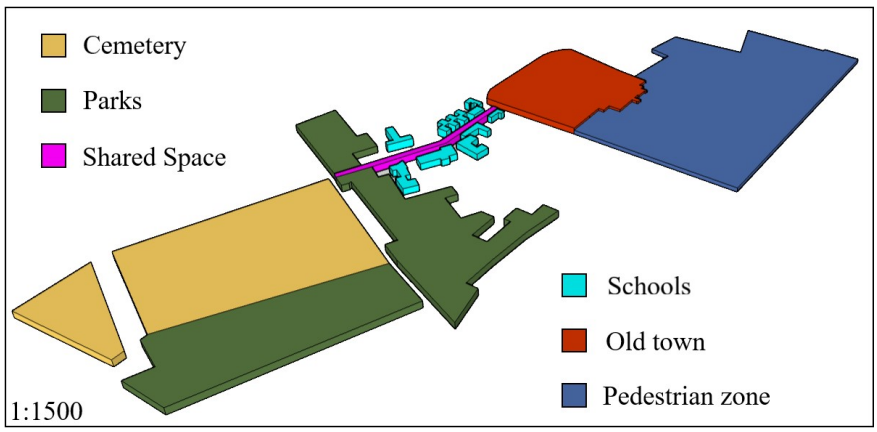
5.2 Engineering (e.g., changes in road infrastructure)

The research confirmed that properly designed traffic environments naturally encourage safer movement and reduce risk without relying solely on enforcement.

Examples of good practice can already be observed locally.

In Varaždin, the consideration of the shared space concept represents a promising example of how urban design could fundamentally reshape the relationship between road users. Using traffic calming measures such as textured surfaces, raised pedestrian crossings, visual differentiation of space and reduced traffic dominance, the street itself can become a regulatory element. Instead of relying exclusively on traffic signs or enforcement, infrastructure design can encourage lower speeds and greater driver awareness, and create an environment in which pedestrians, including children, are prioritized and motor vehicles become guests rather than dominant users of public space. Such solutions can be particularly effective in areas with high pedestrian activity, where the quality of public space must be preserved alongside necessary traffic flow.

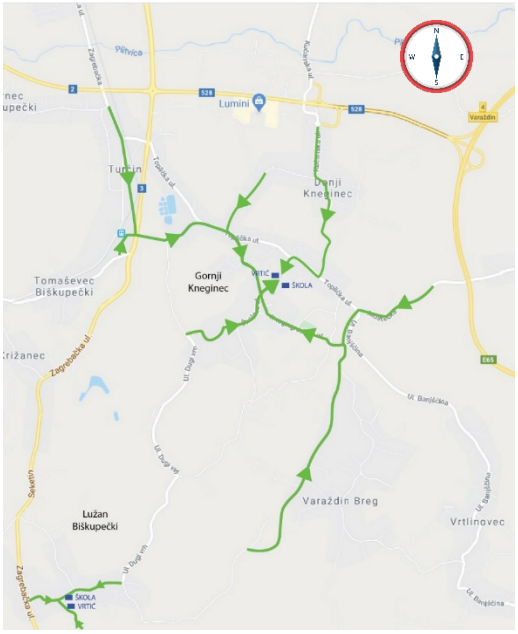
Figure 2. Connecting parts of pedestrian areas using Shared space in Varaždin



Source: (Cvitkovic, I. et al, 2022)

Similarly, in Gornji Kneginec, a more targeted infrastructure-based approach has been implemented through the identification and mapping of safe routes for children traveling to school and kindergarten. By analyzing traffic conditions, parental attitudes and mobility patterns, the municipality introduced practical measures aimed at reducing dependence on car transport while increasing children's independent mobility. These include the designation of safe walking routes, implementation of the “Kiss & Ride” drop-off system to reduce congestion near school entrances, and the introduction of organized walking groups such as the “Pedibus”. Such measures not only improve traffic safety but also contribute to children’s autonomy and promote active travel habits.

Figure 3. Traffic map with a mapped safe route to school and preschool facilities in the Municipality of Kneginec Gornji



Source: (Brlek, P. at al, 2025)

Together, these examples demonstrate that both urban design solutions and smaller-scale infrastructure interventions can significantly improve safety when strategically implemented. Whether through spatial reorganization that reduces vehicle dominance or through clearly defined and supported safe routes to school, engineering measures can create environments that proactively support safe behavior rather than relying solely on corrective enforcement.

5.3 Enforcement (e.g., legal regulations and speed control)

Currently, Croatian traffic laws do not provide a legal framework that supports the implementation of safer practices and solutions for children’s movement, such as formally regulated school zones and child-friendly street designs, despite ongoing efforts to promote traffic safety.

This research highlights the need to establish legally defined school zones around all educational institutions, including mandatory traffic signage and a maximum speed limit of 30 km/h, which is proven to reduce both the likelihood and severity of child injuries. In addition, temporary restrictions on vehicle access during peak school arrival and departure times, like the “school street” concept used in other European countries, could create safer environments for children and encourage walking or cycling.

Enforcement measures should also include increased police presence, automated speed monitoring, and stricter penalties for violations within these zones. Introducing such regulations would create a standardized national framework, significantly improving safety for

children and other vulnerable road users. Standardization is particularly important because individual local initiatives cannot guarantee consistent protection across all schools and municipalities.

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Pregledni rad

POVEĆANJE SIGURNOSTI UČENIKA U ZONAMA ŠKOLA

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SAŽETAK

Djeca u prometu su posebno ranjiva skupina zbog svojih fizičkih, kognitivnih i socijalnih ograničenja u odnosu na odrasle. Njihova niža visina otežava im pravodobno uočavanje prometnih situacija, dok ih istodobno čini slabije vidljivima vozačima, što dodatno povećava rizik od stradavanja. Stoga je nužno promijeniti pristup planiranju i upravljanju prometnim sustavom. Prometnice ne smiju biti oblikovane isključivo prema funkciji protočnosti, već moraju omogućiti sigurnost svih sudionika, osobito najranjivijih poput djece, pješaka, biciklista i motociklista. Ovaj rad problematizira ulogu prometne signalizacije u zonama škola kao jednog od ključnih alata za smanjenje rizika i povećanje sigurnosti djece u prometu. Istraživanje ukazuje na niz izazova, uključujući nedostatnu signalizaciju, neadekvatno uređenje prometnog okruženja te neprilagođene brzine kretanja vozila, koje je potrebno sustavno rješavati kako bi se unaprijedila sigurnost djece. Uz analitički dio, rad predlaže i konkretne mjere za povećanje sigurnosti u zonama škola. Poseban naglasak stavlja se na važnost kontinuirane prometne edukacije, ali i na potrebu za zakonodavnim rješenjima te provedbom pilot-projekata usmjerenih na razvoj sigurnih i djeci prilagođenih školskih ruta.

Ključne riječi: *sigurnost prometa, sigurnost školske djece, cestovna infrastruktura*

Stručni rad

GRAĐEVINSKE MJERE ZAŠTITE GRAĐANA I OBJEKATA PRI TRANSPORTU OPASNIH TVARI U URBANIM SREDINAMA

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SAŽETAK

Suvremeni transport opasnih tvari željezničkim i cestovnim prometnicama predstavlja neizbježan segment gospodarstva, ali istovremeno generira značajne rizike za stanovništvo i materijalna dobra, posebice u gusto naseljenim urbanim područjima. Iako je prijevoz reguliran strogim međunarodnim (RID, ADR) i nacionalnim propisima, povijest nesreća ukazuje na nedostatnost isključivo organizacijskih i tehničkih mjera na samim prijevoznim sredstvima. Ovaj rad analizira nužnost implementacije fiksnih građevinskih mjera zaštite kao primarne barijere u smanjenju rizika. Fokus istraživanja je na kritičnim dionicama gdje prometnice prolaze u neposrednoj blizini stambenih objekata (manje od 50 metara). Kroz analizu specifičnih opasnih tvari poput LNG-a, klora i amonijaka, te pregled međunarodnih praksi (Švicarska, SAD, Nizozemska), rad predlaže konkretna građevinska rješenja poput protueksplozijskih zidova, tankvana i zaštitnih galerija. Zaključno se kritički preispituje primjena ALARP principa u kontekstu javne sigurnosti.

Ključne riječi: *građevinske mjere zaštite, transport opasnih tvari, procjena rizika, protueksplozijski zidovi, RID/ADR.*

1. UVOD

Sigurnost transporta opasnih tvari (OT) predstavlja jedan od najsloženijih izazova u sustavu civilne zaštite i prostornog planiranja. Dok su tehnički standardi za cisterne i vagone visoko razvijeni, infrastruktura kojom se taj transport odvija često datira iz razdoblja kada su volumen prometa i gustoća naseljenosti bili znatno manji. U Republici Hrvatskoj, a posebno na području grada Rijeke, željezničke pruge prolaze kroz samo središte grada, često na udaljenosti manjoj od 10 metara od stambenih zgrada, škola i vrtića.

Cilj ovog rada je ukazati na važnost građevinskih mjera zaštite koje se, prema hijerarhiji sigurnosti, moraju smatrati prioritetnima. Hipoteza rada postavlja tezu da trenutna razina zaštite građana uz kritične prometne dionice nije adekvatna te da se sigurnost ne može temeljiti isključivo na procedurama i kriznom planiranju, već zahtijeva fizičke barijere i infrastrukturne zahvate.

2. ZAKONSKI OKVIR I STANDARDI

Prijevoz opasnih tvari u Republici Hrvatskoj reguliran je nizom zakona i međunarodnih sporazuma:

Zakon o prijevozu opasnih tvari (NN 79/07, 70/17): Temeljni akt koji definira uvjete transporta.

RID (Pravilnik o međunarodnom prijevozu opasnih tvari željeznicom): Definira klasifikaciju, pakiranje i označavanje tvari.

ADR (Europski sporazum o međunarodnom cestovnom prijevozu opasnih tvari): Analogni propis za cestovni promet.

Zakon o zaštiti od požara (NN 92/10, 114/22): Propisuje mjere zaštite objekata od toplinskog zračenja i požara.

Unatoč ovim propisima, postoji pravna praznina u pogledu obveze izgradnje zaštitnih građevina uz postojeće pruge koje prolaze kroz naselja, što ostavlja građane u zoni visokog rizika bez adekvatne fizičke zaštite.

3. ANALIZA RIZIKA I SPECIFIČNOSTI OPASNIH TVARI

Rizik pri transportu OT definira se kao umnožak vjerojatnosti nastanka nesreće i težine njezinih posljedica. U urbanim sredinama, posljedice su potencijalno katastrofalne zbog visoke koncentracije ljudi.

3.1. Kritične tvari i zone utjecaja

U tablici 1. prikazani su parametri najopasnijih tvari koje se redovito transportiraju kroz urbana područja:

Tablica 1. Parametri najopasnijih tvari koje se redovito transportiraju kroz urbana područja

Teret	Glavna opasnost	Domet fatalne zone	Karakteristike širenja
LNG / benzin	Eksplozija (BLEVE) / požar	350 m	Trenutni toplinski udar i udarni val.
Klor	Toksično gušenje	> 2.500 m	Žuto-zeleni oblak, teži od zraka, zadržava se pri tlu.
Amonijak	Kemijske opekline / eksplozija	600 m	Oštar miris, nagriza sluznicu, topljiv u vodi.

Izvor: autorova obrada

3.2. Povijesni kontekst i incidenti

Na riječkom području u posljednjih 20 godina zabilježeno je nekoliko značajnih željezničkih nesreća (2009., 2022., 2023.).

Slika 1. Željeznička nesreća teretnog vlaka u Rijeci

Iako u nijednom od navedenih slučajeva nije došlo do masovnog istjecanja najopasnijih tvari, lokacije nesreća (blizina škola i stambenih zona) ukazuju na to da je izbjegavanje katastrofe bilo rezultat sreće, a ne sustavne građevinske zaštite.

4. GRAĐEVINSKE MJERE ZAŠTITE

Građevinske mjere predstavljaju pasivnu zaštitu koja djeluje neovisno o ljudskom faktoru u trenutku nesreće. Na slici 2 je vidljivo da su takve mjere izostale.

Slika 2. Potencijalno mjesto nesreće

Izvor: Autor

4.1. Protueksplozijski i protupožarni zidovi (Blast Walls)

Ovi zidovi su dizajnirani da apsorbiraju i reflektiraju udarni val te blokiraju izravno toplinsko zračenje.

Materijal: Armirani beton visoke čvrstoće.

Geometrija: Zidovi bi trebali biti visoki minimalno 5 metara, s gornjim rubom zakrivljenim prema izvoru opasnosti kako bi se usmjerio plinski oblak ili udarni val prema gore, dalje od zgrada.

Funkcija: Sprječavanje paljenja fasada i pucanja stakala na obližnjim objektima.

4.2. Sustavi za zadržavanje istjecanja (Tankvane)

Kod transporta tekućih OT, ključno je spriječiti nekontrolirano razlijevanje tvari prema nižim kotama terena.

Izvedba: Betonski kanali ili bazeni s obje strane pruge.

Kapacitet: Projektirani da prihvate sadržaj barem jedne cijele cisterne (cca 50-80 m^3).

Zaštita okoliša: Sprječavaju prodiranje tvari u podzemne vode i kanalizacijski sustav.

4.3. Zaštitne galerije i tuneli

Za najkritičnije dionice, jedino potpuno sigurno rješenje je izolacija transporta.

Galerije: Betonske nadstrešnice koje štite od toplinskog udara i usmjeravaju eventualnu eksploziju uzdužno, štiteći objekte iznad ili neposredno uz prugu.

Tuneli: Izgradnja namjenskih teretnih tunela koji zaobilaze gradska središta (npr. predloženi tunel od luke do zaleđa Rijeke).

4.4. Mjere na stambenim objektima

U zonama gdje nije moguće intervenirati na samoj prometnici, zaštita se mora provesti na zgradama:

Orijentacija: Ulazi i evakuacijski putevi moraju biti na strani suprotnoj od pruge.

Stolarija: Ugradnja protupožarnih i dimotijesnih prozora s laminiranim staklima otpornim na pritisak.

5. MEĐUNARODNA ISKUSTVA I PRIMJERI DOBRE PRAKSE

Usporedba s razvijenim zemljama pokazuje da su građevinske mjere standard, a ne iznimka:

Švicarska: Korištenje betonskih galerija u uskim dolinama i naseljenim mjestima (Lötschberg i Gotthard dionice).

SAD i Kanada: Implementacija masivnih "Blast Walls" zidova nakon nesreće u Lac-Mégantic, posebno uz osjetljive objekte poput bolnica.

Nizozemska: Projekt "Betuweroute" – namjenska teretna pruga izgrađena u betonskim rovovima i iza visokih nasipa koji služe kao prirodni apsorberi udarnog vala.

6. DISKUSIJA I KRITIČKI OSVRT NA ALARP PRINCIP

U procjenama rizika često se koristi ALARP princip (As Low As Reasonably Practicable), koji sugerira da se dodatne mjere sigurnosti ne moraju provoditi ako su troškovi njihove implementacije nerazmjerni smanjenju rizika. Autor smatra da je ovakav pristup u kontekstu zaštite ljudskih života u urbanim sredinama etički i stručno upitan. Ekonomski parametri ne smiju biti ispred prava građana na sigurnost, pogotovo kada se radi o rizicima od katastrofa s potencijalno velikim brojem žrtava.

7. ZAKLJUČAK

Analiza trenutnog stanja transporta opasnih tvari kroz urbane sredine ukazuje na kritičnu potrebu za redefiniranjem prioriteta u zaštiti i spašavanju. Građevinske mjere zaštite – od protueksplozijskih zidova do namjenskih tunela – ne smiju se promatrati kao opcionalni trošak, već kao integralni dio prometne infrastrukture.

Predlaže se: hitna izrada detaljne procjene rizika za svaku dionicu pruge u naseljenim mjestima, obvezna ugradnja "tankvana" i zaštitnih zidova na svim mjestima gdje je udaljenost od stambenih zgrada manja od 50 metara te dugoročno planiranje izmještanja transporta opasnih tvari u namjenske tunele ili obilaznice.

LITERATURA

Zakon o prijevozu opasnih tvari, Narodne novine br. 79/07, 70/17.

RID - Pravilnik o međunarodnom prijevozu opasnih tvari željeznicom, Dodatak C Konvencije o međunarodnom željezničkom prijevozu (COTIF).

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Professional paper

CONSTRUCTION-BASED PROTECTIVE MEASURES FOR THE SAFETY OF CITIZENS AND BUILDINGS DURING THE TRANSPORT OF DANGEROUS GOODS IN URBAN AREAS

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ABSTRACT
The contemporary transport of dangerous goods by rail and road represents an inevitable segment of the economy, but at the same time it generates significant risks for the population and material assets, especially in densely populated urban areas. Although such transport is regulated by strict international (RID, ADR) and national regulations, the history of accidents points to the insufficiency of relying solely on organisational and technical measures applied to the vehicles themselves. This paper analyses the necessity of implementing fixed construction-based protective measures as a primary barrier in risk reduction. The research focuses on critical sections where transport routes pass in the immediate vicinity of residential buildings (less than 50 metres). Through an analysis of specific dangerous substances such as LNG, chlorine and ammonia, as well as a review of international practices (Switzerland, the USA and the Netherlands), the paper proposes specific construction solutions such as blast walls, containment bunds and protective galleries. Finally, the application of the ALARP principle is critically reconsidered in the context of public safety.

Key words: *construction-based protective measures, transport of dangerous goods, risk assessment, blast walls, RID/ADR.*

Stručni rad

SIGURNOSNI ASPEKTI UPOTREBE ELEKTRIČNIH ROMOBILA U PROMETU

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SAŽETAK

Svrha rada jest analizirati sigurnosne aspekte upotrebe električnih romobila u prometu, s posebnim naglaskom na zakonski okvir u Republici Hrvatskoj, trendove prometnih nesreća te stavove i navike korisnika. U radu je primijenjen kombinirani pristup koji uključuje analizu važećih propisa, pregled relevantne domaće i inozemne literature, interpretaciju dostupnih statističkih pokazatelja te obradu rezultata anketnog istraživanja provedenog među 219 ispitanika. Rezultati upućuju na to da porast popularnosti električnih romobila nije bio praćen jednakom razinom razvoja infrastrukture, edukacije korisnika i provedbe propisa. Posebno se izdvajaju nedovoljno poznavanje prometnih pravila, niska učestalost uporabe zaštitne opreme i izražena percepcija nesigurnosti u prometu. Doprinos rada očituje se u povezivanju normativnih, statističkih i empirijskih pokazatelja radi oblikovanja preporuka za sigurniju i održiviju integraciju električnih romobila u urbani prometni sustav.

Ključne riječi: *električni romobili, sigurnost u prometu, prometni propisi, zaštitna oprema, urbana mobilnost*

1. UVOD

Razvoj mikromobilnosti posljednjih godina značajno je promijenio strukturu urbanog prometa, a električni romobili postali su jedan od najzastupljenijih oblika individualnog prijevoza u gradovima. Njihova dostupnost, jednostavnost upotrebe i ekološke prednosti pridonijele su ubrzanom porastu broja korisnika, ali su istodobno otvorile brojna pitanja vezana za sigurnost, regulaciju i integraciju u postojeći prometni sustav (Ćosić, Mlinarić i Jurčević, 2020; Hollingsworth, Copeland i Johnson, 2019). S obzirom na relativnu novost električnih romobila u hrvatskom zakonodavnom okviru, bilo je nužno definirati jasna pravila njihove upotrebe. Istodobno, porast broja prometnih nesreća u kojima sudjeluju električni romobili dodatno naglašava potrebu za sustavnom analizom postojećih propisa, sigurnosnih pokazatelja i ponašanja korisnika. U ovom se radu stoga analizira zakonski okvir za upotrebu električnih romobila u Republici Hrvatskoj, prikazuju statistički podaci o prometnim nesrećama u 2024. i 2025. godini te predstavljaju rezultati anketnog istraživanja provedenog među korisnicima. Cilj je utvrđivanje ključnih sigurnosnih izazova, procjena učinkovitosti postojećih mjera te predlaganje smjernica za unaprjeđenje sigurnosti i održiv razvoj mikromobilnosti u urbanim sredinama.

2. METODOLOGIJA ISTRAŽIVANJA

U radu je primijenjen kombinirani istraživački pristup koji obuhvaća analizu normativnih izvora, pregled relevantne znanstvene i stručne literature, interpretaciju dostupnih statističkih pokazatelja prometnih nesreća te obradu rezultata anketnog istraživanja. Normativna analiza usmjerena je na važeći hrvatski zakonodavni okvir kojim se uređuje uporaba električnih romobila kao osobnih prijevoznih sredstava. Analitički dio rada temelji se na usporedbi statističkih pokazatelja za 2024. i 2025. godinu te na interpretaciji sekundarnih izvora koji upućuju na sigurnosne trendove u području mikromobilnosti. Empirijski dio obuhvaća anonimnu online anketu provedenu među 219 ispitanika mlađih od 45 godina, pri čemu su analizirane njihove prometne navike, percepcija sigurnosti, uporaba zaštitne opreme i poznavanje prometnih propisa. Takav metodološki okvir omogućio je cjelovitiji uvid u sigurnosne izazove povezane s uporabom električnih romobila.

3. ANALIZA SIGURNOSNIH ASPEKATA UPOTREBE ELEKTRIČNIH ROMOBILA

3.1. Zakonski okvir za upotrebu električnih romobila u Hrvatskoj

Električni romobili postaju nezaobilazan dio urbane mobilnosti u Hrvatskoj, no njihova integracija u prometni sustav zahtijeva jasna i usklađena pravila koja će istodobno podupirati razvoj mikromobilnosti i štititi sigurnost svih sudionika u prometu (Zakon.hr, 2022). Izmjenama Zakona o sigurnosti prometa na cestama iz srpnja 2022. godine Hrvatska je uvela specifična pravila za električne romobile i druga osobna prijevozna sredstva, čime je stvoren temelj za njihovo formalno uključivanje u prometni sustav.

Osnovna pravila za uporabu električnih romobila u Hrvatskoj obuhvaćaju minimalnu dob od 14 godina, najveću trajnu snagu motora do 0,6 kW i najveću dopuštenu brzinu do 25 km/h. Obvezna je uporaba zaštitne kacige, a u noćnim uvjetima ili uvjetima smanjene vidljivosti i reflektirajuće odjeće ili prsluka te propisane svjetlosne signalizacije. Zabranjena je vožnja pod utjecajem alkohola i uporaba slušalica koje ometaju sigurno sudjelovanje u prometu. Romobili se primarno trebaju kretati biciklističkim stazama ili trakama, a ako takva infrastruktura ne postoji, dopušteno je kretanje površinama za pješake ili u zonama smirenog prometa, uz povećan oprez. Na cestama je dopuštena vožnja samo na određenim lokalnim i županijskim prometnicama, dok je kretanje autocestama i brzim cestama zabranjeno.

3.2. Statistički pokazatelji prometnih nesreća i sigurnosni trendovi

Naglo širenje električnih romobila donijelo je nove mogućnosti urbane mobilnosti, ali i pojačanu zabrinutost za sigurnost u prometu (Chen, Sun i Li, 2020; Kazemzadeh, Haghani i Sprei, 2023). Analiza stanja u Republici Hrvatskoj tijekom 2024. i 2025. godine pokazuje nepovoljan trend: broj prometnih nesreća u kojima su sudjelovali električni romobili porastao je s 393 na 640, što upućuje na izrazit rast sigurnosnog rizika.

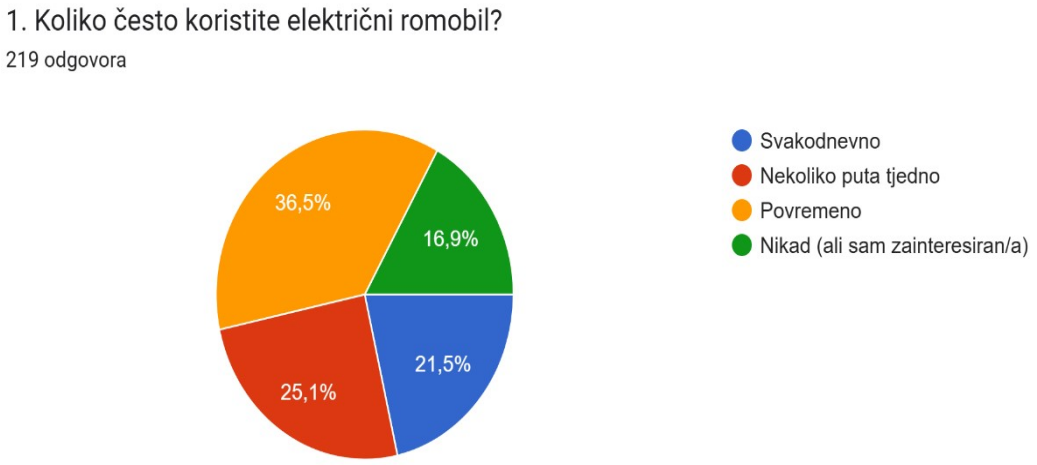
U istom razdoblju broj teško ozlijeđenih povećao se sa 127 na 206, a broj lakše ozlijeđenih s 198 na 324, dok je broj smrtno stradalih ostao nepromijenjen i iznosio je dvije osobe godišnje. Istodobno, podaci udruženja Micro-Mobility for Europe upućuju na poboljšanje sigurnosnih pokazatelja kod dijeljenih električnih romobila na europskoj razini, osobito u sredinama koje su uvele strožu regulaciju, kvalitetniju infrastrukturu i učinkovitije edukativne kampanje. To sugerira da negativni trendovi nisu nužno neizbježni, nego da ovise o kvaliteti regulacije, prometnog okruženja i ponašanja korisnika.

3.3. Rezultati anketnog istraživanja

U sklopu istraživanja provedenog putem online ankete izrađene u Google obrascima analizirani su podaci prikupljeni od ukupno 219 ispitanika u dobi do 45 godina. Cilj anketnog istraživanja bio je ispitati svakodnevne prometne navike sudionika, njihovu percepciju sigurnosti u prometu te razinu poznavanja prometnih pravila koja se odnose na električne romobile.

Istraživanje je bilo anonimno i dobrovoljno, a rezultati su prikupljani isključivo u istraživačke i edukativne svrhe, s ciljem prepoznavanja ključnih problema i oblikovanja mogućih prijedloga za unapređenje sigurnosti u prometu.

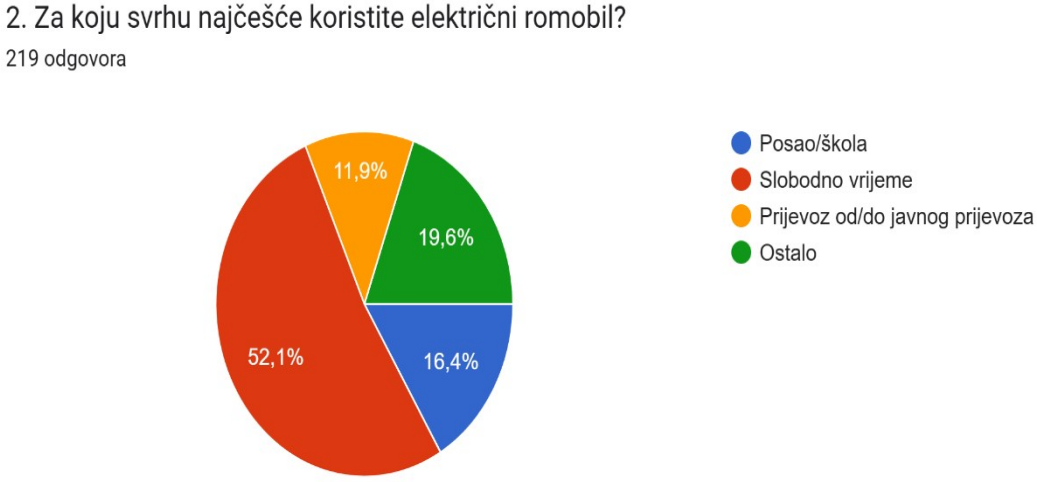
Slika 1. Učestalost upotrebe električnih romobila



Izvor: autori

Postotak ispitanika koji nikad nisu upotrebljavali električni romobil, ali su zainteresirani, otkriva potencijalno tržište koje bi, uz bolju dostupnost ili veću sigurnost, moglo povećati broj korisnika.

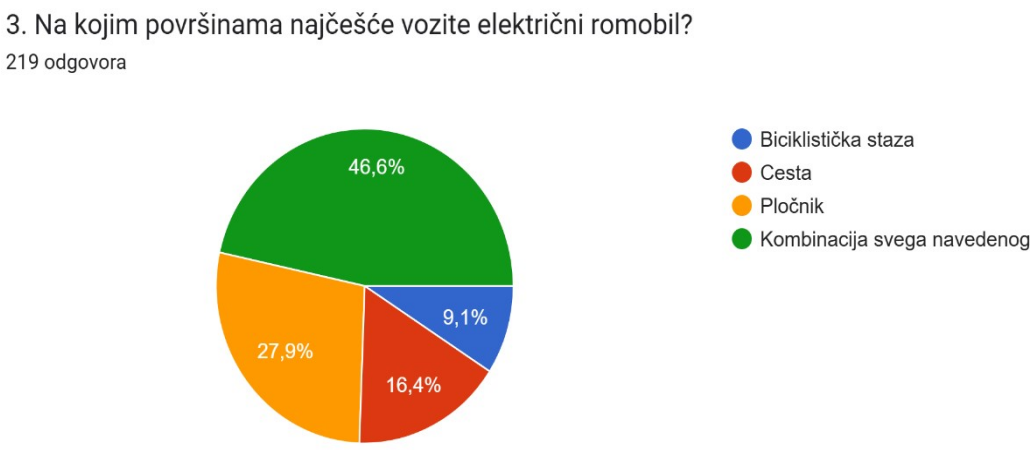
Slika 2. Svrha upotrebe električnih romobila



Izvor: autori

Najveći postotak ispitanika upotrebljava električni romobil za aktivnosti u slobodno vrijeme, što pokazuje da se romobil najviše percipira kao praktično i rekreativno prijevozno sredstvo.

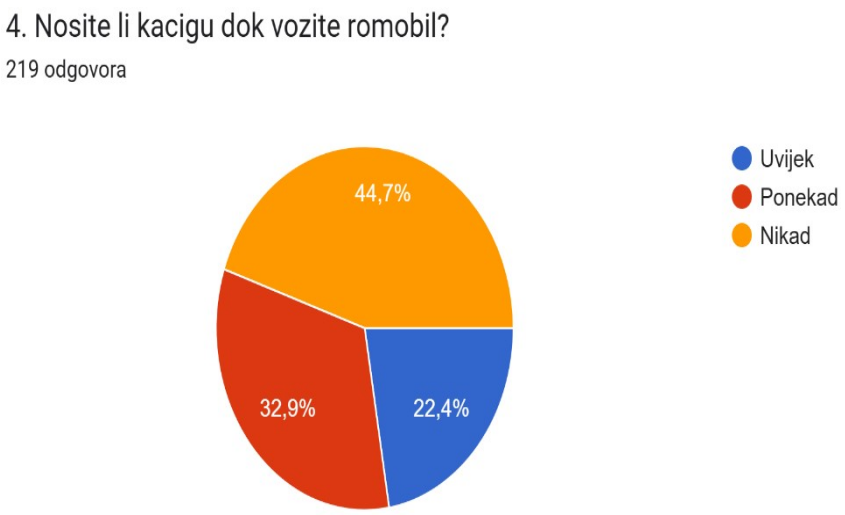
Slika 3. Upotreba površina pri vožnji električnih romobila



Izvor: autori

Najčešće odabrani odgovor „Kombinacija svega navedenog" ukazuje da korisnici električnih romobila vrlo često mijenjaju vrste površina na kojima se voze što je vjerojatno posljedica neprilagođene prometne infrastrukture koja ne omogućuje dosljednu i sigurnu vožnju na jednoj vrsti prometne površine.

Slika 4. Nošenje kacige pri vožnji električnih romobila



Izvor: autori

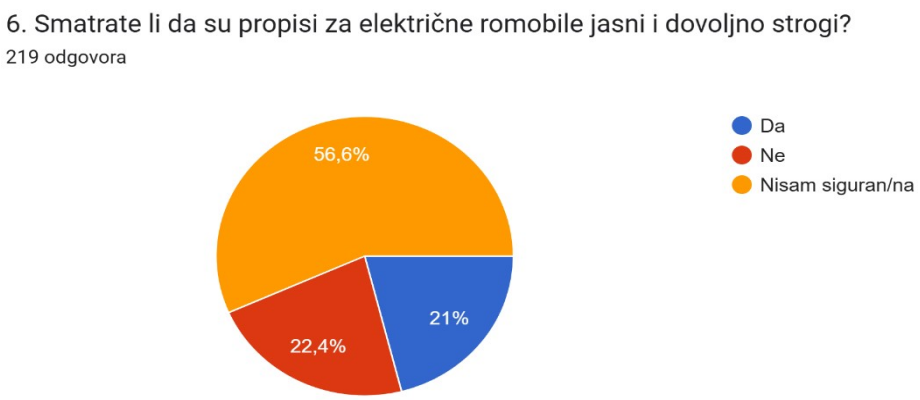
Podaci ukazuju na relativno nisku razinu sigurnosne svijesti među korisnicima električnih romobila. Dodatni problem predstavlja činjenica da korisnici često nisu sigurni kada je i u kojim uvjetima zaštitna oprema obvezna, što može negativno utjecati na njihove navike i povećati rizik težih ozljeda u slučaju nesreće.

Slika 5. Poznavanje prometnih propisa vezanih za električne romobile

Izvor: autori

Rezultati o poznavanju prometnih propisa jasno pokazuju da većina ispitanika nema potpuno i pouzdano znanje o pravilima koja se odnose na električne romobile. Takav nalaz upućuje na potrebu za sustavnijom edukacijom korisnika, dostupnijim i jasnijim informacijama o prometnim propisima te snažnijim uključivanjem osnovnih pravila mikromobilnosti u školske i vozačke programe.

Slika 6. Percepcija ispitanika o strogoći prometnih propisa

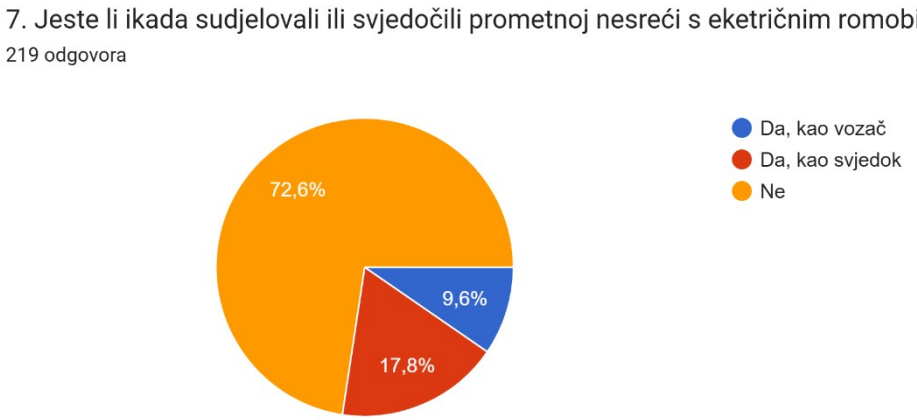


Izvor: autori

Više od polovice ispitanika ne zna procijeniti jesu li postojeći propisi dovoljno jasni i strogi, što upućuje na nedovoljnu vidljivost propisa u javnom prostoru i na nesigurnost u njihovoj praktičnoj primjeni. Zajedno s prethodnim rezultatima, ovaj nalaz pokazuje postojanje izraženog komunikacijskog jaza između normativnog okvira i stvarnog razumijevanja pravila među korisnicima.

Navedeni rezultati ukazuju na potrebu za boljom promocijom i pojašnjenjem važećih pravila, primjerice putem lokalnih samouprava, medija i ciljanih edukativnih kampanja. Ujedno otvaraju prostor za reviziju pojedinih zakonskih rješenja, osobito u pogledu zaštitne opreme, ograničenja brzine i zona kretanja, uz uključivanje korisnika u proces oblikovanja budućih mjera.

Slika 7. Svjedočenje prometnim nesrećama s električnim romobilima



Izvor: autori

Svaki deseti ispitanik sudjelovao je u prometnoj nesreći kao vozač, što nije zanemariv udio i pokazuje da rizici povezani s uporabom električnih romobila nisu iznimka. Osim toga, gotovo petina ispitanika bila je svjedok nesreće, pa više od četvrtine ukupnog uzorka, odnosno 27,4 %, ima neposredno iskustvo ili svjedočanstvo o prometnim nesrećama s romobilima.

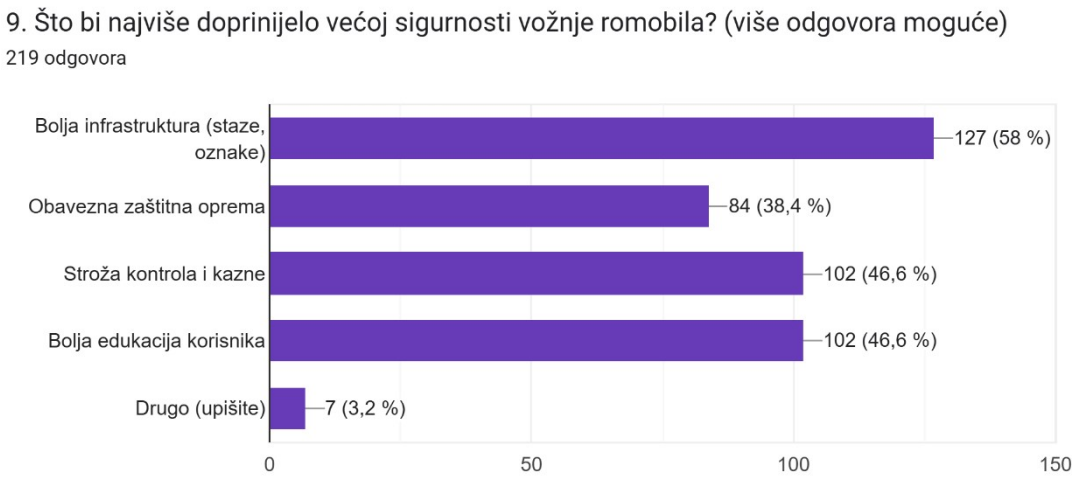
Navedeni nalazi potvrđuju da se električni romobili, unatoč percepciji praktičnosti i jednostavnosti uporabe, povezuju s realnim i učestalim sigurnosnim rizicima u svakodnevnom prometu.

Slika 8. Osjećaj sigurnosti pri vožnji električnih romobila

Izvor: autori

Percepcija sigurnosti nije pretežno pozitivna. Značajan broj korisnika ne iskazuje potpuno povjerenje u sigurnosne uvjete vožnje električnih romobila, što se može povezati s nedostatkom odgovarajuće infrastrukture, neprimjerenim ponašanjem drugih sudionika u prometu, nedovoljnom jasnoćom pravila i njihovom neujednačenom provedbom, kao i s nedostatnom edukacijom o sigurnom kretanju u prometu.

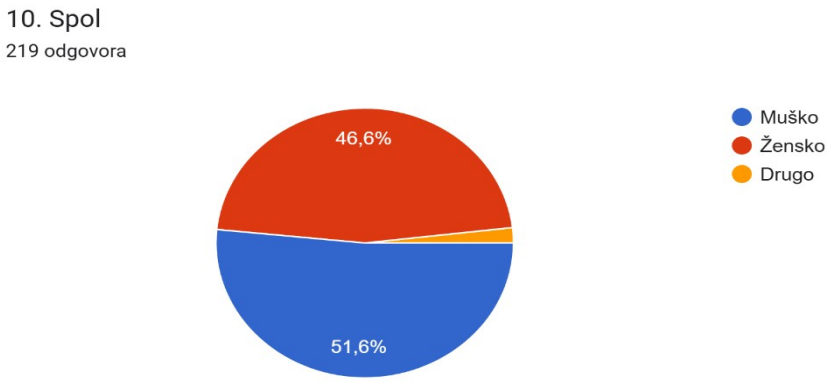
Slika 9. Doprinos sigurnosti pri vožnji električnih romobila



Izvor: autori

Sudionici ankete jasno izražavaju potrebu za sustavnim pristupom sigurnosti vožnje romobila. Kao prioritetne mjere izdvajaju se ulaganje u infrastrukturu, učinkovitiji nadzor i sankcioniranje rizičnog ponašanja, obrazovanje korisnika te standardizacija i šira uporaba zaštitne opreme, osobito u prometno zahtjevnim urbanim sredinama.

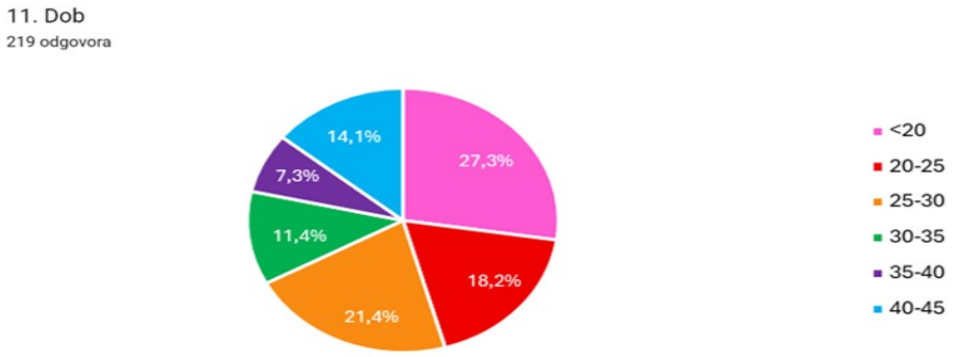
Slika 10. Spol ispitanika



Izvor: autori

Spolna struktura ispitanika relativno je uravnotežena, što pridonosi većoj reprezentativnosti dobivenih stavova u okviru promatranog uzorka.

Slika 11. Dob ispitanika



Izvor: autori

Najveći udio ispitanika pripada najmlađoj dobnoj skupini, odnosno skupini mlađoj od 20 godina, što pokazuje da su mladi među najaktivnijim korisnicima ili najzainteresiranijim potencijalnim korisnicima električnih romobila. Udio ispitanika postupno se smanjuje s porastom dobi, što upućuje na izraženu generacijsku povezanost ovog oblika mikromobilnosti.

Anketno istraživanje provedeno na uzorku od 219 ispitanika u dobi do 45 godina pružilo je vrijedan uvid u prometne navike, percepciju sigurnosti i razinu poznavanja prometnih pravila među korisnicima električnih romobila. Rezultati pokazuju da električni romobili imaju značajan potencijal kao fleksibilan i ekonomičan oblik kretanja, ali i da njihova sigurnija integracija u prometni sustav zahtijeva kvalitetniju infrastrukturu, snažnije edukativne aktivnosti, jasniju komunikaciju propisa i dosljedniju primjenu sigurnosnih standarda.

4. RASPRAVA I PREPORUKE ZA POVEĆANJE SIGURNOSTI

Rezultati analize zakonodavnog okvira, statističkih pokazatelja i anketnog istraživanja upućuju na potrebu za višeslojnim pristupom koji uključuje normativne, infrastrukturne i edukativne intervencije. Mjere za povećanje sigurnosti ne bi trebale djelovati izolirano, nego kao međusobno povezani elementi cjelovitog sigurnosnog sustava urbane mikromobilnosti.

1. **Jačanje kontrole –** sustavniji i redovitiji nadzor nadležnih tijela nad poštovanjem prometnih propisa, uz dosljednije sankcioniranje rizičnih oblika ponašanja.
2. **Promicanje kulture odgovorne vožnje –** provedba edukativnih kampanja, radionica i partnerstava s proizvođačima romobila te jedinicama lokalne i područne samouprave.
3. **Infrastrukturne prilagodbe –** izgradnja kvalitetnih i odvojenih biciklističkih traka, poboljšanje signalizacije, postavljanje jasnih oznaka brzine te uređenje parkirališnih zona za romobile.
4. **Obavezna obuka i osiguranje –** uvođenje praktičnih i teorijskih sadržaja o pravilnoj vožnji, prometnim propisima i sigurnosnoj opremi, uz razmatranje prikladnih modela osiguranja korisnika.

5. ZAKLJUČAK

Električni romobili danas predstavljaju jedno od najbrže rastućih rješenja urbane mobilnosti. Njihova popularnost temelji se na praktičnosti, pristupačnosti i ekološkim prednostima, osobito na kratkim gradskim udaljenostima. Međutim, rezultati rada pokazuju da se njihov razvoj ne može promatrati odvojeno od pitanja sigurnosti. Sigurnost uporabe ne ovisi samo o tehničkim obilježjima vozila, nego i o jasnoći zakonskog okvira, kvaliteti prometne infrastrukture, razini znanja korisnika i dosljednosti provedbe propisa. U radu je potvrđeno da

nedovoljno poznavanje pravila, niska učestalost uporabe zaštitne opreme i nepovoljna percepcija sigurnosti predstavljaju važne ograničavajuće čimbenike za sigurnu integraciju električnih romobila u prometni sustav. Stoga je za unapređenje sigurnosti potreban integrirani pristup koji uključuje razvoj odgovarajuće infrastrukture, edukaciju korisnika, učinkovitiji nadzor te kontinuirano prilagođavanje regulatornog okvira stvarnim prometnim okolnostima. Samo takvim pristupom električni romobili mogu dugoročno pridonijeti stvaranju sigurnijeg, održivijeg i funkcionalnijeg urbanog prometa.

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Professional paper

SAFETY ASPECTS OF THE USE OF ELECTRIC SCOOTERS IN TRAFFIC

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ABSTRACT

The purpose of this paper is to analyse the safety aspects of electric scooter use in traffic, with particular emphasis on the legal framework in the Republic of Croatia, accident trends and user attitudes. The paper applies a combined approach that includes the analysis of regulations, a review of relevant literature, the interpretation of available accident statistics and the examination of survey results collected from 219 respondents. The findings indicate that the rapid growth in the use of electric scooters has not been followed by an equally strong development of infrastructure, user education and enforcement mechanisms. The results further show insufficient knowledge of traffic rules, a low level of protective equipment use and a noticeable perception of insecurity among users. The paper contributes by connecting normative, statistical and empirical indicators and by offering recommendations for the safer and more sustainable integration of electric scooters into the urban transport system.

***Keywords**: electric scooters, traffic safety, traffic regulations, protective equipment, urban mobility*

Original Scientific Paper

ROAD TRAFFIC SAFETY ANALYSIS: TRENDS IN TRAFFIC ACCIDENTS AND BRAKING SYSTEM RELIABILITY OF HEAVY VEHICLES IN CROATIA

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ABSTRACT

Road traffic safety is a relevant social challenge in Croatia and in European union, with heavy vehicles playing a critical role due to their mass inertia and breaking distances. The braking system represents a primary determinant of vehicle safety performance. Modern heavy-duty vehicles gradually integrate advanced braking systems designed to stabilize the vehicle. The problem in society is that the change occurs over the years and age of vehicles therefore play a part in traffic accidents. In order to reach safety goal known as Vision Zero, long term planning and solutions are necessary in order to eliminate fatal road accidents. This paper examines the influence of heavy braking system on traffic safety and present statistical trends in Croatia over recent years using national accident databases. The analysis includes the number of registered crashes, fatalities and injuries, demonstrating trends over the years. Comparative national statistics are considered for several indicators, including: circumstances preceding traffic accidents, types of traffic accidents, road characteristics related to accident consequences, and traffic violations. Additionally, the trend of brake-system influence on the decline in technical inspection failure rates over the same period is analyzed. The findings indicate that as braking system become more modern and reliable, their contribution to vehicle disqualification during inspection decreases. This study aims to highlight the importance of continuous system modernization and policy alignment as necessary condition for approaching Vision Zero objectives.

Key words: *Technical inspection, Road traffic safety, Traffic accident statistics, Heavy vehicles, Braking systems*

1. INTRODUCTION

Road traffic safety represents a critical concern for public health, economic efficiency, and sustainable mobility. Crash severity strongly correlates with vehicle mass and kinetic energy, particularly in heavy-duty vehicles (Evans, 2004). Vehicle-related factors, especially the condition and reliability of critical systems such as braking systems, represent an important component of overall road safety. Studies summarized in the Handbook of Road Safety Measures highlight the significant role of vehicle inspection and maintenance in reducing accident risk and improving operational safety (Elvik et al., 2009). The safety performance of heavy vehicles is strongly influenced by their mass, braking characteristics, and dynamic stability, which differ significantly from passenger vehicles and contribute to increased accident severity (Cebon and Mitchell, 1992). In Croatia, traffic safety is influenced by multiple factors, including the composition and condition of the national vehicle fleet, driver behaviour, road infrastructure, and the enforcement of traffic regulations (Šoštarić et al., 2025). Over recent decades, Croatia has experienced significant changes in vehicle fleet characteristics, accident rates, and traffic violation patterns. Understanding these trends is

essential for the development of effective safety measures and policy decisions. According to the World Health Organization (2023), more than half of people who die in road accidents annually are vulnerable road users. Previous research in Croatia has shown that the development of transport infrastructure, particularly the motorway network, has an important influence on traffic accident trends and the associated socio-economic costs, confirming that road safety should be observed as a broader systemic issue rather than solely as a driver-related problem (Pupavac, 2016). In addition, the increasing complexity of modern transport systems and vehicle technologies requires more advanced analytical and engineering approaches to ensure safety performance and system reliability. Recent technological developments, including the integration of artificial intelligence and advanced engineering tools, are increasingly influencing safety-critical systems and decision-making processes in engineering applications (Maričić et al., 2025). This paper provides an overview of traffic safety in Croatia, focusing on vehicle fleet characteristics, trends in traffic accidents, and the consequences of accidents by vehicle type, with particular attention to freight vehicles and their role in overall road safety.

2. TRAFFIC SAFETY OVERVIEW IN CROATIA

2.1 Vehicle fleet structure and condition

The structure and condition of the national vehicle fleet represent an important factor influencing road traffic safety. Vehicle age, technologcal equipement, and maintenance levels directly affect the reliability of critical safety systems, particulary braking systems. In Croatia, the vehicle fleet is classified according to the European Vehicle categorization system, grouping vehicles based on their intended use and maximum permissible mass.

- Passenger vehicles (M1): Motor vehicles designed for transporting passangerss with up to eight seats in addition to driver's seat, representing the largest share of the fleet.

- Passenger’s buses (M2 & M3): M2 includes smaller buses with a maximum mass up to 5 tonnes, while M3 includes larger buses exceeding 5 tonnes.

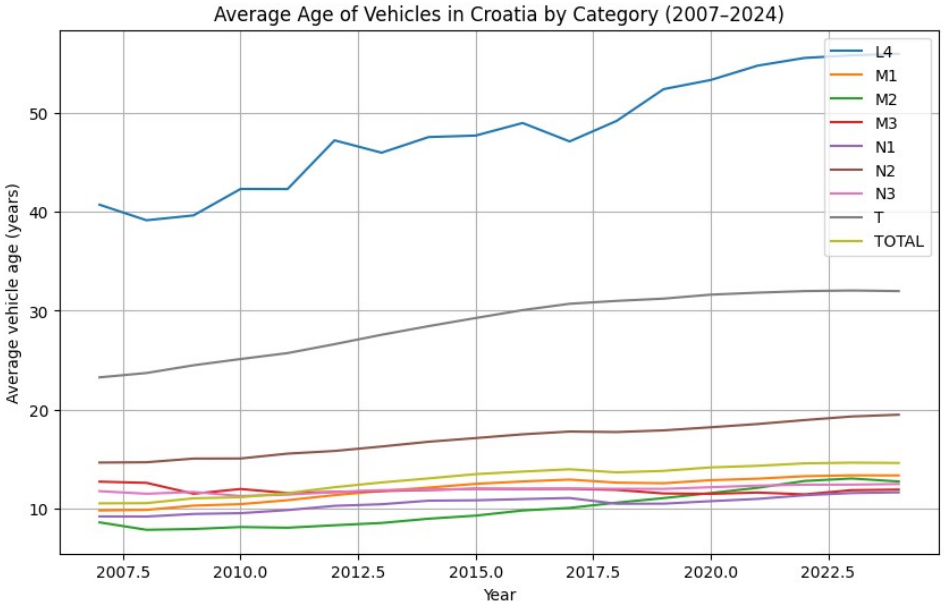
- Goods vehicles (N1 - N3): N1 for light commercial vehicles up to 3.5 tonnes, N2 for medium vehicles between 3.5 and 12 tonnes, and N3 for heavy goods vehicles aboe 12 tonnes

- Other categories: Motorcycles with sidecars (L4), agricultural tractors (T), and trailers (O1-O4).

Analysis of fleet dana from 2007 to 20024 indicates a clear trend of increasing vehicle age. The overall average age increased from 10.55 years in 2007 to 14.63 in 2024, with similar trends for passangers vehicles (M1) and good vehicles (N2). Agricultural tractors exibit the highest average age, exceeding 32 years by 2024.

The ageing of the fleet has implications for road safety, as older vehicles may lack modern safety technologies and are more prone to mechanical failures, emphesizing the imprtance of regular inspections and modernization of critical systems such as brakes. The importance of braking system reliability becomes particularly critical in heavy vehicles, where increased mass and kinetic energy amplify the consequences of any braking inefficiency (Cebon and Mitchell, 1992).

Figure 1. Average age of vecihles in croatia by vehicle category for the perind 2007-2024.



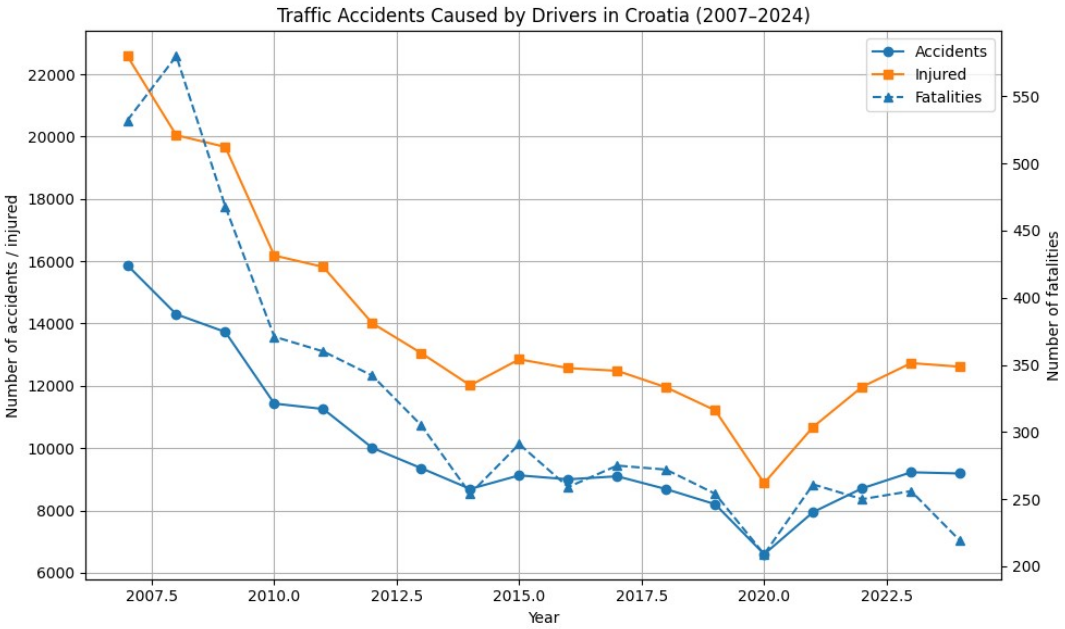
Source: processed by authors based on MUP (2020-2024),

3. TREND SIN TRAFFIC ACCIDENTS CAUSED BY DRIVERS

3.1 Long-Term Accident Trends

Traffic accidents caused by drivers constituate the dominant share of roads accidents in Croatia. Between 2007 and 2024 (figure 2), the total number of such accidents declined from 15,871 to 9,186, a reduction of approximaly 42 %. Fatalities decreased drom 532 to 219 (59 %), while injured persons declined from 22,585 to 12,613 (44%). Thease trends indicate significant improvements in road traffic safety over the analysed period.

Figure 2. Statistics of traffic Accidents Caused by driver sin croatia (2007-2024)

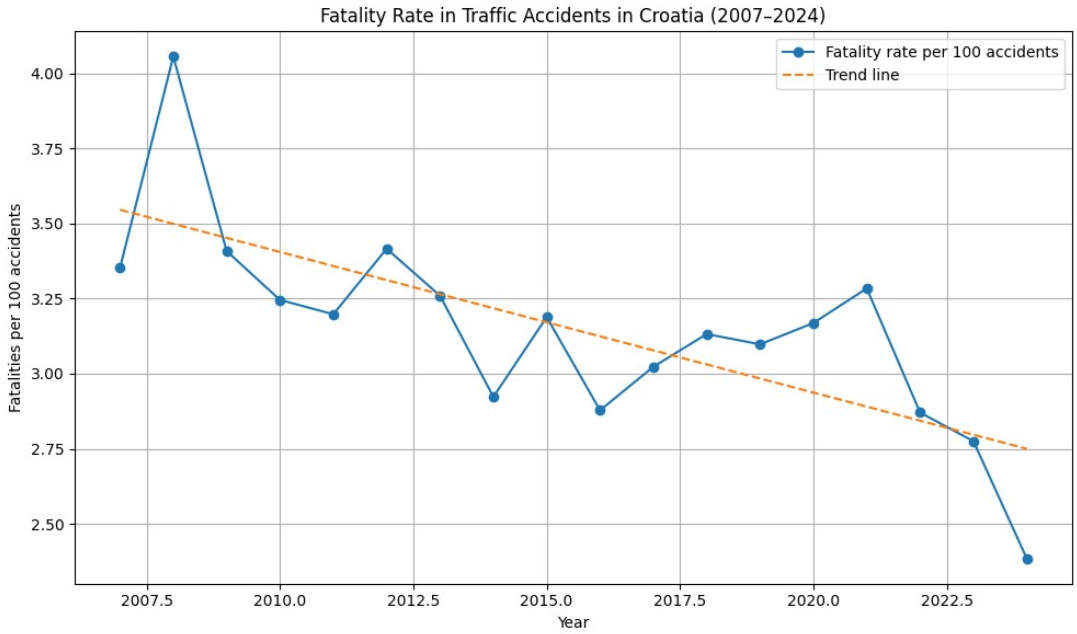


Source: processed by authors based on MUP (2020-2024),

3.2 Accident severity

The fatality rate per 100 traffic accidents seres as an indicator of accident severity. In Figure 3. the statistics of traffic accidents Caused by drivers in Croatia can be seen. A gradual reduction over the analysed period suggests improvemensts in vehicle safety systems, road infrastrucure, and emergency response.

Figure 3. Statistics of traffic Accidents Caused by drivers in Croatia (2007-2024)

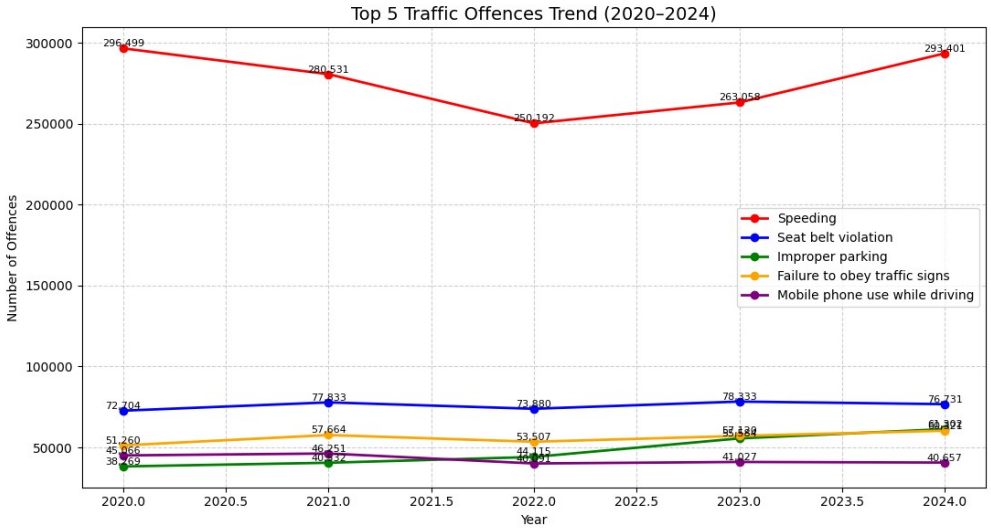


Source: processed by authors based on MUP (2020-2024),

3.3. Traffic Violations

In 2024, a total of 786,367 traffic violations were recorded, an increase of 11 % compared to 2023, what is seen in Figure 4. Speeding accounted for the largest share (293,401 cases), highlighting it as a persistant traffic safety isssue. Other common violations include improper parking, traffic signs violations, seat belt non-use, and moblile phone usage while driving. Figure 4 presents statistics of traffic violations from 2020 to 2024.

Figure 4. Traffic Offences trends (2020 - 2024)



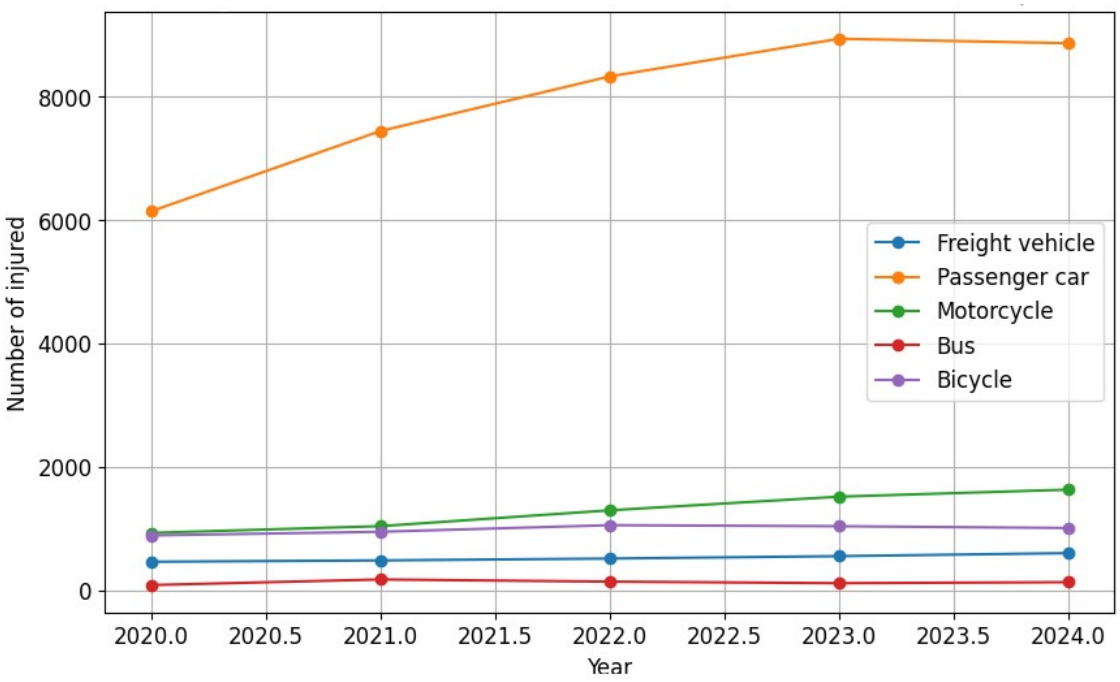
Source: processed by authors based on MUP (2020-2024),

4. TRAFFIC ACCIDENTS AND CONSEQUENCES BY VEHICLE TYPE (2020-2024)

4.1 Freight Vehicles

Frehight vehicles are of particular interest due to their mass, operational characteristics, and frequent participation in long-distances transport. From 2020 to 2024, the number of traffic accident involving freight vehicles increased from 4,915 to 6,656. Despite the increase in accidents, the number of fatalities remained relativly stable, fluctuating between 8 and 11 per year. Injury numbers for freight vehicles accidents show a continuous increase from 459 in 2020 to 599 in 2024, reflecting higher traffic volumes nad increased exposure. Figure 5 represents statistics for injured persons in traffic accidents by vehicle type.

Figure 5. Injured persons in traffic accidents by vehicle type (2020-2024)

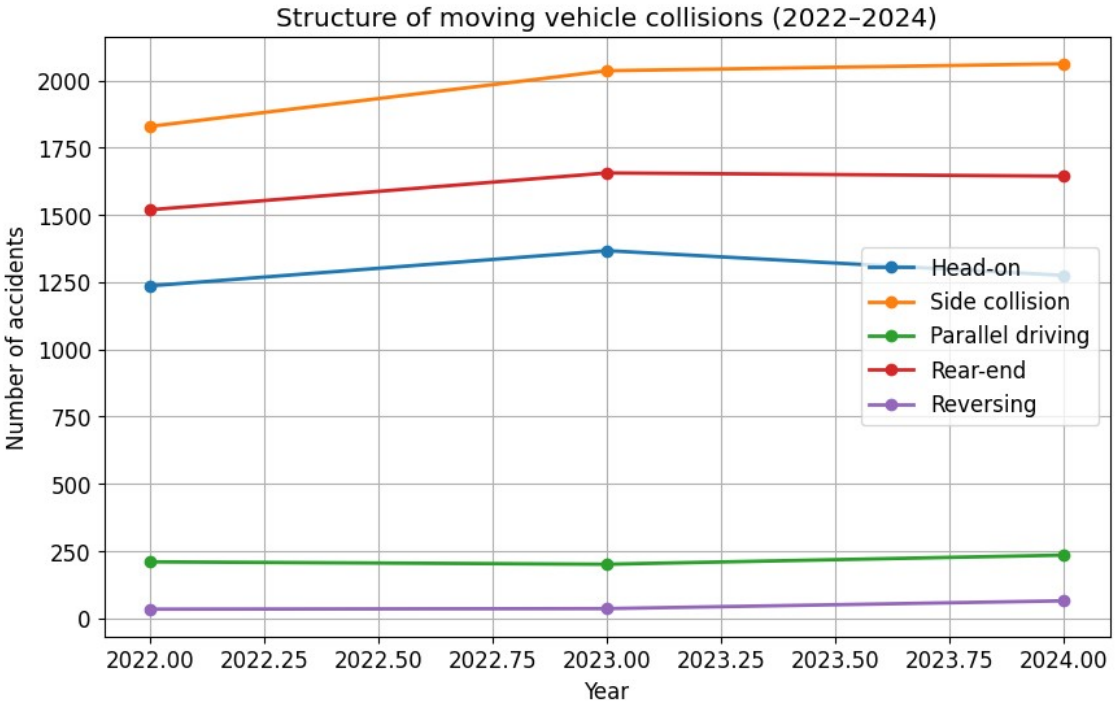


Source: processed by authors based on MUP (2020-2024),

4.2 Comparrison with other vehicle types

Passanger cars account for the largest share of accidents, with a gradual increase from 34,331 in2022 to 47,123 in 20024. Motorcycles, although fewer in number, demonstrate a disproportionately high fatality rate, rising from 44 fatalities in 2020 to 70 in 2023 before slightly decreasing to 67 in 2024. Bicycles and buses show relatively stable accident and injury levels. Figure 6 shows the structure of moving vehicle collision over the period od 2022 – 2024., catagorised into five collision types: head-on, side collisions, parallel driving, rear-end, and reversing incidents. Side collisions represent the most frequent type throught the observed period, showing a steady upward trend from approximately 1,820 cases in 2022 to over 2,050 in 2024. Authors reviewed statistics and in 2018. it was 1987, in 2019 it was 1813 and in 2020 1435 and then 1619 in 2021. That indicates a persistent and growing issue, likely associated with urban traffic density and intersection conflicts. Rear - end collision or failure to porly maintain a safe following distance, constituatethe second most common category, increasing from around 1,500 in 2022 to peak in 2023, followed by stabilisation in 2024.

Figure 6. Structure of moving vehicle collisions (2022-2024)



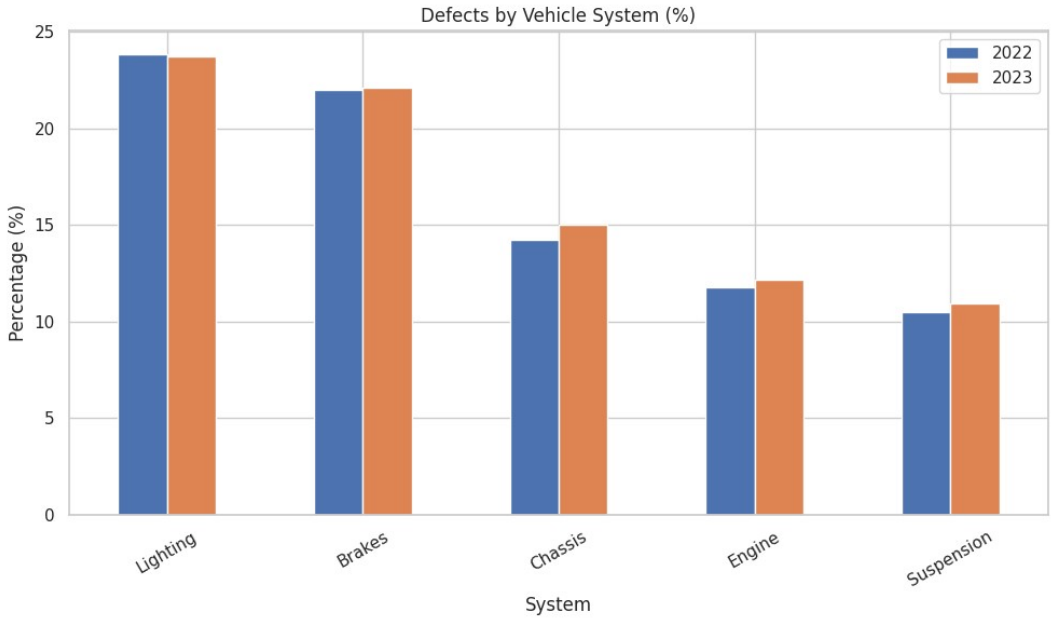
Source: processed by authors based on MUP (2020-2024)

5. TEHNICAL INSPECTION OF VEHICLES

A comparative analysis of technical inspection data for the period 2022–2023 reveals several important trends related to vehicle roadworthiness and system reliability. The total number of inspected vehicles increased from 2,322,406 in 2022 to 2,406,952 in 2023, representing an increase of approximately 3.6%. At the same time, the number of technically defective vehicles slightly decreased from 431,625 to 428,385, indicating a modest improvement in overall vehicle condition. However, despite this improvement, the total number of detected defects increased from 2,370,123 to 2,430,791, while the average number of defects per defective vehicle rose from 5.49 to 5.67. This suggests that although fewer vehicles are classified as defective, those that are defective tend to exhibit a higher number of individual faults, indicating increasing technical complexity. Particular attention should be given to braking systems, which remain among the most critical vehicle subsystems. The number of braking system defects increased slightly from 531,288 to 535,498, while their relative share decreased marginally from 22.42% to 22.03%. At the same time, the average number of braking-related defects per vehicle increased from 1.23 to 1.25. These results confirm that braking systems continue to represent a major source of technical defects, maintaining a consistently high proportion of total vehicle failures. The slight decrease in their relative share, however, suggests that other subsystems, such as structural components and engine-related systems, are becoming increasingly relevant in overall vehicle reliability. Overall, the findings indicate a dual trend: a gradual improvement in the proportion of roadworthy vehicles, combined with an increasing number and complexity of defects per vehicle. This highlights the importance of continuous monitoring, regular maintenance, and modernization of critical safety systems, particularly braking systems, in order to improve road traffic safety and support long-term safety objectives. These findings are consistent with the concept of integrated safety strategies, which are essential for achieving long-term goals such as Vision Zero, especially considering that the impact of freight vehicles on accident outcomes is strongly influenced by their higher mass and longer stopping distances, which increase

collision severity and reduce the margin for driver reaction (Elvik et al., 2009; Cebon and Mitchell, 1992).

Figure 7. Structure of moving vehicle collisions (2022-2024)



Source: processed by authors based on Centre for Vehicles of Croatia

6. DISCUSSION

The analysis reveals several important insights into road traffic safety trends in Croatia. The gradual ageing of the national vehicle fleet represents a significant concern, as older vehicles are generally associated with reduced reliability of safety-critical systems and a higher likelihood of mechanical failure, which may contribute to increased accident risk. At the same time, long-term trends indicate a substantial reduction in the number of accidents and fatalities, suggesting an overall improvement in road safety. These positive developments can be attributed to a combination of factors, including advancements in vehicle safety technologies, improved road infrastructure, and more effective regulatory frameworks. Despite these improvements, certain risk factors remain pronounced. Freight vehicles, although less frequently involved in accidents compared to passenger cars, tend to produce more severe consequences due to their mass and operational characteristics. Similarly, motorcycles continue to represent a particularly vulnerable category of road users, with disproportionately high injury and fatality rates, indicating the need for targeted safety measures. In addition, speeding remains a persistent traffic violation, highlighting the continued importance of enforcement strategies and driver education in reducing accident occurrence. Overall, the findings emphasize that further improvements in road traffic safety in Croatia require a comprehensive and integrated approach, including fleet modernization, enhanced driver training, stricter enforcement of traffic regulations, and continuous infrastructure development. The observed increase in system complexity is consistent with broader trends in engineering, where advanced technologies such as AI-driven optimization and digital simulation are increasingly embedded into technical systems, resulting in higher performance but also greater system complexity (Maričić et al., 2024; 2025). These results are consistent with international research, which demonstrates that effective road safety improvements are typically achieved through the combined implementation of technological, regulatory, and maintenance-related measures, rather than through a single dominant intervention (Elvik et al., 2009).

7. CONCLUSION

Road traffic safety in Croatia has improved over the last two decades, as evidenced by reductions in accidents, fatalities, and injuries. However, several structural challenges remain, particularly related to the ageing vehicle fleet, the operational characteristics of freight vehicles, and persistent traffic violations such as speeding.

The analysis of technical inspection data highlights a dual trend: while the number of defective vehicles has slightly decreased, both the total number of detected defects and the average number of defects per vehicle have increased. This points to growing technical complexity and a higher concentration of faults in a smaller subset of vehicles.

Braking systems remain one of the most critical sources of technical defects, consistently accounting for a significant share of total failures. At the same time, the increasing contribution of other subsystems, including structural and engine-related components, indicates a shift toward more complex and systemic vehicle reliability challenges.

From a practical perspective, further improvements in road traffic safety require targeted and coordinated measures. These should include accelerated fleet renewal, stricter and more data-driven technical inspections, enhanced monitoring of critical safety systems, and continued investment in driver education and enforcement of traffic regulations. Such an integrated approach is essential to address emerging technical risks and to sustain long-term improvements in road safety.

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Izvorni znanstveni rad

ANALIZA SIGURNOSTI CESTOVNOG PROMETA: TRENDOVI PROMETNIH NESREĆA I POUZDANOST KOČIONIH SUSTAVA TEŠKIH VOZILA U REPUBLICI HRVATSKOJ

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SAŽETAK

Sigurnost cestovnog prometa predstavlja značajan društveni izazov u Republici Hrvatskoj i Europskoj uniji, pri čemu teška vozila imaju važnu ulogu zbog svoje mase, inercije i duljih zaustavnih putova. Kočioni sustav predstavlja jedan od ključnih čimbenika sigurnosne pouzdanosti vozila. Suvremena teška vozila postupno integriraju napredne kočione sustave usmjerene na povećanje stabilnosti i sigurnosti vožnje, no promjene u voznom parku odvijaju se postupno, a starost vozila i dalje značajno utječe na nastanak prometnih nesreća. U radu se analizira utjecaj kočionih sustava na sigurnost cestovnog prometa te se prikazuju statistički trendovi prometnih nesreća u Republici Hrvatskoj na temelju nacionalnih baza podataka. Analiza obuhvaća broj prometnih nesreća, smrtno stradalih i ozlijeđenih osoba, kao i usporedne pokazatelje poput okolnosti nastanka nesreća, tipova nesreća, karakteristika prometnica te prometnih prekršaja. Posebna pažnja posvećena je analizi tehničkih pregleda vozila i utjecaju kočionih sustava na tehničku ispravnost vozila. Rezultati ukazuju na to da modernizacija i povećanje pouzdanosti kočionih sustava dovode do smanjenja njihovog udjela u neispravnostima utvrđenima tijekom tehničkih pregleda. Istodobno, uočava se porast složenosti tehničkih nedostataka vozila. Dobiveni rezultati naglašavaju važnost kontinuirane modernizacije vozila, unapređenja sustava tehničkih pregleda te usklađivanja sigurnosnih politika kao preduvjeta za ostvarenje dugoročnih ciljeva sigurnosti cestovnog prometa, uključujući koncept Vision Zero.

Ključne riječi: *Tehnički pregled vozila, Sigurnost cestovnog prometa, Statistika prometnih nesreća, Teška vozila, Kočioni sustavi*

IV. SUSTAINABLE MOBILITY, RAILWAY SYSTEMS AND TECHNICAL SOLUTIONS

IV. ODRŽIVA MOBILNOST, ŽELJEZNIČKI SUSTAVI I TEHNIČKA RJEŠENJA

Review

PROS AND CONS OF A UNIFIED TRACK ACCESS CHARGING SYSTEM FOR RAIL FREIGHT CORRIDORS

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ABSTRACT

European Rail Freight Corridors, established by Regulation 913/2010, aim to strengthen the competitiveness of international rail freight transport through coordination, primarily among infrastructure managers. This coordination covers activities including investment planning, traffic management, the provision of adequate infrastructure capacity, and facilitated use of that capacity. However, one key element not addressed by this regulation concerns track access charges, which remain within the remit of national regulatory frameworks. As a result, multiple track access charging systems are applied along a single international rail corridor. Such heterogeneity in charging systems leads to cost uncertainty for railway undertakings, directly undermining the competitiveness of rail transport compared to other modes. This paper analyses the advantages and disadvantages of introducing a corridor-level track access charging system, as a precondition for more effective functioning. The analysis is conducted using a SWOT framework prepared from the perspectives of infrastructure managers and railway undertakings. From the infrastructure managers' perspective, the analysis examines impacts on revenues, pricing autonomy, and administrative costs, while from the railway undertakings' perspective it focuses on cost predictability, operational planning, and market competitiveness. The results indicate that corridor-level charging system would provide railway undertakings with simplified charging arrangements and reduced administrative burden, while for infrastructure managers it would require balancing administrative efficiency gains against risks to revenue stability. Based on the identified incentive asymmetry between key stakeholders, the paper provides a policy discussion on a roadmap towards unified charging system.

Key words: *track access charges, rail freight corridors, SWOT analysis, infrastructure managers, railway undertakings*

1. INTRODUCTION

A railway undertaking operating along a railway freight corridor in Europe passes through multiple countries, each applying its own track access charging system. These systems rely on different calculation formulas, employ distinct adjustment parameters, and generate divergent pricing signals for identical operational characteristics of a train. This diversity does not result from the absence of a regulatory framework. The EU establishes common principles for track access charging yet allows substantial scope for national interpretation. At the same time, Regulation 913/2010, which established the Rail Freight Corridors, introduced coordination among infrastructure managers across several governance and operational domains, while leaving the calculation and structure of track access charges under national competence.

The extent of charging diversity has been documented in numerous comparative studies over the past two decades. Nash (2005), reviewing 23 European charging systems, identified more than a tenfold variation in charges per train-kilometre between the lowest and highest values. These differences extend beyond overall charge levels. Marschnig et al. (2019) show that direct costs may vary by up to a factor of five, while the average total charge for international freight trains amounts to approximately EUR 3 per train-kilometre. Variations in calculation formulas, parameter structures, and regulatory and market priorities have also been confirmed by more recent research (Asmari and Ricci, 2025). Although national charging systems have been partially simplified over the past decade (Opała, 2022), significant differences persist in the application of mark-ups above direct costs. This finding is reinforced by IRG-Rail (2024), according to which only three of the 21 analysed systems differentiate between domestic and international freight traffic. Collectively, these studies demonstrate that substantial disparities in both charging structures and charge levels remain despite long-standing regulatory harmonisation efforts.

The consequences of this lack of alignment are directly reflected in the operational environment of railway undertakings engaged in international freight transport. The challenges associated with charging diversity extend beyond differences in price levels. Conflicting incentive signals may be equally detrimental, as charging systems that encourage load consolidation and the operation of long, heavy trains in one country may favour shorter and lighter trains in neighbouring networks (Prodan and Teixeira, 2015).

Additional barriers arise from the structure of charging regimes themselves. Thompson (2008) identified constraints associated with two-part charging systems with substantial fixed components and proposed the introduction of single-part charging regimes along major corridors. Nationally determined mark-ups above direct costs have also been shown to systematically increase charges for cross-border services (Jost, 2017). From a theoretical perspective, Bloch and Gagnepain (2025) demonstrate that independently determined charges along international routes lead to cumulative increases in total access costs, whereas coordinated charging approaches can mitigate this effect.

Beyond operational implications, charging diversity constitutes a structural obstacle to harmonisation efforts. Differences in national subsidy policies and market conditions complicate alignment, while cost-recovery-oriented charging regimes may discourage entry by new market participants (Arrigo and Di Foggia, 2014). These barriers persist in the context of a long-term decline in rail freight's modal share within the EU (ECMT/OECD, 2005; ERFA, 2022). Empirical evidence further indicates that existing corridor coordination mechanisms have not significantly contributed to increasing cross-border freight volumes (Bacian, 2021; European Commission, 2021).

The persistence of charging fragmentation has therefore stimulated institutional debate on corridor-level harmonisation. As early as 2005, the European Conference of Ministers of Transport recommended harmonising of charging structures for freight trains in order to reduce the costs of international services and improve competitiveness (Nash, 2005). Subsequently, the International Union of Railways proposed the introduction of common charging parameters integrated into a single corridor Network Statement (UIC, 2014), while the European Rail Freight Association advocated extending corridor governance competencies to include the collection of charges for corridor train paths (ERFA, 2016). However, none of these initiatives has evolved into binding regulatory requirements.

A key explanation lies in the fact that infrastructure managers operate under significantly different national financing models, where variations in public subsidy levels directly influence charge levels and the extent of mark-ups above direct costs (Montero-Pascual et al., 2023). Even recent interpretative guidelines issued by the European Commission do not prescribe harmonisation of charging systems at corridor level (European Commission, 2025).

Academic research has largely addressed charging diversity from a national perspective, while the institutional framework itself does not foresee corridor-level harmonisation. Nash et

al. (2018), synthesising four case studies, conclude that wear-and-tear charges frequently fail to reflect actual infrastructure costs, whereas mark-ups above direct costs increasingly dominate total infrastructure charges. One of the few studies examining charging at corridor level is García-Ródenas et al. (2025), which develops an optimisation model for the Mediterranean Rail Freight Corridor and demonstrates that corridor-level charging produces outcomes substantially different from nationally determined approaches. Despite these contributions, a systematic assessment of the advantages and disadvantages of moving toward a unified corridor-level charging system and the trade-offs faced by different stakeholder groups, remains largely unexplored.

Against this background, the main research question of this paper is: what are the advantages, limitations, and risks of introducing a corridor-level track access charging system based on a common charging framework acceptable to all infrastructure managers along the corridor? To address this question, the paper aims to analyse the heterogeneity of existing national charging systems along the selected rail corridor, assess the implications of introducing a corridor-level charging system, and identify the key operational, governance, and policy constraints affecting its implementation.

This paper addresses this research gap by applying a structured SWOT analysis to the introduction of a corridor-level charging system from the perspectives of infrastructure managers and railway undertakings. The analysis focuses on the Rhine–Danube Rail Freight Corridor, which traverses seven countries applying substantially different charging approaches. The paper first presents the institutional and regulatory context together with a comparative overview of charging systems along the corridor. Building on this empirical background, the analytical framework is introduced, and the SWOT methodology is applied separately to both stakeholder groups. The results are subsequently interpreted through the lens of incentive asymmetry between infrastructure managers and railway undertakings, forming the basis for the conclusions and policy discussion presented in the final section.

2. INSTITUTIONAL CONTEXT AND EMPIRICAL EVIDENCE

2.1. Rail Freight Corridors in the EU railway framework

In 2007, the European Commission proposed the establishment of a rail network giving priority to freight transport along existing international routes, in response to the declining competitiveness of rail freight relative to road transport, which dominates the European freight market (European Commission, 2007). The initial concept of developing dedicated, freight-only railway corridors was abandoned due to the high investment costs and long implementation timelines such projects would require. Instead, the strategic approach focused on identifying routes generating high freight volumes and harmonising them in terms of governance, planning and operational rules.

It was concluded that the identification of suitable cross-border freight corridors, combined with strengthened cooperation among infrastructure managers (IMs), could significantly improve the performance of international rail freight services. This cooperation was envisaged in several planning and operational domains, including investment planning, train path allocation, and the prioritisation of freight traffic. These principles were formalised through Regulation 913/2010, which established the European Rail Freight Corridor (RFC) network as a framework for coordinated, market-oriented freight transport across national borders.

Today, the RFC network consists of ten active corridors. Given their inherently cross-border nature, RFCs required the establishment of a common governance body capable of aligning the actions of multiple institutional actors which in a multi-level governance structure supported with advisory groups representing railway undertakings (RUs) and terminal operators.

At the operational level, Regulation 913/2010 introduced harmonisation and coordination in several key areas, including the coordination of maintenance and renewal works, allocation

of capacity to freight trains, traffic management and performance monitoring through common key performance indicators. These objectives were operationalised through joint capacity planning, the establishment of Corridor One-Stop Shops (C-OSS) as a single interface for train path requests, and the development of corridor products such as Pre-arranged Paths (PaPs) and reserve capacity. These instruments represent a structural shift from a purely demand-driven capacity allocation model towards a supply-oriented approach, in which IMs predefine international freight capacity and offer it to the market.

While this model improves coordination and predictability at corridor level, it also introduces structural trade-offs in terms of flexibility and adaptability to specific operational requirements. This may limit the ability of RUs to respond to customer needs and, consequently, result in the loss of potential market share (European Commission, 2023).

The regulatory framework governing the calculation and structure of track access charges (TACs), which remains outside the scope of corridor-level coordination, is outlined in the following section.

2.2. Track access charging: regulatory framework and policy context

TACs are the fees that RUs must pay for the use of railway infrastructure. They represent an important source of revenue for IMs and, together with direct government contributions, constitute a core component of railway network financing. At the same time, TACs function as a regulatory and economic instrument for steering demand for specific types of capacity and patterns of infrastructure usage (European Commission, 2025).

The EU regulatory framework governing TAC is structured around two principal instruments. Directive 2012/34 establishes that charges for the minimum access package shall be set at the cost that is directly incurred as a result of operating the train service, while permitting mark-ups under conditions of market bearability and non-discrimination. This directive requires IMs to publish Network Statements containing the charging methodology and applicable tariffs, and mandates cooperation among IMs for the coordination of charging and capacity allocation across networks. Regulation 2015/909 further specifies the modalities for calculating direct costs, defining eligible and ineligible cost categories, permitting modulation by parameters such as axle load, train mass, and speed. The most recent interpretative guidelines clarify that mark-ups are an optional exception to the mandatory direct cost principle and recommend cooperation among IMs on common market segment definitions for cross-border services, while explicitly noting that this does not imply harmonisation of charge levels (European Commission, 2025).

Despite this common regulatory basis, the practical interpretation and implementation of the direct cost principle remain within the competence of national authorities, resulting in diverse implementation models across Member States. The variables with the greatest impact on charges include train type, time of day, train speed, and line category or strategic importance. Adjustments to these parameters are particularly challenging for international operations due to their significant variation across countries (Opała, 2022).

At the operational level, the Charging Information System (CIS) has partially addressed the transparency problem by providing RUs with indicative corridor-based charge estimates. CIS is a web-based platform operated by RailNetEurope, with data input provided by 23 IMs and allocation bodies. It functions as an umbrella application that integrates national charging systems and provides indicative estimates for the use of international train paths, stations, and shunting services. Estimation accuracy is reported to be between 90% and 95% on average (IRG-Rail, 2024). However, CIS remains an informational tool without legal binding force, and RUs must still formally apply the national charging methodologies defined in individual IMs' Network Statements.

2.3. Comparative analysis of TAC systems along RFC Rhine-Danube

The structural diversity of TACs is illustrated through the example of the Rhine–Danube Rail Freight Corridor, which represents the main East–West axis connecting Romania, Hungary, Slovakia, the Czech Republic, Austria, Germany, and France. The corridor extends over approximately 6,500 km and links industrial regions of Central and Central-Eastern Europe with major maritime gateways on the Black Sea, North Sea, and Baltic Sea (RFC Rhine–Danube, 2025). Charging data were collected from the applicable Network Statements for the timetable periods 2025–2027. The analysis covers the mathematical structure of charging formulas, the composition of charging components, differentiation parameters, line categorisation approaches, and applied incentive mechanisms.

The mathematical structure of national charging formulas and their classification by formulation type are presented in Table 1. Six out of the seven analysed systems apply an additive charging structure, while the Czech model incorporates multiplicative elements within an overall additive framework through weighting factors reflecting different traffic characteristics. The remaining system, Germany, applies a Ramsey–Boiteux pricing approach, distributing fixed infrastructure costs across more than forty market segments. Beyond formulation type, diversity is also reflected in the number of charging components applied. The observed range, from two to seven components, does not correlate with network size but rather reflects national traditions in cost accounting practices and regulatory choices concerning pricing transparency and economic signalling.

Table 1. Overview of charging formula structures

State	Infrastructure manager	Formula	Type of formula
FR	SNCF Réseau	$TAC = RC + RCE + RCTE - A/B + RM + RA + RP + RS$	Additive, extended
DE	DB InfraGO AG	$TAC = (uKZ + VKA \pm wE) \times voz - km$	Ramsey–Boiteux
AT	ÖBB-Infrastruktur AG	$TAC = (voz - km \times z) + (btk - km \times btk) \pm Zu/Ab$	Additive
CZ	Správa železnic	$Cv = (L \times ZRP) + (L \times ZI \times M \times Px \times kETCS) + CPK$	Additive, with multiple. component
SK	ŽSR	$Ump = U1 + U2 + U3 + U4$	Additive
HU	MÁV Zrt.	$TAC = (vkm \times Rvkm) + (btkm \times Rbtkm) + Ctp$	Additive
RO	CFR SA	$TUI = TUItonaj + TUIcirc + TUIel$	Additive

Source: Network Statements of the respective IMs

The comparative overview of component representation presented in Table 2 confirms the existence of a common cost basis derived from Regulation 2015/909. Traffic management, infrastructure maintenance, and the use of electric traction power supply equipment are included in all analysed charging systems. Differences arise primarily in the way these cost elements are structured and aggregated. Two systems incorporate traffic management and maintenance within a single composite component, whereas the remaining five allocate separate components to each service, thereby enabling a clearer allocation of costs according to their causal origin.

Table 2. Representation of charging structure components in the analysed systems

Component	FR	DE	AT	CZ	SK	HU	RO
Traffic management	✓	✓	✓	✓	✓	✓	✓
Infrastructure maintenance	✓	✓	✓	✓	✓	✓	✓
Train traction equipment	✓	✓	✓	✓	✓	✓	✓
Mark-up	✓	✓	○	—	—	✓	—
Congestion	○	—	✓	—	—	—	—
Performance	✓	✓	✓	✓	—	—	✓

Note: ✓ applies; ○ planned but suspended or in preparation; — does not apply

Source: Authors, based on Network Statements

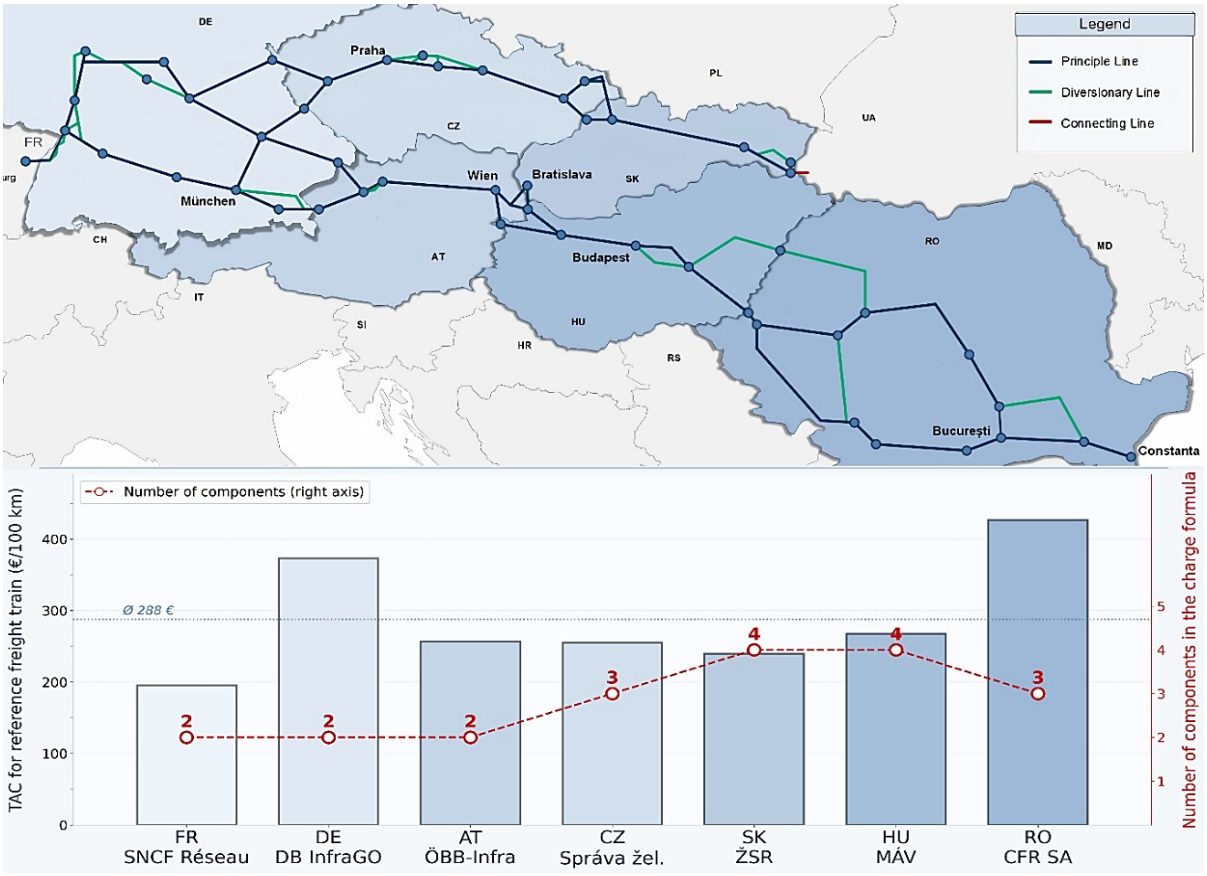
A pronounced structural difference can be observed in the way fixed costs are incorporated into charging structures. Only three systems apply mark-up mechanisms, each based on fundamentally different approaches. France applies a fixed annual charge, Germany distributes full costs across more than forty market segments following a Ramsey–Boiteux pricing logic, while Hungary applies a mandatory mark-up adjusted through state subsidies. Austria plans to introduce a mark-up component only from 2029 onwards. For freight RUs, this implies that along a single corridor route no payment beyond direct costs may apply to one section, a subsidy-adjusted mark-up on another, and full cost recovery based on market segmentation on a third.

Charging elements display a similar pattern. Formal compliance with the EU regulatory framework is accompanied by considerable diversity in practical implementation. Train-kilometres and gross tonne-kilometres are included in nearly all systems. However, one system calculates charges exclusively based on train-kilometres without explicitly accounting for train mass. Train mass appears in six systems in different forms, either as a measured value, a weighted variable, or a classification parameter. The way mass is incorporated determines how accurately TACs reflect infrastructure wear and marginal costs.

Modulation mechanisms and incentive schemes provided under Directive 2012/34/EU are also applied unevenly. Congestion charging is effectively operational only within a limited part of one system and remains absent elsewhere. Cancellation penalties exist in six of the seven analysed systems, but their structure ranges from fixed charges per kilometre to progressive multipliers between 2% and 120% of the base charge. Incentives for combined transport differ substantially in intensity, with reductions ranging from weighting coefficients equivalent to a 45% charge decrease to discounts of 33% for intermodal services or 20% for newly generated traffic. The absence of comparable mechanisms in other systems results in fragmented rather than corridor-wide incentive effects.

The practical implications of these differences are quantified through the calculation of TACs for a reference freight train, the results of which are presented in Figure 1.

Figure 1. Infrastructure access charges for a reference freight train along the RFC Rhine–Danube



The reference scenario is defined as a standard international freight train with a gross mass of 1,000 tonnes, operating over a distance of 100 km under electric traction and assigned to the highest available line category in each national system. The calculation is based on the applicable charging formulas and tariff values specified in the respective Network Statements. Where national charging systems include multiple components (e.g. train-km and gross tonne-km), all relevant elements are incorporated. Modulation parameters are applied consistently across countries, assuming standard operating conditions. Currency conversions are performed using average exchange rates for the reference period. Under these assumptions, calculated charges range from EUR 195 to EUR 426 per 100 km. While the central section of the corridor exhibits clustering around the average value of EUR 288, terminal countries deviate significantly, recording the lowest and highest charge levels. The resulting maximum-to-minimum ratio of 2.18:1 illustrates the substantial economic divergence faced by RUs operating along international corridors. The designation “highest available line category” corresponds to nationally defined classifications, which are not directly equivalent across systems.

An overview of system diversity indicators is presented in Table 3. The total TAC for a 1,000-tonne freight train operating along the entire corridor is estimated at approximately EUR 15,000–18,000. This variation reflects not only differences in price levels but also the incompatibility of underlying tariff structures. Consequently, RU must navigate seven charging systems, apply different input parameters and consolidate results into a single transport price offered to the final customer. These differences therefore constitute not merely an administrative burden but a structural constraint on the functioning of the corridor as a single market space.

Table 3. Quantitative indicators of charging system diversity along the RFC Rhine–Danube

Indicator	Value	Note
Number of analysed systems	7	FR, DE, AT, CZ, SK, HU, RO
Range of number of components	2–7	AT (2) to FR (6–7)
Range of rail lines categories	0–40+	AT/CZ (uniform) to DE (market segments)
Time differentiation	3 of 7	FR, DE, AT (limited)
Dominant formula type	Additive	6 out of 7 systems (86%)
TAC range (EUR/100 km)	195–426	FR to RO for reference train
Ratio max./min.	2.18:1	RO/FR
Central part of the RFC	240–268	AT, CZ, SK, HU
Average TAC on the RFC	≈ 288 EUR	Arithmetic mean of 7 systems

Source: Authors

3. ANALYTICAL FRAMEWORK AND METHOD

To address the multidimensional nature of corridor-level TAC, this paper applies a SWOT analysis as its primary analytical framework. The approach is used to systematically assess incentives, constraints, and strategic interactions arising from the introduction of a corridor-level charging framework.

The SWOT matrix is derived from a comparative analysis of national charging systems along the Rhine–Danube Rail Freight Corridor, complemented by the EU regulatory framework and relevant literature. Factors are classified according to their impact on stakeholders: those directly affecting the operational and financial position are considered internal (strengths and weaknesses), while those arising from the regulatory, market, and governance environment are treated as external (opportunities and threats). Each factor is further categorised based on the direction of its impact. The identification of specific factors within each quadrant was derived from the structural differences documented in the comparative analysis, where each difference was assessed according to whether it originates from the charging methodology itself or from the external regulatory and governance environment, and whether its expected effect on the respective stakeholder group is favourable or adverse.

The assessment is conducted separately for IMs and railway undertakings RUs, reflecting their distinct roles within the rail system. IMs operate as regulated infrastructure providers under national financing frameworks, whereas RUs operate in competitive transport markets, resulting in structurally different responses to charging reforms.

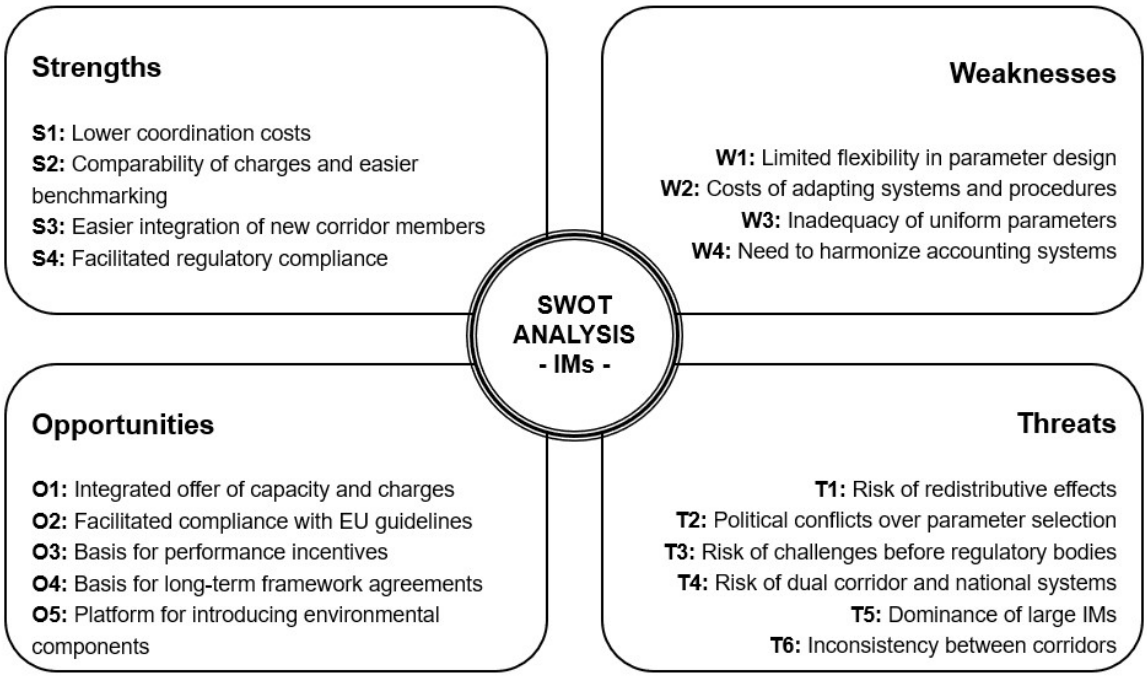
Within this framework, the SWOT analysis captures efficiency effects, coordination benefits, and market implications, as well as institutional constraints, revenue risks, and governance challenges. The method is applied as an exploratory analytical tool to structure qualitative evidence and support the policy interpretation presented in the final section of the paper.

4. RESULTS AND DISCUSSION

4.1 SWOT analysis from the perspective of Ims

The SWOT analysis from the perspective of IMs, presented in Figure 2, aims to evaluate the institutional and operational implications of introducing a corridor-level track access charging system.

Figure 1. SWOT analysis from the perspective of IMs



Source: Authors

As illustrated, the strengths identified for IMs primarily reflect organisational efficiency gains and improved regulatory positioning resulting from replacing nationally fragmented charging logics with a shared corridor-level framework. First, *lower coordination costs (S1)* arise from the elimination of repeated bilateral negotiations between neighbouring IMs when developing corridor products. Under a corridor-level charging system, IMs apply predefined common calculation rules instead of aligning national charging models on a case-by-case basis. The relevance of this effect increases with the geographical scope of the corridor, since coordination complexity grows with the number of participating countries. Second, *comparability of charges and easier benchmarking (S2)* enables IMs to directly compare charging levels without converting heterogeneous parameters and components. This transparency improves the identification of inefficiencies and provides a structured basis for discussions on cost levels and cost drivers.

Third, *easier integration of new corridor members (S3)* reduces expansion barriers. A new IM joining the corridor adopts an already defined charging structure rather than requiring adjustments from existing members. This shortens integration timelines and lowers transaction costs associated with corridor enlargement, which is particularly relevant in the context of network extensions toward new markets and regions. Finally, *facilitated regulatory compliance (S4)* results from the collective validation effect of a shared methodology. A common charging approach reduces the probability that an individual IM will face regulatory objections regarding compliance with Directive 2012/34/EU or Regulation 2015/909. However, this advantage depends on the common framework itself being compliant, otherwise, regulatory risk becomes systemic rather than individual.

The weaknesses associated with a corridor-level charging system primarily relate to reduced adaptability of national systems and the administrative burden of transitioning from heterogeneous national frameworks to a common charging system. The first limitation concerns *limited flexibility in parameter design (W1)*. Corridor-level charging system inevitably constrains the ability of IMs to tailor charging parameters to the specific characteristics of their networks, such as the share of electrified lines, traffic density, or infrastructure age. Parameters optimal for one network may be suboptimal for another, particularly on heterogeneous corridors where infrastructure conditions differ significantly

across countries. A second weakness involves the *costs of adapting systems and procedures (W2)*. Transition to a common charging structure requires modifications to billing and IT systems, internal procedures, staff training, and potentially accounting practices. These one-off adjustment costs may be substantial, especially for smaller IMs with limited administrative capacity, and their magnitude is proportional to the deviation of the existing national charging model from the common framework.

Closely related is the *inadequacy of uniform parameters (W3)*. A single parameter set cannot adequately reflect the cost structures of networks with high fixed costs and low traffic volumes, typical of smaller systems, and those benefiting from economies of scale, typical of larger networks. As a result, a common charging framework may systematically underestimate costs for some IMs and overestimate them for others. A further limitation concerns the *harmonisation of accounting systems (W4)*. A common charging methodology requires comparable cost categories as input variables, such as maintenance, traffic management, and depreciation. Divergent national cost classification and allocation practices may lead to inconsistent application of identical formulas, meaning that indicators such as cost per train-kilometre may represent different cost scopes across systems.

The identified opportunities relate to transforming the charging framework from a national accounting instrument into a corridor-level operational and policy tool, thereby strengthening corridor governance beyond capacity allocation. The first opportunity is the *integrated offer of capacity and charges (O1)*. A corridor-level charging system enables the application of a single calculation logic across the corridor, with consistent definitions of units, traffic categories, modifiers, and incentives. This facilitates the integration of charging into corridor capacity products, such as PaPs, as the C-OSS can apply uniform pricing logic across all sections. A second opportunity is *improved compliance with EU guidelines (O2)*. The corridor-level charging system provides a structured framework for implementing Regulation 2015/909, including direct cost calculation, mark-ups, and incentive mechanisms, enabling consistent application and mutual verification among participating IMs.

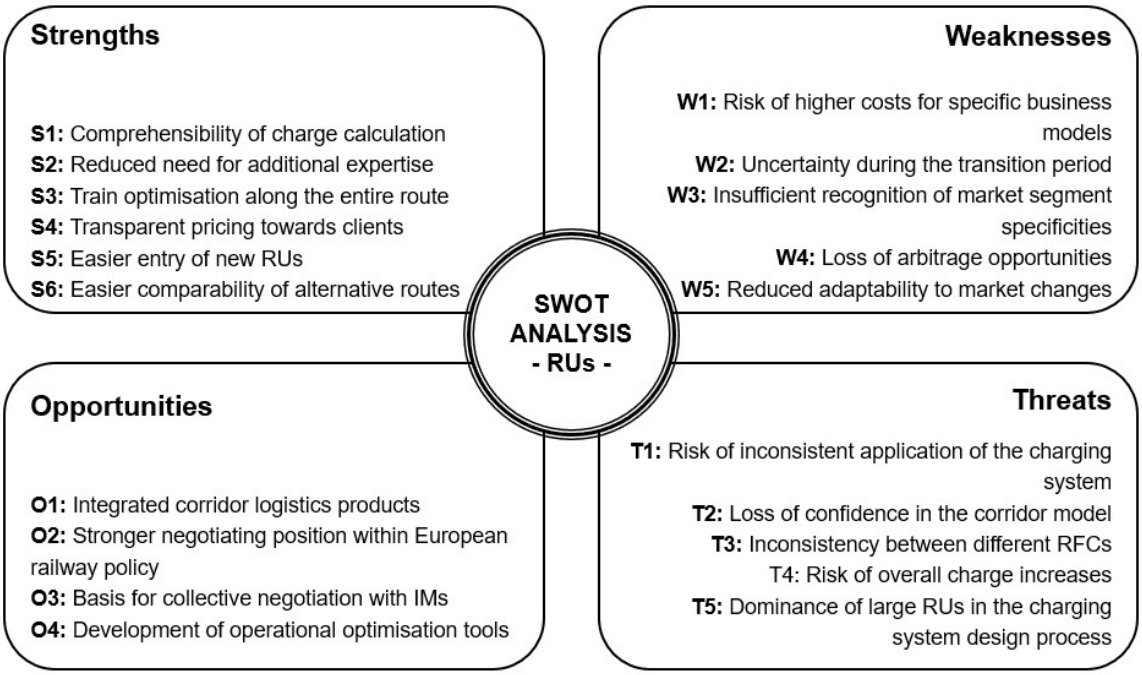
The third opportunity is the basis for *performance incentives (O3)*. A corridor-level charging system facilitates the introduction of performance regimes by ensuring consistent baseline values and measurement of deviations across the corridor, thereby increasing credibility for RUs and reducing disputes over bonuses and penalties. It also supports the development of *long-term framework agreements (O4)*. Stability in parameter definitions, traffic categories, and calculation logic enables IMs to offer contracts with predictable charging rules, reducing methodological risk for RUs in multiannual planning. Finally, the system provides a *platform for environmental components (O5)*, allowing coordinated implementation of factors such as noise and emission differentiation across the corridor and avoiding distortions caused by unilateral national measures.

The threats associated with introducing a corridor-level charging system primarily concern distributional effects, governance conflicts, and regulatory risks. A key concern is the *risk of redistributive effects (T1)* and resulting uncertainty in revenue levels and national budget implications. Changes in cost allocation across traffic categories may require significant restructuring for IMs, potentially generating resistance. Closely related are *political conflicts over parameter selection (T2)*, as choices of weighting factors, train categories, or time differentiation may favour certain traffic types or IMs. Further risks include *regulatory challenges (T3)*, where decisions by a single national regulator may affect the entire corridor, and the emergence of *dual systems (T4)*, increasing administrative complexity and inconsistencies between corridor and national charging. In addition, the *dominance of large IMs (T5)* may influence system design, while *inconsistency between corridors (T6)* could shift fragmentation from the national to the corridor level, undermining transparency and predictability.

4.2 SWOT analysis from the perspective of RUs

The SWOT analysis from the perspective of RUs operating along the corridor, presented in Figure 3, aims to identify the implications of applying a corridor-level charging system to their business operations.

Figure 2. SWOT analysis from the perspective of RUs



Source: Authors

The strengths identified for RUs primarily relate to improved cost transparency, reduced informational asymmetries, and enhanced operational decision-making under a corridor-level charging system. First, *improved comprehensibility of charge calculation (S1)* enhances end-to-end cost predictability by replacing multiple national methodologies with a single calculation logic. This reduces the likelihood of errors and enables faster and more reliable price quotations. Closely related is the *reduced need for specialised expertise (S2)*, as knowledge of a common charging framework becomes transferable along the corridor, lowering reliance on country-specific experts or external consultants. This effect is particularly relevant for smaller RUs with limited administrative capacity.

A further strength is the *optimisation of train characteristics across the entire route (S3).* Consistent incentives related to parameters such as axle load, train length, or environmental performance allow operators to optimise rolling stock and operational decisions at corridor level, rather than adapting to potentially conflicting national signals. In addition, *transparent price formation (S4)* improves commercial credibility, as RUs can explain infrastructure costs using a single, consistent logic, facilitating communication with clients and supporting long-term contractual arrangements. Finally, a common charging system *lowers barriers to entry (S5)* and *improves route comparability* (*S6*), enabling new entrants to access corridor markets more easily and allowing all RUs to compare alternative routes using a consistent methodological framework.

The weaknesses associated with a corridor-level charging system primarily relate to reduced strategic flexibility and transitional uncertainty. A key limitation is the *risk of higher costs for specific business models (W1)*, as RUs optimised for favourable features of national systems may face increased costs or require operational adjustments. Closely related is *uncertainty during the transition period (W2)*, which complicates cost forecasting, financial planning, and pricing strategies.

Further weaknesses include the limited recognition of market segment specificities (*W3*), as aggregated traffic categories may not fully capture differences between intermodal, bulk, or time-sensitive freight. In addition, the *loss of arbitrage opportunities (W4*) removes competitive advantages previously derived from navigating national charging differences. Finally, *reduced adaptability to market changes (W5)* represents a regulatory constraint, as adjustments to a corridor-level framework are inherently slower and more complex than modifications within individual national systems.

The opportunities associated with a corridor-level charging system reflect its potential to transform infrastructure charging from a fragmented national constraint into a strategic corridor-level instrument. First, it enables the development of *integrated corridor logistics products* (*O1*), as consistent charging logic allows RUs to design services with unified cost structures, simplifying internal planning and supporting standardised market offerings. Second, it strengthens the *negotiating position of RUs in European rail policy debates (O2*), as transparent and comparable charging frameworks facilitate evidence-based discussions on competitiveness, regulatory distortions, and alignment with other transport modes.

A further opportunity lies in the basis for *collective engagement with IMs (O3)*. This approach would allow RUs to formulate joint positions on charging design at corridor level, shifting engagement from fragmented national discussions to coordinated input through corridor governance structures. This increases the influence of RUs in shaping methodological revisions. In addition, common charging framework enables the *development of corridor-wide optimisation tools (O4)*. Unified calculation rules support the creation of software solutions for cost and routing optimisation that function across the entire corridor, which would be significantly more complex under heterogeneous national systems.

The threats associated with a unified corridor-level charging system primarily concern governance risks, credibility, and potential unintended distributional effects. A first threat is the *risk of inconsistent application of the charging system (T1)*. Even with a formally common charging framework, differences in interpretation or procedural implementation by individual IMs may persist, leading to divergence between nominal corridor-level charging system and practical outcomes. Such discrepancies undermine transparency and predictability. Closely related is the *risk of loss of market confidence (T2)*. If the common charging framework is perceived as insufficiently aligned with operational realities or market segment needs, RUs may lose trust in corridor-based products and revert to national planning approaches.

Another significant threat concerns *inconsistency between RFCs* (T3). If different corridors adopt distinct corridor-level charging system, fragmentation merely shifts from the national to the corridor level. Operators using multiple corridors would then face renewed complexity, partially offsetting the benefits of introducing common charging frameworks. In addition, there is a *risk of an overall increase in charges* (T4). The proposed approach may be used to introduce additional components or modifiers into the charging formula, increasing complexity and potentially the overall cost burden, particularly in the absence of strong regulatory oversight. Finally, dominance of large *RUs in the methodology design process* (T5) represents a governance risk. Larger operators possess greater resources to participate in working groups and consultations, potentially leading to outcomes that reflect their operational models more closely than those of smaller or specialised operators.

5. CONCLUSION AND POLICY DISCUSSION

This paper examined the implications of introducing a corridor-level TACs system. The empirical assessment of the Rhine–Danube corridor demonstrates that heterogeneity in charging systems extends beyond tariff levels to the fundamental architecture of national charging frameworks, including formula structures, differentiation parameters, line categorisation schemes, and supplementary charging elements. The test calculation for a reference freight train confirms that identical operational characteristics may result in substantially different TAC costs along a single international corridor. These findings indicate

that charging fragmentation represents not merely an administrative burden, but an economic constraint affecting the competitiveness of cross-border rail freight transport.

The analysis further shows that RUs face a dual complexity. TACs must first be incorporated into end-user pricing when preparing commercial offers and subsequently settled individually with each IM under nationally defined charging systems. Although coordination instruments such as the Charging Information System improve transparency, they do not eliminate charging system differences. As a result, RFCs governance and defined instruments have achieved partial operational harmonisation in capacity allocation and traffic management, while the economic dimension of TAC charging remains nationally fragmented.

The SWOT analysis reveals a clear asymmetry of incentives between IMs and RUs. For RUs, the introduction of a corridor-level charging framework primarily enhances cost predictability by reducing informational asymmetries, lowering market entry barriers, enabling consistent economic signals across borders, and strengthening the commercial credibility of corridor-based services. For IMs, however, it generates both efficiency gains and institutional risks. While coordination costs may decline and benchmarking transparency improve, it simultaneously limits national flexibility, raises concerns regarding revenue redistribution, and challenges established cost-allocation principles embedded in national financing models.

This asymmetry carries important policy implications. Establishment of corridor-level charging system cannot be treated solely as a technical optimisation measure but rather implies a redistribution of financial risks and regulatory competences within the European rail system. IMs operate under heterogeneous public funding arrangements that combine state compensation and TAC revenues in varying proportions. Consequently, any common charging framework on the corridor level inevitably interacts with national budgetary structures. Without mechanisms ensuring revenue neutrality or transitional adjustment, resistance from national authorities is likely to outweigh perceived efficiency gains.

The findings suggest that a realistic policy pathway lies in gradual structural alignment of the charging framework, understood as convergence in formula structures, cost categories, and differentiation parameters while retaining nationally determined parameter values, rather than immediate unification under a single tariff schedule. An initial step would involve aligning methodological elements, including definitions of direct cost categories, differentiation parameters, and formula structures, while preserving controlled national flexibility in parameter values. Such an approach could reduce system incompatibilities without triggering significant redistributive shocks. At the same time, enhanced coordination among national regulatory bodies is required to ensure legal consistency, while corridor governance structures must incorporate safeguards to prevent dominance by either large IMs or major RUs in the design process.

More broadly, the analysis highlights an inconsistency within the current framework of railway corridors. The constraint identified in this paper reflects a wider pattern: operational coordination at corridor level has no corresponding counterpart in market and economic regulation. If the strategic objective of European rail policy is to increase the modal share of rail freight and strengthen cross-border integration, the economic dimension of corridor functioning cannot remain institutionally separated from its operational dimension. The balance between these objectives defines the core political-economy challenge of corridor-level charging reform.

This paper represents an initial exploratory contribution to this debate. By combining empirical evidence on TAC charging systems heterogeneity with a stakeholder-oriented SWOT framework, it provides a systematic assessment of incentives and constraints without proposing a fully specified aligned charging model. Future research should therefore focus on developing concrete methodological approaches for corridor-level charging system, including common parameter frameworks with adjustable national coefficients and mechanisms for coordinated mark-up design. Further progress requires numerical simulation studies or real-world case analyses. The development of calibrated quantitative examples,

either through modelling or pilot implementation on a selected corridor, would enable assessment of revenue redistribution effects, competitiveness impacts, and budgetary implications under alternative harmonisation scenarios.

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Pregledni rad

PREDNOSTI I NEDOSTACI JEDINSTVENOG SUSTAVA NAPLATE PRISTUPA PRUZI ZA ŽELJEZNIČKE TERETNE KORIDORE

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SAŽETAK

Europski teretni željeznički koridori, uspostavljeni Uredbom 913/2010, imaju za cilj ojačati konkurentnost međunarodnog željezničkog teretnog prijevoza kroz koordinaciju, prvenstveno među upraviteljima infrastrukture. Ta koordinacija obuhvaća aktivnosti poput planiranja ulaganja, upravljanja prometom, osiguravanja odgovarajućeg kapaciteta željezničke infrastrukture te olakšanog korištenja tog kapaciteta. Međutim, jedan ključni element koji ovom uredbom nije obuhvaćen odnosi se na naknade za pristup željezničkoj infrastrukturi, koje i dalje ostaju u nadležnosti nacionalnih regulatornih okvira. Kao rezultat toga, duž jednog međunarodnog željezničkog koridora primjenjuje se više različitih sustava naplate pristupa infrastrukturi. Takva neujednačenost sustava naplate dovodi do neizvjesnosti troškova za željezničke prijevoznike, što izravno narušava konkurentnost željezničkog prijevoza u odnosu na druge vrste prijevoza. Ovaj rad analizira prednosti i nedostatke uvođenja sustava naplate pristupa infrastrukturi na razini koridora, kao preduvjeta za učinkovitije funkcioniranje. Analiza se provodi primjenom SWOT okvira, pripremljenog iz perspektive upravitelja infrastrukture i željezničkih prijevoznika. Iz perspektive upravitelja infrastrukture analiziraju se učinci na prihode, autonomiju određivanja cijena i administrativne troškove, dok se iz perspektive željezničkih prijevoznika naglasak stavlja na predvidljivost troškova, operativno planiranje i tržišnu konkurentnost. Rezultati pokazuju da bi sustav naplate na razini koridora željezničkim prijevoznicima omogućio pojednostavljene postupke naplate i smanjeno administrativno opterećenje, dok bi za upravitelje infrastrukture zahtijevao uravnoteženje između povećane administrativne učinkovitosti i rizika za stabilnost prihoda. Na temelju utvrđene asimetrije poticaja među ključnim dionicima, rad donosi i raspravu o javnim politikama s prijedlogom puta prema uspostavi jedinstvenog sustava naplate.

Ključne riječi: *naknade za pristup željezničkoj infrastrukturi, teretni željeznički koridori, SWOT analiza, upravitelji infrastrukture, željeznički prijevoznici*

Original Scientific Paper

DESIGN OF A SINGLE-AXLE BOGIE FOR A REGIONAL RAIL VEHICLE

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ABSTRACT

Railway passenger transport remains one of the most sustainable modes of mobility, particularly when operated by electric traction. Its high capacity, safety, ride comfort, and low environmental burden make it suitable for regional services. However, a substantial share of regional rolling stock still relies on outdated vehicle concepts, which constrains further progress in efficiency, reliability, and environmental performance. In response to these challenges, this paper presents the design and structural assessment of a new single-axle bogie intended for regional passenger rail vehicles. The proposed concept was developed with respect to typical regional operating conditions, including moderate running speeds, negotiation of tight-radius curves, and variable passenger loading. The bogie is presented as a three-dimensional model comprising the structural subsystems, namely the frame, the suspension arrangement, and the wheelset guidance system. The suspension design incorporates both primary and secondary stages; the secondary suspension employs air springs to maintain a constant vehicle floor height under changing static loads, thereby contributing to ride comfort, running stability, and operational safety. The bogie frame, designed as a welded steel structure made of S355J2, was evaluated by finite element analysis under service loading. The numerical results confirmed that the maximum equivalent stresses remained below the allowable material limit and that the maximum displacement reached 1.106 mm, which remained within an acceptable range for the intended regional application. These findings indicate that the proposed bogie frame satisfies the strength and stiffness criteria and represents a promising solution for the modernization of regional railway vehicles within sustainable transport systems.

Key words: *a single-axle bogie, a rail vehicle, a three-dimensional model, regional transport, FEM analysis*

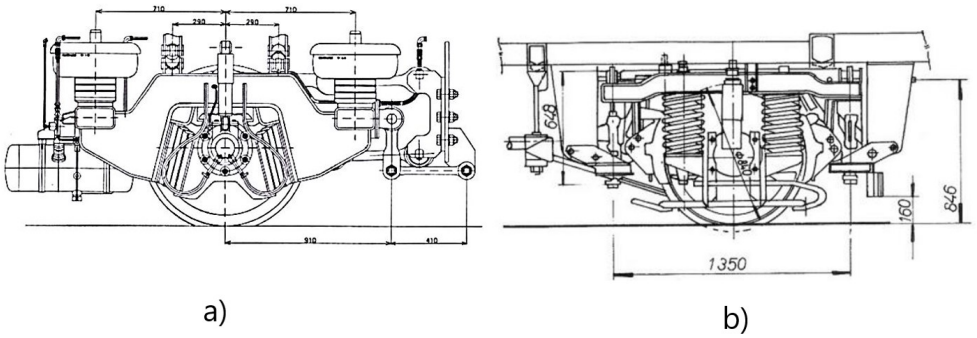
1. INTRODUCTION

Rail transport is commonly identified as one of the most sustainable forms of public transportation, especially when environmental criteria are considered (Bouraima et al., 2024; Dudziak et al., 2022; Kagramanian et al., 2023; Sistuk, 2024). At the same time, the railway

sector is undergoing continuous technological change, which increases the need for new technical solutions that can improve efficiency, dependability, and environmental acceptability. However, passenger preference for railways is not determined solely by ecological aspects. Comfort, safety, network accessibility, and acceptable travel times are also decisive factors influencing its attractiveness. One of the major goals in current railway vehicle development is to deliver railway vehicles capable of satisfying stricter demands in terms of performance, ride quality, user accessibility, and environmental compatibility. As interest in rail-based mobility grows, expectations regarding vehicle quality also rise. Modern passengers increasingly require safe, comfortable, and accessible trains, and low-floor design has become one of the most important characteristics in this context (Dudziak et al., 2023; Song et al., 2026). A persistent problem is that many countries still operate a substantial number of aging rail vehicles whose service lives have already been extended beyond the originally intended period. Although refurbishment programs are often used to reduce investment costs, these measures usually prolong the operation of vehicle concepts that were not originally designed as low-floor units. Consequently, modernization of older railway vehciles alone cannot be regarded as a sufficient long-term answer. A more durable way to strengthen the appeal and sustainability of rail transport is the deployment of newly developed low-floor vehicles designed from the outset to provide higher comfort and safety (Banic et al., 2022; Fanta et al., 2022; Gerlici et al., 2017a; Hauser et al., 2017b). A suitable response to these requirements can be found in regional rail vehicles that combine independent traction with single-axle bogies and are therefore capable of operating on local non-electrified lines. This arrangement offers a flexible and progressive vehicle concept for present-day railway operation, with advantages that include broader route applicability, improved passenger conditions, and a smaller environmental burden (Chudzikiewicz et al., 2024; Gorbunov et al., 2019). Because the bogie has a fundamental influence on dynamic behavior, ride comfort, and operational safety, this study focuses on the conceptual development of an innovative single-axle bogie intended specifically for such regional rail vehicles (Fischer, 2025; Fischer et al., 2024; Gerlici et al., 2013).

Currently, single-axle railway bogies are used in light regional rail vehicles designs, such as an ALSTOM Coradia Lirex, a Jenbacher Integral, and a ZNTK Poznań Regio Tramp, as well as a DB 670. In the Czech Republic and Slovakia, they are most commonly found in the form of the 810 series and its modifications.

Figure 3. Technical drawing of the single-axle rail bogie: a) Regio Tramp, b) Class 810



a) b)

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2. A VEHICLE BODY

A design of a regional rail vehicle body in which the proposed single-axle bogie could be implemented is shown in Fig. 2 and Fig. 3.

Figure 4. A design of a regional rail vehicle body

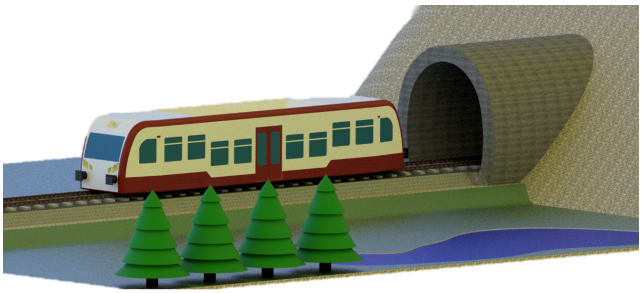

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Figure 5. A front view of a regional rail vehicle

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It can be seen that the body is partially low-floor. The low-floor section has a designated area for storing bicycles, as well as space for people with reduced mobility and space for prams. There is also a designated area for a toilet, which is accessible to people with reduced mobility. This section has seats for passengers (Fig. 5). The high-floor section has passenger seats and the driver's cab, which is separated from the passenger area by partitions and doors. The bogies would be located under the high-floor section. Space for the vehicle's equipment is reserved on the roof of the vehicle. If space permitted, the combustion engine with traction generator would also be located on the roof of the vehicle. However, from a design point of view, this would be a very challenging location, as the vibrations generated primarily by the operation of the combustion engine would spread throughout the vehicle structure, resulting in a significant reduction in travel comfort. These vibrations can be eliminated, for example, by mounting the engine with the generator in hydraulic silent blocks, which would absorb a large amount of the vibrations generated. A more advantageous solution would be to place these components in the area under the high floor.

Figure 6. Basic dimensions of a regional rail vehicle

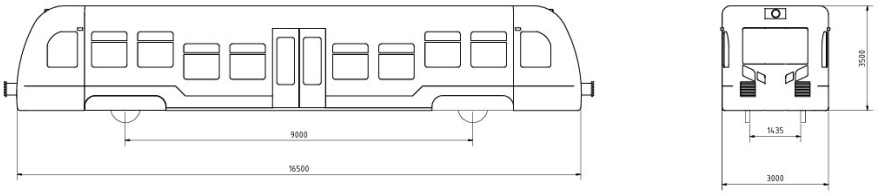

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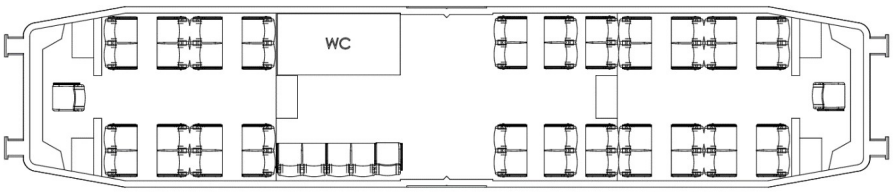
Figure 7. An interior layout of a regional rail vehicle



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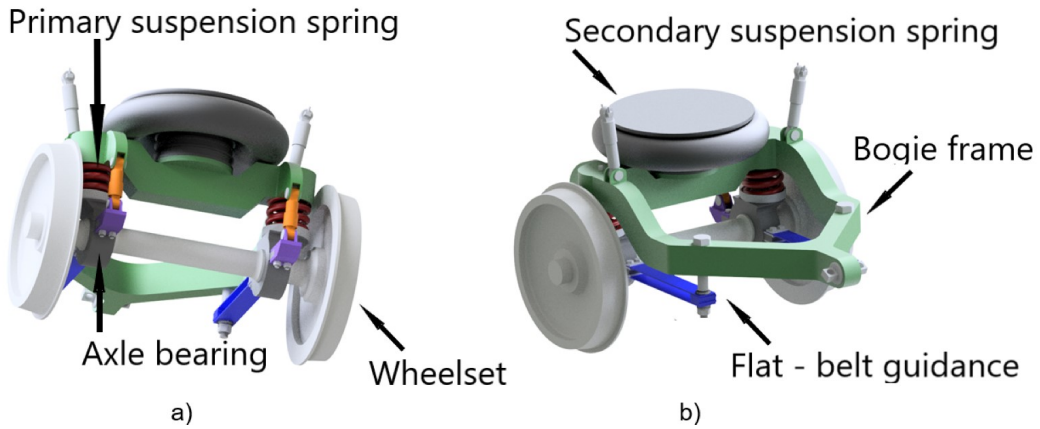
3. DESIGN LOAD CASES AND A STRUCTURAL CONFIGURATION OF THE BOGIE

Under actual service conditions, bogie frames are subjected to highly variable loading that depends on multiple influences, such as the number of passengers carried, the condition of the track, deviations from ideal track geometry, local defects in the rail structure, and other operating circumstances. Owing to this variability, the load history acting on the bogie cannot be described precisely by a simple deterministic function. Instead, the design and testing of newly developed bogies are based on a representative substitute load spectrum (Gerlici et al., 2017b; Hauser et al., 2017a; Topczewska et al., 2022). This approach is used not only in experimental validation but also increasingly in virtual structural verification and optimization. The loading cases considered in the design process are derived from applicable regulatory documents, including UIC recommendations, European and national standards, and, where relevant, operator-specific technical requirements. In all cases, the prescribed loads must correspond to the service environment for which the vehicle is intended. The bogie presented in this study was designed for a wheel diameter of 840 mm and for standard-gauge railway track with a gauge of 1,435 mm. Its single-axle arrangement includes the essential structural and functional elements required to support the vehicle body and to ensure reliable guidance during motion. Longitudinal traction forces are transmitted through a central kingpin. At the rear part of the frame, dedicated brackets are provided for two dampers whose task is to suppress oscillatory behavior associated with suspension movement and frame vibration in operation (Stoilov et al., 2024; Stojanović et al., 2024). These dampers act between the axle bearing housings and the bogie frame in the region of the primary suspension as it is depicted in Fig. 6.

Figure 8. A 3D model of the single-axle rail bogie: a) A rear view, b) A front view



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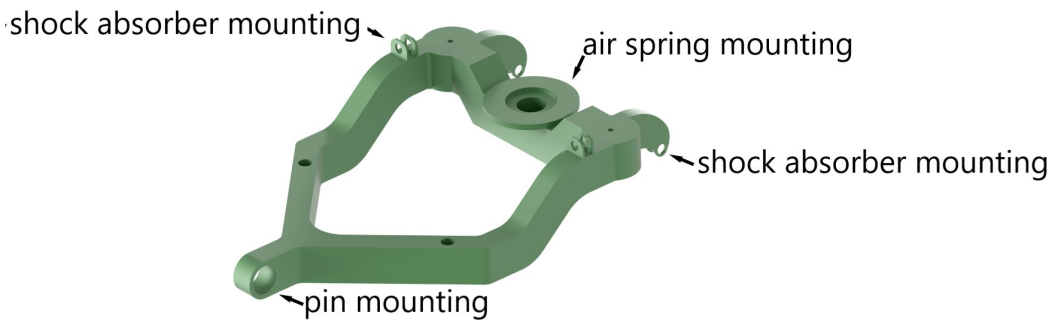
Another pair of dampers is installed vertically between the vehicle body and the bogie frame, where the dominant oscillatory effects are associated with the secondary suspension stage. A disadvantage of the chosen layout is that the secondary air spring is positioned relatively far from the kingpin. For this reason, the vehicle load is not carried solely through the air spring, and part of it is transferred through the kingpin itself. This increases the mechanical demand placed on the kingpin and may slightly reduce ride comfort.

4. A BOGIE FRAME AND A SUSPENSION CONCEPT

The frame is the main structural component of the bogie and provides the supporting basis for all other installed parts. An internal frame arrangement was selected chiefly with the aim of reducing overall mass (Fig. 7). The structure takes the form of a welded beam assembly composed of two longitudinal members, the front portions of which are lowered. The cross member is locally offset in its central part in order to reduce the installation space required by the air spring of the secondary suspension. End beams are included to increase transverse rigidity and to provide mounting interfaces for the wheelset guidance pins as well as the damper supports. For wheelset guidance, a flat-belt system was adopted. This concept is well known from conventional passenger coach applications, where it has demonstrated reliable long-term service in a very large number of vehicles. The belts are usually arranged on both sides of the bogie in parallel with the longitudinal beams. Depending on the design application, they may be produced either from steel or from composite materials. Because they exhibit high stiffness in the transverse direction, their lateral deformation remains very small (da Silva Moreira et al., 2024; Szalai et al., 2023). The principal benefits of flat-belt guidance are its low weight and limited space requirements. From the material standpoint, the bogie frame was designed from S355J2 structural steel with guaranteed weldability according to EN 12 663-1. Rectangular hollow sections with a wall thickness of 12 mm were used. The subsequent structural calculations showed that this thickness provides a suitable balance between sufficient strength and economical material usage.

Figure 9. A designed internal bogie frame



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The choice of the secondary suspension was determined primarily by the vehicle's operational mission. The bogie is intended for a motor railcar exposed to considerable variations in passenger occupancy during daily service. For that reason, an air spring was selected as the most appropriate solution. Its main advantage is the possibility of adjusting internal pressure so that the required buffer height can be maintained even when the static load changes. In addition, air suspension offers favorable compliance properties, which are particularly valuable in lightweight regional vehicles operating under varying passenger demand. Another practical benefit of this concept is that it allows a comparatively simple bogie frame arrangement.

5. THE FINITE ELEMENT ANALYSIS

The numerical investigation was performed in order to confirm that the proposed bogie frame is able to withstand service-related loading conditions represented by realistic boundary conditions. The structural verification was carried out as a static strength assessment with emphasis on vertical loading of the bogie frame, using the Finite Element Method.

The simulations were conducted in the ANSYS environment, which is commonly used in structural mechanics, dynamics, and fluid-related analyses. Other software packages often employed for comparable tasks include Abaqus and Adams. The key benefit of numerical simulation lies in the possibility of evaluating geometrically complex structures that are difficult or impractical to assess analytically. On the other hand, the required computational time depends strongly on the available hardware, and any geometric or load modification generally necessitates a repeated analysis cycle (Decker et al., 2023; Ézsiás, et al., 2024; Miltenovic et al., 2015).

Several boundary conditions were introduced into the strength calculation. A vertical force of 99,500 N was applied at the location of the secondary suspension air spring, representing the mean gravitational load transferred from the car body to one bogie. This corresponds to an overall load of roughly 199,000 N shared by both bogies. Additional applied loads comprised 8,000 N acting on the damper brackets for each of the two suspension levels. The loads are shown in Fig. 8.

The finite element model of the frame, which is shown in Fig. 9, was meshed with elements of approximately 10 mm nominal size. The resulting mesh contained 310,232 elements and 528,230 nodes. In zones of more complicated geometry and in areas where stress concentration was expected, the mesh was automatically refined using smaller elements in order to improve result accuracy. Evaluation of the equivalent stress field according to the

von Mises criterion showed that the frame fulfills the strength requirement, since the maximum equivalent stress did not exceed the yield limit of 355 MPa.

Figure 8. Boundary conditions for defined calculation

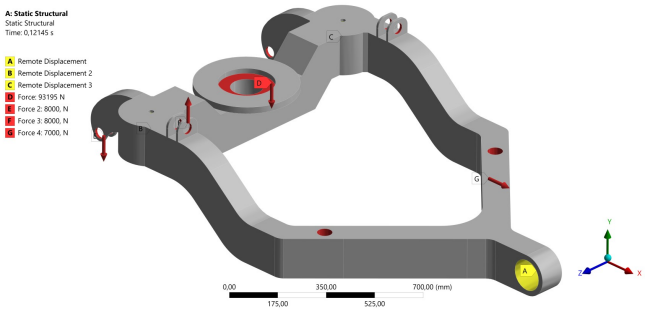

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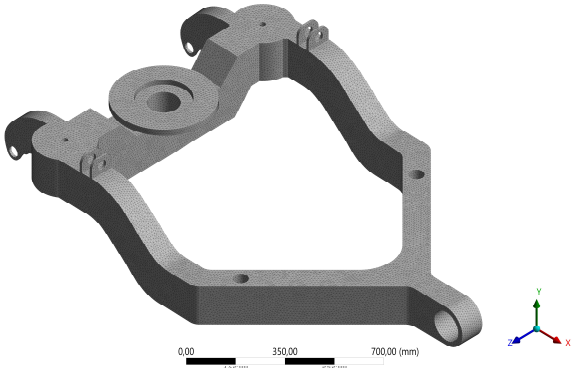
Figure 9. A created finite element model of the bogie frame



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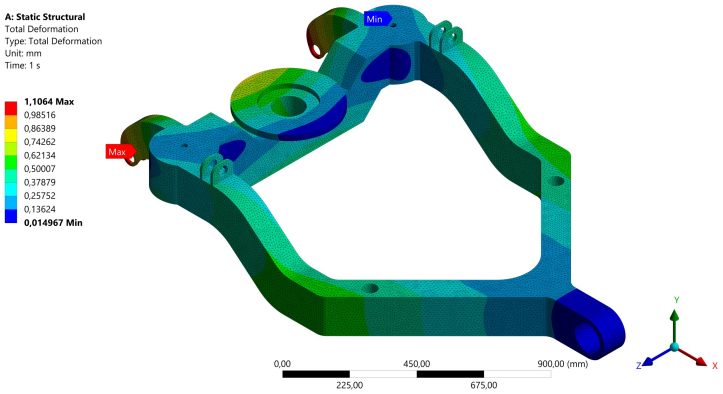
The displacement results indicated a maximum deformation of about 1.106 mm (Fig. 10). Larger deformation values generally correspond to greater torsional compliance of the bogie frame, which improves its capacity to accommodate vertical track irregularities. In contrast, smaller deformation values indicate higher torsional rigidity and therefore more favorable lateral stability characteristics.

Figure 10. Calculated deflections of the bogie frame structure



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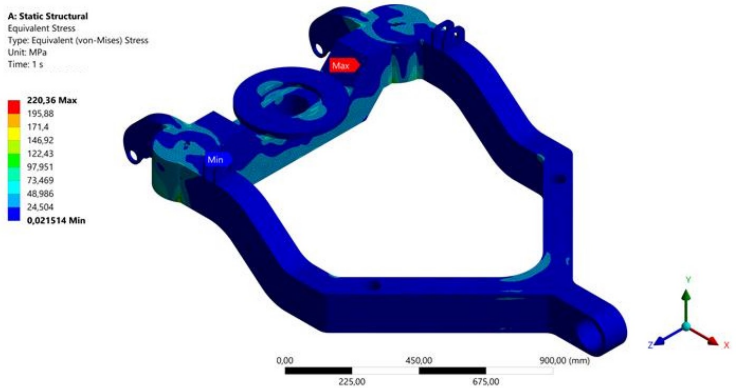
The stress distribution obtained from the analysis, assessed according to the von Mises criterion, confirmed that the bogie frame meets the required strength conditions, as the maximum equivalent stress reached 220.36 MPa, which is below the material yield strength of 355 MPa. The resulting stress distribution is shown in Figure 11.

Figure 11. A distribution of stresses in the bogie frame



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Future research should extend the present static strength assessment toward a broader verification of the proposed bogie concept under realistic operating conditions (Lovska et al., 2024; Lovska et al., 2022; Panchenko et al., 2023). Since this is a newly developed single-axle bogie arrangement, further work should include multibody dynamic simulations in order to evaluate its running behavior on straight track as well as in curves and over representative track irregularities. Particular attention should be paid to the identification of the critical speed, wheel–rail contact forces, ride comfort indicators, and running safety parameters, including derailment-related criteria (Gerlici et al., 2025). Another important research direction is structural optimization of the bogie frame with respect to mass reduction. However, such optimization should not be pursued uncritically, because a sufficient vehicle mass may also be beneficial from the viewpoint of wheel–rail adhesion and stable traction performance. In addition, future work should address fatigue durability, weld-sensitive regions, and the interaction between structural stiffness and suspension tuning, so that the overall design can be assessed not only from the viewpoint of static strength, but also with respect to long-term operational reliability, passenger comfort, and traffic safety.

6. CONCLUSIONS

This paper introduced a compact single-axle bogie concept aimed at regional passenger rail vehicles with a partially low-floor body arrangement. The proposed solution combines a lightweight welded frame with two-stage suspension, where the secondary stage uses an air spring to maintain the required buffer height under changing static loads caused by daily fluctuations in passenger occupancy. Such a choice is technically consistent with the operational mission of regional railway vehicle, where comfort, stability, and accessibility requirements must be met without excessive structural mass. The structural feasibility of the bogie frame was verified by a static FEM strength assessment focused on service-representative vertical loading. The numerical model applied a vertical force of 99,500 N at the air spring position (mean gravitational load per bogie) and additional 8,000 N forces on damper brackets for both suspension stages. The frame mesh (≈310,232 elements and

528,230 nodes, with local refinement in expected stress-concentration regions) enabled evaluation of the equivalent stress field using the von Mises criterion. The results indicated a maximum equivalent stress of 220.36 MPa, remaining below the 355 MPa yield limit of the selected S355J2 steel, and a maximum deformation of about 1.106 mm, suggesting adequate stiffness for the investigated load case. At the same time, these findings should be interpreted as an initial design validation rather than a complete approval-grade demonstration. The current assessment is limited to static loading and does not yet quantify fatigue durability, weld detail sensitivity, or dynamic effects under real track irregularities. In addition, the selected layout places the secondary air spring relatively far from the kingpin, meaning that part of the vehicle load is transferred through the kingpin, increasing its mechanical demand and potentially reducing ride comfort. nance implications of the flat-belt wheelset guidance in real service. Future research should therefore extend the present analysis toward a broader verification of the proposed bogie concept under realistic operating conditions. In particular, multibody dynamic simulations should be carried out to evaluate running behaviour on straight track, in curves, and over representative track irregularities. Such analyses would enable the assessment of critical speed, wheel–rail contact forces, ride comfort indicators, and running safety parameters, including derailment-related criteria. Further work should also address fatigue durability, weld-sensitive regions, and possible structural optimization of the bogie frame with respect to mass reduction. However, mass optimization should be considered carefully, since a certain vehicle mass can contribute positively to wheel–rail adhesion and stable traction performance. Through these steps, the proposed bogie concept could be evaluated not only from the viewpoint of static strength, but also in terms of long-term operational reliability, passenger comfort, and traffic safety.

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Izvorni znanstveni rad

KONSTRUKCIJA JEDNOOSOVINSKOG OBRTNOG POSTOLJA ZA REGIONALNO ŽELJEZNIČKO VOZILO

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SAŽETAK

Željeznički putnički prijevoz i dalje ostaje jedan od najodrživijih oblika mobilnosti, osobito kada se odvija uz električnu vuču. Njegov veliki kapacitet, sigurnost, udobnost vožnje i nisko opterećenje okoliša čine ga prikladnim za regionalne usluge. Međutim, znatan dio regionalnog voznog parka i dalje se oslanja na zastarjele koncepte vozila, što ograničava daljnji napredak u učinkovitosti, pouzdanosti i ekološkim svojstvima. Kao odgovor na te izazove, u ovom se radu prikazuje projektiranje i strukturna procjena novog jednoosovinskog okretnog postolja namijenjenog regionalnim putničkim željezničkim vozilima. Predloženi koncept razvijen je s obzirom na tipične uvjete regionalnog prometa, uključujući umjerene brzine vožnje, prolazak kroz zavoje malog radijusa i promjenjivo opterećenje putnicima. Okretno postolje prikazano je kao trodimenzionalni model koji obuhvaća konstrukcijske podsustave, i to okvir, sustav ovjesa i sustav vođenja osovinskog sklopa. Konstrukcija ovjesa uključuje primarni i sekundarni stupanj; sekundarni ovjes koristi zračne opruge za održavanje stalne visine poda vozila pri promjenjivim statičkim opterećenjima, čime doprinosi udobnosti vožnje, stabilnosti kretanja i operativnoj sigurnosti. Okvir okretnog postolja, projektiran kao zavarena čelična konstrukcija od čelika S355J2, procijenjen je metodom konačnih elemenata pri radnom opterećenju. Numerički rezultati potvrdili su da su maksimalna ekvivalentna naprezanja ostala ispod dopuštene granice materijala te da je maksimalni pomak iznosio 1,106 mm, što je ostalo unutar prihvatljivog raspona za predviđenu regionalnu primjenu. Ovi nalazi pokazuju da predloženi okvir okretnog postolja zadovoljava kriterije čvrstoće i krutosti te predstavlja obećavajuće rješenje za modernizaciju regionalnih željezničkih vozila unutar održivih prometnih sustava.

Ključne riječi: *jednoosovinsko okretno postolje, željezničko vozilo, trodimenzionalni model, regionalni prijevoz, FEM analiza.*

Original Scientific Paper

STUDY OF FEASIBILITY OF USING SANDWICH COMPONENTS IN A WALLS' STRUCTURE OF A UNIVERSAL CONTAINER

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ABSTRACT

The research is focused on the implementation of sandwich-type components into containers structure to improve its walls strength under the operational loads. This solution is applied on an example of end walls of a container. The study was conducted for a universal container with a standard size of 1CC. The calculations led to the results, that the considered improvement of a container design contributes to reduce the stresses in the container structure by 15% in comparison with its original design. As an important task of the research, a calculation of the economic effect of application of the designed sandwich-type components into the container walls was carried out to substantiate the proposed solution to improve the container. It is determined that the economic effect will be achieved by reducing the costs of repairing containers during their operation. The calculation was carried out for a 177 container units' fleet. The economic effect of the implementation of the designed container structure is determined according to the conditions of its use for a calculation period of 10 years. The results of the calculations showed that the measure pays off in the first year of the calculation period. At the same time, the economic effect in the first year of the calculation period will be about 5,000 Euros. The economic effect during the cumulative sum in the last year of the calculation period will be more than 33,000 Euros. Hence, the use of sandwich components as walls of a universal container is economically feasible.

Key words: *improvement, sandwich components, container repair cost, container damage reduction, economic effect*

1. INTRODUCTION

Container transportation is a very popular type of goods transportation not only among countries within a continent, but also between continents (Alshoufi et al., 2024; Drozhzhyn, 2024; Filina-Dawidowicz and Kostrzewski, 2022). This type of transportation of goods represents a system of intermodal goods transport, where intermodal containers are used. It is the process of unitization of goods in exports. Containers as transport units have standardized dimensions. They allow to be loaded and unloaded, stacked, transported efficiently over long distances and transferred from one type of transport to another (ships, railway vehicles or road semi-trailers) (Dávid et al., 2021; Korlak, 2022;). An advantage of containerization consists in shorter times of loading and unloading different kinds of transport means (Jachimowski and Kłodawski, 2025; Kayar and Avşar, 2026). Railway transport plays

important role in intermodal transport, because it is effective and efficient kind of goods transport between inland countries (Zhu et al., 2025; Banic et al., 2025). Such a way of transport contributes to protection of environment at a sufficient speed and reliability of transport (Kostrzewski et al., 2024; Nehring et al., 2023).

However, the number of loading and unloading processes with containers have also negative impacts to their structure. Containers are handled by various types of handling machines, such as cranes, front loaders and others. Moreover, goods are loaded and unloaded to and from containers by many manners, such as forklifts, hydraulic arms and others. Thus, containers' structures are exposed to mechanical damages and faults (Stánicz and Török, 2026). The types of goods transported in containers is very diverse. This has led to the creation and implementation in operation of a large number of them according to their structural features and technology of container maintenance. An universal container is one of the most popular types of containers (Fig. 1).

The possibility of transporting containers by almost all means of transport causes damage to their structures in operation. Cracks and ruptures of a container wall cladding are one of the most serious damages of containers. They are illustrated in Fig. 2. Such damage necessitates the need for unscheduled types of container repairs. On the way, they are dangerous due to the loss of goods during transportation and also threaten safety of transportation. Therefore, there is a need to create and implement solutions aimed at improving the strength of container walls in operation.

Figure 8. Universal container: a) with a carrying capacity of 24 tons; b) with a carrying capacity of 40 tons

a) b)

Source: a) ContainerTrade.net (2026); b) Indiamart.com (2026)

Figure 9. Damage of a container cladding: a) tear; b) fracture

a) b)

Source: The Presentation.ru (2026)

A literature review of publications about this topic was conducted to analyse the current state of the issue of improving container structures to improve their strength when perceiving operational loads.

The use of square pipes as frame components was proposed to improve the strength of the container in the research by Gerlici et al., 2024. The features of calculating the strength of such a frame were highlighted and the feasibility of the proposed improvement was proven. At the same time, the authors did not study the issue of improving the strength of the container side walls.

In publication (Cheng et al., 2024), the container design was proposed and the results of its strength calculation under the main load modes were presented. However, the authors did not pay attention to the issue of improving the strength of the container structure.

The authors (Zha and Zuo, 2016) proposed in their research an increasing the rigidity of its structure. This solution is justified not only by theoretical calculations, but also by experimental studies. However, such an implementation does not contribute to improving the strength of the container side walls.

Improving the strength of the container can also be achieved by introducing new materials into its design. The use of carbon fibre materials in the design of the container is proposed by Turkay, 2016 in the scientific research. This solution certainly has a number of advantages compared to steel, which is a typical material for the manufacture of containers, but also requires appropriate capital investments for its use. In work (Lovska et al., 2026), the improvement of the container strength is achieved by introducing braces into the frame structure. At the same time, these braces connect the lower corner fittings with the transverse beams of the frame and contribute to the reduction of longitudinal loads acting on the container during transportation. The authors have not proposed solutions aimed at reducing transverse loads on the container structure.

A new container design for the transportation of fruit and vegetable cargo is proposed in work (Khadjimukhametova and Merganov, 2020). The features of the calculation of the container strength are highlighted. It is proven that the proposed solutions for the structural design of the container are appropriate. However, these improvements do not contribute to the improvement of the strength of the container side walls. A similar drawback can be noted in relation to the solutions highlighted in work (Ibragimov, 2015), which also provides solutions for improving the container for fruit and vegetable products.

The use of sandwich panels in a wagon body structure is justified in the publication by Ayman Al-Sukhon and Mostafa S.A. ElSayed, 2021. The research was conducted on an example of an open wagon. It is noted that this modernization can take place both during the production and modernization of railway vehicles. However, no justification for such an improvement was carried out for containers.

The publication (Placek et al., 2017) justifies the introduction of sandwich panels as the end walls of a container. It was found that considering the proposed improvement, it becomes possible to reduce the dynamic loads that a container perceives by 10% compared to a typical design. The results obtained were confirmed by computer modelling of the dynamic load of a container. However, the authors did not determine the lateral load of a container with walls made of sandwich panels.

An analysis of literature sources proves that improvement of container designs is a rather urgent task. Along with this, the issue of improving the strength of container walls needs to be addressed. After all, it has not been given due attention at the moment. Therefore, research devoted to creating solutions aimed at improving the strength of container walls is quite timely and important.

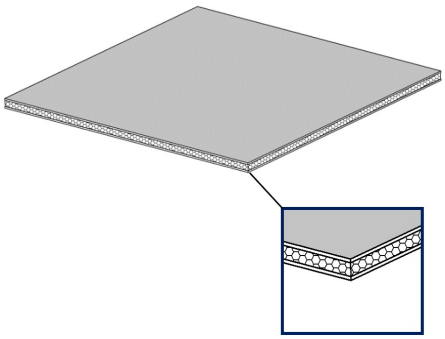
The main goal of the presented research is to provide a technical and economic justification of the use of sandwich components as walls of a universal container. To achieve this goal, the following tasks have been defined:

- To propose a methodology for calculating the economic effect of using sandwich components as container walls
- To calculate the economic effect of using sandwich components as container walls.

2. MATERIALS AND METHODS OF RESEARCH

It is proposed to implement sandwich-type components into its design to improve the strength of the container walls during operational modes (Fig. 3). Each sandwich panel is formed by two metal sheets with an energy-absorbing material placed between layers. The material for making the sheets is steel grade 09G2S, and foam aluminium is considered as energy-absorbing material.

Figure 10. A sandwich panel

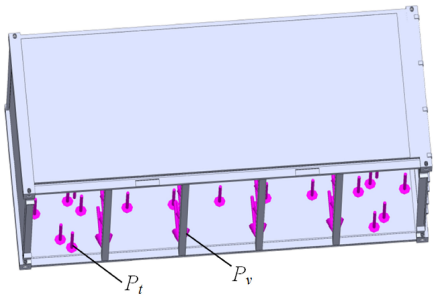


Source: Authors

This solution is implemented in an example of end walls. It was found that considering the proposed improvement, it becomes possible to reduce the dynamic loads that the container perceives by 10% compared to the typical design (Vatulia et al., 2023). The results of calculations on the strength of the container showed that the stresses in its design are lower by 15% than in the typical one (Fig. 4 and Fig. 5).

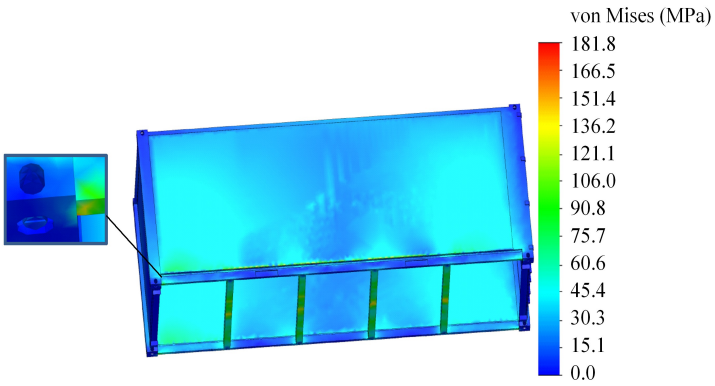
It is proposed to calculate the economic effect to substantiate the proposed technical solution (Balaka, 2005). It is predicted that the economic effect will be achieved by reducing the costs of repairing containers in operation. A container of the existing design was taken as the base sample, and a new version with a sandwich-type component design was taken as the new version. The calculation was carried out for the annual repair program of containers of standard size 1 CC - 177 units.

Figure 4. Calculation diagram of the container



P_t – the side wall load;
P_v – the vertical load
Source: Authors

Figure 5. Stress state of the container



Source: Authors

The economic effect of implementing the measure is determined according to the conditions of its use for the calculation period (10 years). The cumulative economic effect is determined as the sum of annual economic effects for the calculation period with mandatory consideration of the time factor according to the formula:

$$E_T = P_T - Z_T, \tag{1}$$

where E_T – the economic effect of implementation for the calculation period, P_T – the cost estimate of the results of implementing this measure for the calculation period, Z_T – the cost estimate of the costs of implementing this measure for the calculation period.

The total cost of a new technology in the first year of equipment implementation consists of one-time costs for its purchase, transportation and setup, and in subsequent years of the calculation period from the costs of operating the equipment. Hence, the economic effect is obtained from the difference in costs for the existing and new technology. The determination of the economic effect is carried out under the condition of mandatory reduction of different time estimates of results and costs to a single point in time of the calculation year for all options for implementing the scientific and technological progress measure.

The reduction of different time results and costs of all years of the measure implementation period to the calculation year is carried out by multiplying their cost estimate for each year by the reduction factor considering the inflation prediction:

$$\alpha_t = \frac{\left(1+E_P\right)^{t_R - t_P}}{\left(1+I\right)^{t_R - t_P}}, \tag{2}$$

where E_P – annual interest rate on deposits, E_P = 0.14, I – average annual inflation rate, forecasted during the project implementation period (20%); t_R – calculation year, t_P – year under consideration.

The procedure for calculating savings in current costs for container repair according to the basic and new design options.

3. EMPIRICAL DATA AND ANALYSIS

Calculation of the cost of materials for container repair is determined by the formula:

$$B_M = \sum_{i=1}^{n} \left(M_i \times C_i\right), \tag{3}$$

where M_i is the consumption of the i-th item of material, unit, C_i is the price per unit of material, EUR.

Savings in current material costs per container repair are determined by:

$$\Delta B_M = B_M^B - B_M^N. \tag{4}$$

The cost of electricity for container repair is determined by the formula:

$$B_{EL} = C_{EL} \times W \times t, \tag{5}$$

where C_{EL} – price per 1 kWh of electricity, EUR, W – power of electrical equipment for container repair, kW, t – operating time of electrical equipment for container repair.

The cost of basic wages for production workers to repair a container is determined by the formula:

$$B_{OZP} = GTS \times \lambda \times T, \quad (6)$$

where GTS – hourly tariff rate for the average worker, EUR, λ – number of production workers, people, T – labour intensity of container repair, hours.

The savings in current costs for basic wages for production workers per repair of one container is:

$$\Delta B_{OZP} = B^{B}_{OZP} - B^{N}_{OZP}, \quad (7)$$

where B^{B}_{OZP}, B^{N}_{OZP} – costs of basic wages for production workers for container repair, respectively, for the basic and new design variants, EUR.

The costs of additional wages for production workers for container repair are determined as a percentage of the costs of basic wages, namely for the payment of the P bonus (30%), long service D_{ER} (17%), additional payment for work at night D_{NZ} (13.3%) hours, as well as on holidays D_{SE} (2.2%).

The savings in current costs for additional wages for production workers per repair of one container is:

$$\Delta B_{DZP} = B^{B}_{DZP} - B^{N}_{DZP}, \quad (8)$$

where B^{B}_{DZP}, B^{N}_{DZP} – costs of additional wages for production workers for container repair, respectively, for the basic and new design variants, EUR.

Deductions of social measures are determined as 22% of the costs of basic and additional wages. General production costs are taken at the rate of 80% of the costs of basic wages for production workers.

4. RESULTS AND DISCUSSION

This section includes the results of calculations of the observed parameters. The main outputs are economic effects of application of the proposed container wall structure in real operation. The calculation of these economic effects is performed considering the reduction coefficients, which are listed in Table 1. It was concluded after carrying out the relevant calculations, that the measure pays off in the first year of the calculation period (Table 2), (Fig. 6). At the same time, the economic effect in the first year of the calculation period will be about 5,000 Euros. The economic effect, cumulatively in the last year of the calculation period, will be 33,000 Euros (Table 3), (Fig. 7).

Table 1. The value of the reduction coefficients by years of the calculation period

Years of the accounting period				
2026	2027	2028	2029	2030
Factor of including expenses of different periods to the accounting period				
1.0	0.909	0.826	0.751	0.683
Years of the accounting period				
2031	2032	2033	2033	2034
Factor of including expenses of different periods to the accounting period				
0.621	0.564	0.513	0.467	0.424

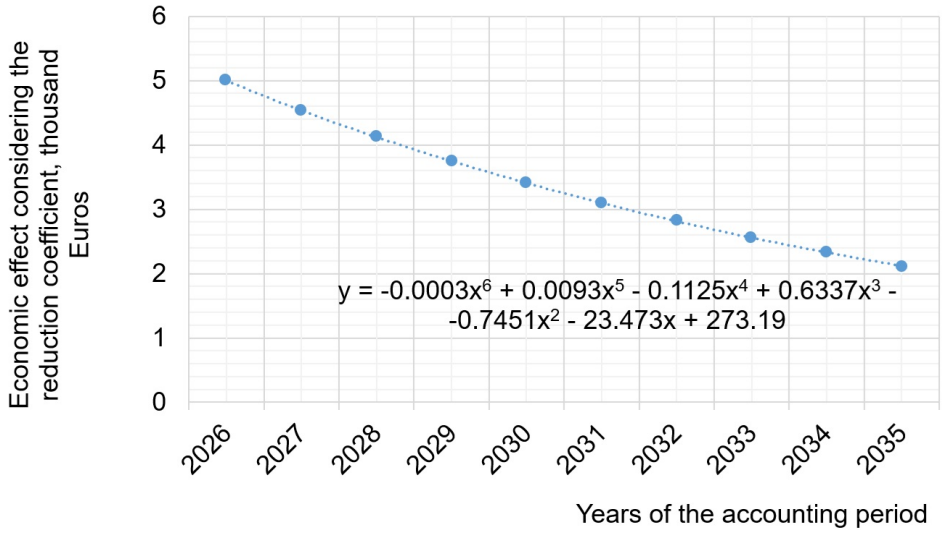
Source: Authors

Table 2. Economic effect considering the reduction factor by years of the calculation period

Years of the accounting period				
2026	2027	2028	2029	2030
Economic effect, thsnd. €				
5.0	4.536	4.122	3.748	3.408
Years of the accounting period				
2031	2032	2033	2033	2034
Economic effect, thsnd. €				
3.098	2.814	2.558	2.33	2.116

Source: Authors

Figure 6. Economic effect considering the reduction factor according to the calculation period



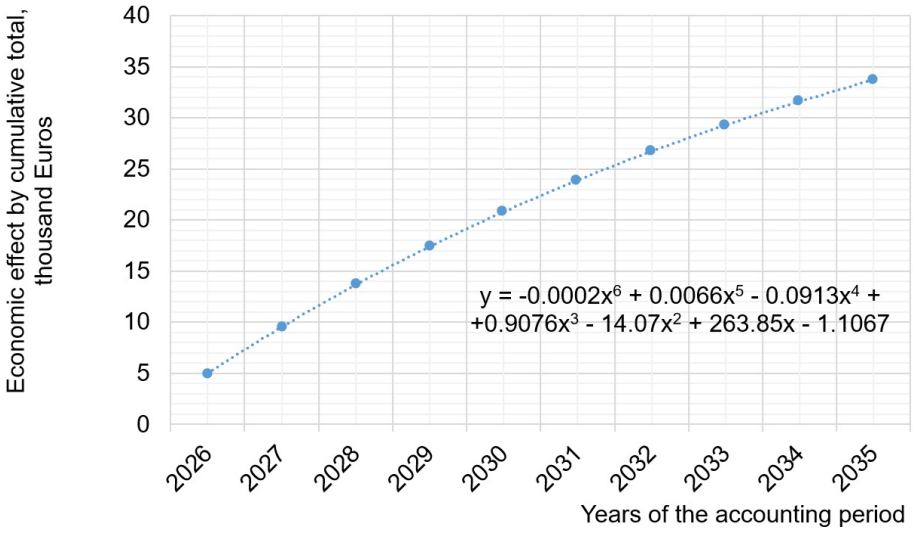
Source: Authors

Table 3. Economic effect by cumulative total over the years of the calculation period

Years of the accounting period				
2026	2027	2028	2029	2030
Economic effect, thsnd. €				
5.0	*9.526*	*13.648*	*17.396*	*20.8*
Years of the accounting period				
2031	*2032*	*2033*	*2033*	*2034*
Economic effect, thsnd. €				
23.9	*26.72*	*29.28*	*31.6*	*33.72*

Source: Authors

Figure 7. Economic effect of the cumulative total sum according to the calculation period



Source: Authors

The performed calculations prove that the introduction of sandwich panels as a container wall cladding is economically feasible. The advantage of this study in comparison with reviewed research in section 1 is that the authors not only proposed a solution to improve the container design but also calculated the economic effect of implementing such a solution into operation. It is important to note that the demand for container transportation is constantly growing. Thus, the economic effect may be greater in practice. The condition for using the results of the study is compliance with periodic technical maintenance of containers in operation. The main drawback of the study is that the calculation does not consider possible operational risks. The main operational risks of this implementation are the level of inflation in the national economy, the magnitude of investment risk, alternative investment opportunities, military conflict, pandemic, etc. Therefore, the magnitude of the economic effect must be adjusted in case that risks arise. A further direction of this study is to conduct experimental studies of the strength of the container cladding with walls made of sandwich components. This is planned to be done in laboratory conditions, using the similarity method and the method of electrical strain gauges.

5. CONCLUSIONS

It is proposed to manufacture containers walls from sandwich panels to reduce their damage during operation. This solution will reduce stresses in the container walls by 15% compared to their typical design.

A method for calculating the economic effect of using sandwich components as container walls is proposed. This method includes calculating the cost of materials for container repair; calculating the cost of electricity for container repair; calculating the cost of basic wages for production workers; calculating the cost of additional wages for production workers; calculating deductions for social measures; depreciation deductions.

A calculation of the economic effect of using sandwich components as container walls is carried out. The calculation made it possible to conclude that improving containers is advisable. At the same time, the economic effect can be achieved by reducing the cost of repairing containers in operation.

The economic effect in the cumulative total in the last year of the calculation period will be 33,000 euros.

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Izvorni znanstveni rad

STUDIJA ISPLATIVOSTI PRIMJENE SENDVIČ-KOMPONENTI U STRUKTURI STIJENKI UNIVERZALNOG KONTEJNERA

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SAŽETAK
Istraživanje je usmjereno na primjenu komponenti sendvič-tipa u strukturi kontejnera radi poboljšanja čvrstoće njegovih stijenki pod radnim opterećenjima. Ovo je rješenje primijenjeno na primjeru čeonih stijenki kontejnera. Istraživanje je provedeno na univerzalnom kontejneru standardne veličine 1CC. Proračuni su pokazali da razmatrano poboljšanje konstrukcije kontejnera doprinosi smanjenju naprezanja u strukturi kontejnera za 15 % u usporedbi s njegovom izvornom konstrukcijom. Kao važan zadatak istraživanja, proveden je izračun ekonomskog učinka primjene projektiranih komponenti sendvič-tipa u stijenkama kontejnera kako bi se opravdalo predloženo rješenje za poboljšanje kontejnera. Utvrđeno je da će se ekonomski učinak postići smanjenjem troškova popravka kontejnera tijekom njihove eksploatacije. Izračun je proveden za flotu od 177 kontejnerskih jedinica. Ekonomski učinak primjene projektirane konstrukcije kontejnera određen je prema uvjetima njegove uporabe za obračunsko razdoblje od 10 godina. Rezultati izračuna pokazali su da se mjera isplati već u prvoj godini obračunskog razdoblja. Istodobno, ekonomski učinak u prvoj godini obračunskog razdoblja iznosit će oko 5.000 eura. Kumulativni ekonomski učinak u posljednjoj godini obračunskog razdoblja iznosit će više od 33.000 eura. Stoga je primjena sendvič-komponenti kao stijenki univerzalnog kontejnera ekonomski opravdana.

Ključne riječi: *poboljšanje, sendvič-komponente, trošak popravka kontejnera, smanjenje oštećenja kontejnera, ekonomski učinak*

Original Scientific Paper

INITIAL SPARK OF CHANGE - SUBSIDIES FOR CYCLE LOGISTICS IN GERMANY AND THEIR IMPACT

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ABSTRACT

Germany is currently among the largest markets for electric cargo bikes and hosts a substantial share of global cargo bike manufacturers. While these vehicles will not fully replace larger commercial vehicles in logistics, their deployment in specific contexts can significantly mitigate a range of local and global externalities associated with freight transport. The (re-)introduction of electric cargo bikes as a distinct vehicle class within the modal split represents a bold policy intervention that has been partially and temporarily supported by comprehensive subsidy schemes at federal and state level. These schemes, targeting private, commercial and public users, have contributed to an accelerating shift in logistics towards smaller, low-emission delivery vehicles. In particular, subsidies for commercial and public-sector use hold the potential for far-reaching effects on urban planning, as cities increasingly adapt infrastructure and street space to accommodate new forms of logistics and mobility. This paper provides a comprehensive overview of recent cargo bike subsidy schemes in Germany, which peaked in the years of the COVID-19 pandemic, and evaluates their potential impact on logistic operations. The analysis draws on federal programs and state-based subsidy schemes. The findings indicate strong commercial and public interest in electric cargo bikes and suggest that subsidies appear to have provided an initial stimulus for public-value-oriented transportation, subsequently transferring momentum to an increasingly confident and diversified cargo bike market. Persisting barriers to further diffusion, both public and private, are identified in infrastructural limitations, maintenance challenges, and growing politicalization of urban traffic planning.

***Keywords**: Subsidy Program, Commercial, Cargo Bike, Cycle Logistics, Germany*

1. INTRODUCTION

Across different historical periods, governments have repeatedly used financial schemes to accelerate publicly desired transitions in the transport sector. Prominent examples include the large-scale subsidization of rail infrastructure in the nineteenth and twentieth centuries, the long-standing fiscal support of private motorized transport and, more recently, the promotion of electric vehicles through purchase premiums and tax incentives (Kopper, 2022; Metzler et al., 2018; Schulthoff et al., 2025; Creutzberg et al., 2025; Aasness and Odeck, 2015). Such interventions typically aim to overcome market entry barriers of new

technologies and internalize social, economic, and ecological benefits that are not adequately reflected in market prices.

In contemporary Europe, particularly in Germany, transport policy is increasingly shaped by the objectives of the decarbonization of transport, the mitigation of air pollution and noise, the alleviation of congestion in densely populated cities, and the containment of the immense external costs generated by current logistics systems. Freight transport plays a significant role in this context. While indispensable for economic activity, last-mile logistics contributes disproportionately to emissions, land use pressure, and conflicts over public spaces in cities of any size (Plazier et al., 2024; Silva et al., 2023).

From the perspective of companies in the freight transport sector, a successful logistics transition primarily entails the reduction of negative externalities without sacrificing efficiency. On the one hand, this can be achieved operationally through increased utilization of transport resources, which is generally advantageous for service providers from a business perspective. On the other hand, it involves the adoption of sustainable modes of transport. The latter, however, exposes fundamental trade-offs between the required investments and potentially costly process adjustments and sustainability objectives (Javanpour et al., 2025). As a result, logistics service providers may exhibit a general commitment to sustainability, but the actual implementation of sustainable modes remains very limited, as efficiency considerations typically take precedence (Abassi and Nilsson, 2016). More broadly, the adoption of any sustainable initiative is often constrained by high investment costs, intense price pressure, and prevailing uncertainties (Centobelli et al., 2017). Nilsson et al. (2017) further emphasize that the complex value creation structures in the transport sector, characterized by a high degree of subcontracting, constitute a significant barrier to the realization of sustainable investments.

Despite these initial hurdles, current research suggests that light electric vehicles (LEVs) like cargo bikes can offer advantages. Although cargo bikes have existed in various forms for more than a century, they have been experiencing a real renaissance since the 2010s and have since developed into a commercially relevant vehicle category in Germany (Assmann et al., 2024). Combining comparatively low acquisition and operating costs with zero local emissions and high spatial efficiency, electric cargo bikes offer distinct advantages for specific logistics applications, particularly in densely populated environments (Robichet et al., 2022). This does include urban centers, as well as narrow centers of settlements of any size. Multiple studies of cycle logistics, as the application of cargo bikes for logistics purposes is increasingly referred to, therefore suggest economic benefits (Kania and Assmann, 2024; Knese, 2024; Elbert and Friedrich, 2020). Externalized costs of conventional transportation include multiple locally and globally harmful emissions, erosion of infrastructure, safety and health expenses. As cycle logistics avoids or reduces these costs, public actors increasingly support cargo bikes in freight transport (Büttgen et al., 2021; Koning and Conway, 2016). While they cannot replace conventional delivery vehicles across all use cases, they are a viable alternative for a substantial share of last-mile deliveries. While the short-term return on investment for cargo bikes may appear unfavorable due to infrastructure gaps and operational adjustments, the total cost of ownership often decreases over time through lower maintenance, energy efficiency, and the avoidance of congestion-related delay (Robichet et al., 2022).

Just as sustainability requires foresight, economic viability in the transport sector must be evaluated through a future-oriented lens. To bridge the gap between upfront capital expenditures and long-term profitability, reliable financial subsidies and government incentives for acquisition costs are introduced. The first dedicated subsidy schemes for cycle logistics began at federal and state levels around 2018 and 2017, respectively (BAnz, 2018; StM Baden-Württemberg, 2019). The choice of vehicle model, especially for cargo bikes, is a key factor in determining cost-effectiveness – it requires preliminary planning of the area of application. Cargo bike configurations exist for a wide range of logistics applications, ranging

from vehicles without electric assistance to LEVs. It is essential to select a vehicle that is tailored to the required load capacity, range and maneuverability in order to maximize operational efficiency and ensure long-term cost-effectiveness. According to a survey by the German agency cargobike.jetzt GmbH (2024), subsidies for the purchase of a cargo bike can serve as a catalyst. They make the switch to a cargo bike more financially attractive by reinforcing the savings potential that already exists.

Against this background, supportive policy instruments are frequently justified as a means of initiating and accelerating behavioral and structural change in favor of public value. By lowering investment risks and entry costs, subsidies can foster social, economic, and ecological benefits simultaneously, ranging from improved urban livability and reduced emissions to innovation and local value creation. The past decade of cargo bike subsidy programs for public and commercial actors grants an empirical basis for assessing their success. In many cases, funding programs were fully exhausted, often in a very short period of time, indicating a high demand. At the same time, several schemes have since been paused, modified, or terminated, often due to budgetary constraints or shifting political priorities. This constellation of a high demand, temporary programs, and growing market maturity, creates a unique opportunity for an early evaluation of policy outcomes.

This paper addresses the following research question: How comprehensive and effective were financial support schemes for commercial and public cargo bike acquisition in Germany, and how strong did they vary? In this context, program effectiveness is assessed using indicators such as program uptake, number of subsidized vehicles, program continuation or renewal, and geographic distribution where data is available. By systematically comparing federal and state-level support schemes, this study contributes to the emerging evidence base on cargo bike policies and offers insights into the role of targeted subsidies in fostering sustainable logistics transitions.

2. DEFINITIONS AND METHODOLOGY

The term cargo bike describes constructions with loading areas in front of or behind the steering unit or saddle, as well as freight transport combinations created by the use of trailers. In principle, cargo bikes are classified as either bicycles or, in the case of exceeding specific performance limits, as LEVs. The legal treatment of such cases is largely dependent on the technical specifications and the type of drive system in issue (Kremer, 2024; Assmann, 2024). In order to standardize requirements, the European Norm EN 17860 has been developed, which differentiates between various categories, primarily between single-track and multi-track cargo bikes, heavy-duty bikes, trailers, and systems with electric drive assistance (DIN EN 17860). Additionally, in Germany, the legal definition of an electrically assisted vehicle is set out in the StVZO (StVZO, 2012). According to this definition, a cargo bike is only considered a bicycle if the motor assistance does not exceed a speed of 25 km/h and the nominal continuous power of the motor is limited to a maximum of 0.25 kW. In terms of geometric dimensions, single-track vehicles are permitted to have a maximum width of 1 m, a height of 2.5 m, and a total length of 4 m, while multi-track designs are legally permitted to have an extended width of up to 2 m. Vehicles that exceed the aforementioned technical restrictions or performance parameters are legally classified as LEVs and are therefore subject to further requirements regarding registration, insurance, and driver's license. Currently, the vast majority of all cargo bikes on German roads are legally considered bicycles (Kremer, 2024; Assmann, 2024).

Although these normative classifications define the technology's legal boundaries and technical potential, the actual socio-economic impact and adoption of these vehicles is ultimately reflected by market dynamics. In 2025, cargo bikes ranked fourth among the best-selling bicycle models with sales of 220,300 units. Of these, only 35,000 are without and 185,300 include electric assistance. While cargo bikes without electric assistance therefore make up only 2 percent of total bicycle sales, cargo bikes with electric assistance (*Cargo*

pedelecs) already account for just under 10 percent of total sales (ZIV, 2026). References to cargo bikes in the following work therefore imply cargo transporting vehicles, classified as bicycles and either without or – in most cases – with electric support, unless further specified (as, e.g., in Table 1).

Cycle logistics, as a consequence, refers to the transport of goods using bicycles and LEVs, primarily electric cargo bikes, in commercial or public-service logistics operations. While the main areas of application for cycle logistics are commercial and public purposes, private logistics, e.g., transportation of groceries, can be considered part of cycle logistics as well. Logistics is increasingly performed per cargo bike, serving as an ecologically sustainable alternative to conventional transport methods (Gruber et al., 2024).

Subsidies generally serve as political instruments for achieving economic, ecological, or social objectives and transforming existing structures in a sustainable way. These instruments are implemented at various levels: while financial and legal subsidies are primarily located at the federal or state level, the municipal level focuses on structural interventions. Regarding cycle logistics, Wrighton et al. (2017) differentiate between types of subsidies, ranging from campaigns for local actors to the expansion of infrastructure and the targeted commissioning of cycle logistics providers for municipal needs. In addition to this, Gruber et al. (2016) categorize programs into incentives such as purchase premiums or leasing models, infrastructural measures such as road expansion, regulatory measures such as adjustments to regulations, and non-material support such as consultations. The strategies are aimed at a broad spectrum of target groups, with companies in the logistics sector and companies requiring service and delivery vehicles being particularly relevant for the following analysis. In addition, public institutions and local authorities are encouraged to use cargo bikes for local logistics tasks. The according direct financial support in the form of public subsidy programs is examined in this work.

The methodological basis for collecting data on the nationwide funding landscape for cargo bikes is a content analysis in terms of a multi-stage research approach that combines systematic secondary data analysis with primary data collection. The objective of this study is to provide a comprehensive reconstruction of fundings, administrative requirements and the respective resulting number of supported vehicles. A systematic review of existing literature and publications was conducted to identify subsidies, focusing on funding guidelines of programs. It is important to note that past or exhausted funding guidelines have a transparency gap, as outdated programs are regularly removed from public platforms to avoid misinterpretations of current policy. Despite the expired term, outdated funding lines are analyzed, where available in public repositories or archives, in order to obtain a comprehensive outline of data on scope, timeline and other parameters of respective programs. In this context, both the federal entities of national programs and the responsible offices of states were contacted with structured inquiries to provide additional criteria on the subsidies and their results. The requests, first sent out in November 2025, focused on the number of subsidized vehicles for commercial and public purposes, the quantitative distribution between specific cargo bike models and the respective spread among rural and urban areas, as these data points are not publicly available in most cases. In addition, primary data analysis was used by interviewing representatives, to gain deeper insights into the processes and the chronological sequence of the programs. The resulting expert input by states' representatives, who often personally supervised respective subsidy programs, was used primarily for validation of program characteristics and timeline reconstruction, while quantitative program metrics were based on documented administrative or published data wherever possible. Requested data was partially provided inconsistently: Cargo bike models and geographic spread were rarely documented by the programs, limiting the data set; singular data points on these aspects are discussed outside of comprehensive comparison of subsidies below. Likewise, not all programs could provide subsidy numbers excluding private users or specifically indicate the number of *electric cargo bikes* among total subsidies. Respective formulations in Table 1 indicate these limitations accordingly.

The dataset was constructed using predefined inclusion criteria. Only direct purchase subsidy programs explicitly allowing commercial or public acquisition of cargo bikes were included. Infrastructure-only funding and private-use-only subsidy programs were excluded unless directly linked to commercial or public cycle logistics use. Data collection covered the period from 2017 to 2026 and relied on official funding guidelines, ministry publications, press articles, funding bank documentation, and direct confirmation from administering authorities, where available. The dataset aims to capture all identifiable federal and state level direct purchase subsidy programs for cargo bikes, intended to be used commercially or publicly, within the defined time frame. Due to varying transparency levels between funding bodies and the mentioned discontinuation of older program documentation, minor gaps in the coverage of historical subsidy schemes cannot be fully excluded.

3. DATA ANALYSIS

The dataset in Table 1 comprises all identified direct subsidy programs for commercial and public cargo bikes on federal and state levels in Germany. Of the 16 German states, 12 were identified as having, at some point, implemented dedicated funding schemes to subsidize the discussed specific acquisitions, amounting to direct support of cycle logistics. Representatives from all of these states were available for comment and provided additional information on program outcomes. Table 1 summarizes the relevant data used for further analysis. A detailed discussion of all observed subsidy schemes would exceed the scope of this work; therefore, the following section provides a synthesized and comparative analysis of the programs. The representation of parameters was confirmed by the providing parties. Structurally, both federal subsidies are discussed initially as nationally overarching and therefore hardly comparable items. The following analysis of state level subsidies builds on the data presented in Table 1 and subsequently incorporates additional qualitative input in order to identify similarities and differences among the respective programs.

Table 1. Overview of Cargo Bike Subsidy Schemes for Commercial and Public Use, State and Federal Level

Executing Entity / State	Period of Programs	Scope of Support per Vehicle	No. of Subsidized Vehicles for Commercial / Public Use	Further Details	Sources
BAFA, federal	Programs since 2018, 2021–2027	25 %, max. 3,500 EUR	>10,000 electric cargo bikes and trailers since 2021	Funding by several federal ministries over the years. Subsidy used to be 30 %, max. 2,500 EUR.	BAnz, 2018; BAnz, 2021; BMUKN, 2025; BMWE, 2026
BALM, federal	2023–2026	50–60 %, max. 6,000 EUR	116 electric cargo bikes	Exclusively for SME, requires comprehensive *mobility* concepts. Applicable for projects up to 60,000 EUR.	BAnz, 2023; B.A.U.M. Consult GmbH, 2026; BALM, 2025
Baden-Württemberg	2017–2023	25 %, max. 2,500 EUR	4,696 electric cargo bikes	Drop in demand led to end of scheme, leasing was possible.	L-Bank, 2026; StM Baden-Württemberg, 2019
Berlin	2021	max. 2,000 EUR	180 electric cargo bikes	Provided funds were exhausted quickly on the first day.	IBB Business Team GmbH, 2021
Brandenburg	2021–2024	50–80 %, max. 4,000 EUR	599 electric cargo bikes	18 percent of subsidies in two largest cities, rest more rural.	MIL Brandenburg, 2024; MdJD Brandenburg, 2023
Bremen	2022	40 %, max. 1,000 EUR	25 cargo bikes and trailers	Focus on private use, 750 cargo bikes subsidized in total.	SKUMSW Bremen, 2022; SBMS Bremen, 2026
Hamburg	2019–2021	33 %, max. 2,000 EUR	128 electric cargo bikes	Focus on private use, 1,198 cargo bikes subsidized in total.	hamburg.de GmbH, 2020
Hesse	2019–2025	70–90 %	55 municipalities procured cargo bikes	Focus on private use, 3,511 cargo bikes subsidized in total.	HMUKLV, 2019
Lower Saxony	2021–2023	max. 800 EUR	9 electric cargo bikes	Focus on private use, 1,907 cargo bikes subsidized in total.	NBank, 2022
North Rhine-Westphalia	2018–2024	30 %, max. 2,100 EUR	13,700 cargo bikes (incl. private use)	Public actors, e.g., municipalities: 60 %, max. 4,200 EUR. Approx. 28 % private use.	MWIKE NRW, 2023; MWIDE NRW, 2018; BRA, 2024
Saarland	2021–2024, 2026	25 %, max. 1,000 EUR	507 electric cargo bikes (incl. private use)	Before 2023, subsidy was 50 %, max. 2,000 EUR.	MUKMAV Saarland, 2025; MWAEV Saarland, 2021
Saxony	2021–2024	max. 1,500 EUR	940 electric cargo bikes	Drop in demand towards end of program runtime.	SMWA Sachsen 2021; SMWA Sachsen, 2023
Saxony-Anhalt	2024–2027	60–90 %	23–36 approved applications	Usually one cargo bike per application – focus not on cargo bikes.	MID Sachsen-Anhalt, 2025
Thuringia	2020–2023	40 %, max. 2,000 EUR	188 cargo bikes and trailers	Focus on private use, 845 cargo bikes subsidized in total.	TMUEN, 2020

Sources beyond interviews and provided data are compiled in “Sources” column

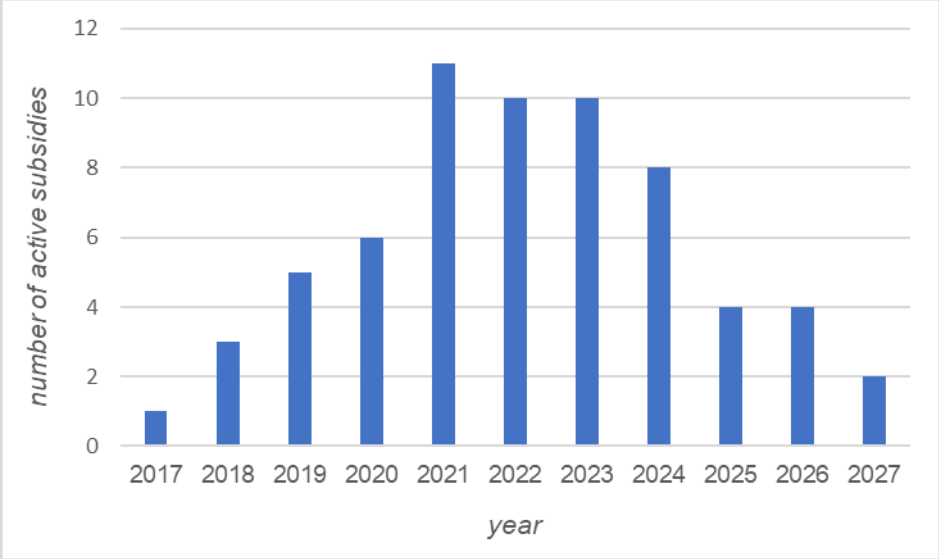
Federal subsidies of cargo bikes for commercial and public use in Germany first started in 2018, in a directive to promote climate sensitive technology. This national subsidy excluded compact cargo bikes, as it required the vehicles to support at least one cubic meter and 150 kg of cargo, translating roughly to what are today called *commercial cargo bikes* (CCB) (BAnz, 2018). Since 2021, renewed in 2024 and currently viable until 2027, a specific cargo bike directive subsidizes a variety of cargo bike models. The authority managing the program is the Federal Office for Economic Affairs and Export Control (BAFA), while funding was and is provided by subsequent federal ministries for economic and environmental issues. The maximum subsidy per cargo bike was raised from 2,500 EUR to 3,500 EUR, potentially to account for costly sophistication in the still emerging technology (BMWE, 2026; BAnz, 2021). This nationally available subsidy is presumably the largest provider of support for this specific purpose of cycle logistics, as it continues to fund a significant number of acquisitions: Until May 2025, 10,000 vehicles were subsidized, excluding the predating program from 2018 to 2021 (BAFA, 2025).

An additional, less direct subsidy of cargo bikes on national level is managed by the Federal Logistics and Mobility Office (BALM), with funding provided by the Federal Ministry of Transportation (BAnz, 2023). The target group comprises small and medium-sized enterprises (SMEs), and the subsidy is intended for the implementation of comprehensive corporate mobility plans. Provided data on scope (column three) therefore refers to integrated plans for the introduction of electric cargo bikes into company transport, rather than subsidies per vehicle. Subsidizing cycle logistics vehicles constitutes only a small fraction of this scheme. This design reflects the principle of *lex specialis*, according to which cargo bikes are not eligible for standalone funding under this program, as they are covered by a separate federal scheme; consequently, support is granted only when cargo bikes are embedded within broader mobility concepts.

All other observed subsidies in this work are provided on state level. The four absent German states in Table 1, namely Bavaria, Mecklenburg-Western Pomerania, Rhineland-Palatinate and Schleswig-Holstein, had no similarly dedicated funding programs for cargo bikes. Instead, municipal programs and the ongoing BAFA directive are particularly promoted in these regions' communications on the topic. The subsidies of the remaining 12 states differ in many ways and show close similarities in others. With the exception of one municipal (Bremen) and one EU-funded (Saxony-Anhalt) subsidy program, the funding is provided by state-level ministries, instructing offices or financial institutions to manage implementation.

The programs differ widely in focus: some German states provide funding exclusively for the acquisition of cargo bikes for commercial and various public purposes, such as use by municipalities, public utility companies, associations or religious institutions (Baden-Württemberg, Berlin, Brandenburg, Saxony). Others combine support for these cargo bike purposes with subsidies for private users, usually focusing heavily on the latter – either through guideline formulation or due to high demand from the population (Bremen, Hamburg, Lower Saxony, Thuringia). Where not tracked separately, this shared program design complicates quantitative analysis. A third expression of subsidy programming includes cargo bikes in directives as one of multiple sustainable technology options, including investments in infrastructure (Hesse, North Rhine-Westphalia, Saarland, Saxony-Anhalt). Here, cargo bikes are considered a subordinate part of a larger picture, similar to the federal BALM program.

Graph 1. Timeline of Active Cargo Bike Subsidies for Commercial and Public Use in Germany



Source: Table 1, own compilation and representation

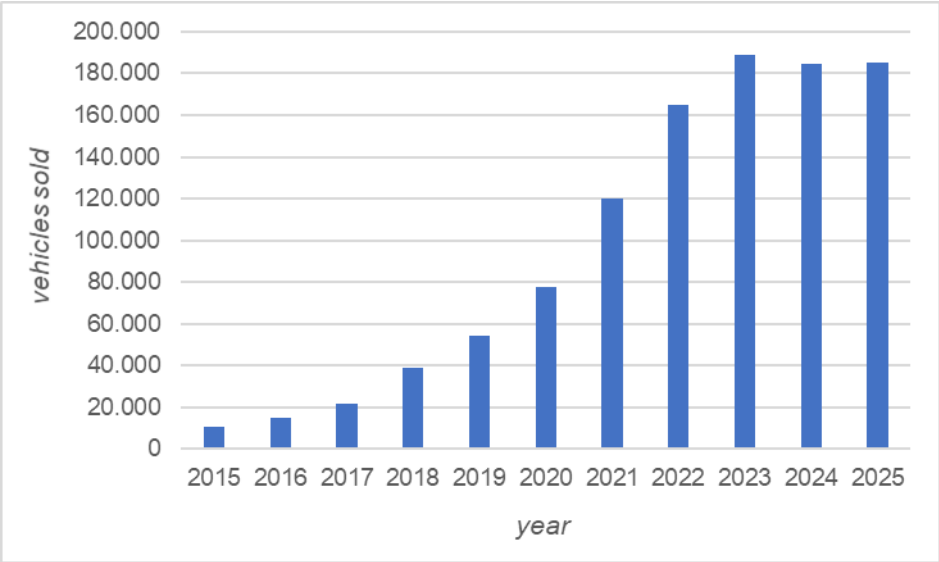
Starting off early with a state subsidy program for electrical vehicles in Baden-Württemberg in 2017, most relevant schemes for commercial or public actors began around 2021 (see Table 1 and Graph 1). The peak came and went quickly, with only four schemes still active by 2026. While larger, long-running subsidy directives (with subsidies for thousands of cargo bikes) saw a drop in demand in later years (Baden-Württemberg, Brandenburg, Saxony), smaller and singular programs were exhausted in minutes to hours (Bremen, Berlin). There is possibly significant demand for further subsidies in these cases. Most subsidy schemes were implemented temporarily or until a pre-defined budget was exhausted. Thus, there is usually no official explanation provided for the discontinuation of programs. In some cases, it might be explained by shrinking demand, while in others, political priorities might have changed. Multiple other reasons for ends of schemes can be subsumed as a claimed move towards infrastructure funding, a necessary aspect for future cycle logistics application (Kuzia, 2024). States whose own funding programs have been discontinued are now often referring applicants to the ongoing federal BAFA program (DPA Thüringen, 2023), marking a shift in responsibility toward this central authority in commercial cargo bike subsidy.

As with their target group focus and runtime, the subsidized vehicles themselves varied with the state programs. Most subsidies were restricted to (electric) cargo bikes, as defined above. About half of the states respectively in- and excluded (electric) trailers and cargo bikes for the transport of persons in the eligible vehicles. Others included further LEVs (Baden-Württemberg, likewise the only state to subsidize leasing of vehicles), speed pedelecs (pedal assistance up to 45 km/h) (Lower Saxony) or generally environmentally sustainable small vehicles (Saxony-Anhalt). All subsidies required the vehicles to be mass-produced, newly bought and able to transport additional payload with inseparable attachments (varying minimum capacity, upwards of 20 kg). Some states define a maximum capacity of the cargo bike (Thuringia, Saxony), in contrast to the minimum capacity in the first federal subsidy described above, therefore excluding CCBs purposefully. Individual states are therefore shown to have promoted various versions of cargo bikes and other small vehicles. The resulting numbers of supported acquisitions in Table 1 are therefore specified individually, indicating electric cargo bikes where possible. Other requirements for subsidy are usually a verifiable earmarking period of the intended purpose of three years, as well as company headquarters and/or prevalent use of the vehicle in the respective German state. Lastly, all programs require the application for subsidy prior to the acquisition of the vehicle.

As visible in column three of Table 1, the scope of subsidies on an individual basis, as reimbursement per vehicle, broadly varies. This financial ambiguity between geographical entities extends to the larger program funding itself: it varies from six-figure, one-time programs to multi-million Euros subsidies, reissued over many years, as in the federal BAFA program. Applying for support in vehicle acquisition with small programs require fast action, as demand regularly exceeds supply. Depending on their state, commercial and public applicants can expect subsidies between 25 and 50 percent of direct vehicle purchase costs (leasing and accessory costs are usually excluded), amounting to an overall maximum per-vehicle subsidy of 4,200 EUR for public actors in North Rhine-Westphalia or 4,000 EUR for commercial actors and associations in Brandenburg, averaging around 2,000 EUR for most states. Higher percentages of vehicle costs can be subsidized under some conditions in multiple states, including municipal applicants (Hesse, Saxony-Anhalt, North Rhine-Westphalia), if the vehicle is verifiably made available to the public (Brandenburg) or in combination with decommissioning of a car (Hamburg). While the federal BAFA program increased its maximum subsidy to 3,500 EUR, the Saarland program halved its support to 25 percent and a maximum of 1,000 EUR in 2023 – choosing contradicting paths towards scarce future subsidy supply. Legally, the cargo bike subsidies to private companies are issued as *de minimis* aid, a capped subsidy (<300,000 EUR in three years), which EU member states can grant to private actors without distorting market-wide competition and necessity to notify the European Commission (Publications Office of the European Union, 2024). This limit is relevant for federal and state programs which provide subsidies for private companies.

As detailed responses to inquiries reveal, interest in subsidies does not exclusively origin from the urban areas of the German states: In Brandenburg, 82 percent of cargo bikes are subsidized outside of the two urban centers (>100,000 inhabitants). In Thuringia, 41 percent of subsidies are for cargo bikes in the rural area, including a share of 27 percent for commercial or public use (while the remaining 59 percent of urban cargo bikes include a lower non-private share of 18 percent). In Saxony, over the four years of subsidy programs, a third to a fourth of subsidized cargo bikes went to rural areas of the state. Even though the cargo bikes' unique features are often demonstrated in dense urban areas, their use apparently extends to other geographical parts of Germany, as population and economic activity generally requires (cycle) logistics.

Graph 2. Development of Electric Cargo Bike Sales in Germany



Source: ZIV (2026), own compilation and representation

The individual cargo bikes considered here, which have been subsidized through state and federal funding for nearly a decade, amount to a total of just over 30,000 vehicles, as displayed separately in column four of Table 1. Given the substantial market volume of approximately one million electric cargo bikes sold during the same period (see Graph 2), the subsidies analyzed here represent only a small share of total sales. However, they also account for only a fraction of overall cargo bike subsidies, as considerably larger funding volumes exist for private cargo bike purchases, partially reflected in column five of Table 1, as well as subsidies at the municipal or other levels. State subsidies peaked (measured by highest number of active programs, see Graph 1) during the sharp increase in cargo bike sales in Germany between 2021 and 2022. During this period, cycle logistics emerged as a relevant component for German supply chains. In particular, private demand may have been stimulated by the COVID-19 pandemic, as cargo bikes offered a low-contact alternative to public transport and coincided with the introduction of new delivery and mobility practices. The resulting increase in visibility raised awareness among public actors and intensified calls for sustainable mobility concepts, infrastructure, and targeted subsidies. The exact impact of the observed programs cannot be quantitatively determined beyond the total number of supported vehicle acquisitions. Effects on indirect outcomes or broader logistical ripple effects require further large-scale investigation.

In summary, there are similarities in subsidy programs, regarding target groups, definitions, scope and timeline. The diversity of schemes reflects the versatility of the vehicle itself. Beyond private usage, multitudes of options exist for commercial and public actors to utilize innovative vehicles for economic or public-value-based reasons (Düerkop et al., 2025; Grubmüller et al., 2025). Public and commercial users embrace support in all states, while the success of the federal programs is ongoing. The incentives through subsidies coincided with the rapid demand rise of the cargo bike market in general. Some successful state level schemes are renewed, while most are either paused or finalized by 2026.

4. DISCUSSION AND CONCLUSION

On federal and state level, a multitude of German subsidy programs could be compared in this work. Many successfully supported the acquisition of thousands of cargo bikes, either for the purposes of cycle logistics by commercial and public users or for private use. In general, the latter seems to dominate in the subsidy landscape. Programs, limited in timeframe or funding were exhausted quickly, implying a greater demand even.

The general focus of state subsidies for private use of cargo bikes (in contrast to use for commercial and public purposes) is obvious when comparing *shared* programs: In Bremen, Thuringia, Lower Saxony and Hamburg, between ~0.5 and ~20 percent of total subsidies were going towards commercial or public use. Some initially shared programs later excluded private users (North Rhine-Westphalia, Saarland). Hesse focused on private use subsidies as well, supporting municipalities to acquire cargo bikes in a separate scheme. Other programs targeted broad promotion of sustainable transportation, with (electric) cargo bikes enclosed. Specifically tailored programs for the focus of this work are rare on the state level (Saxony, Brandenburg, Berlin), which explains general referral to the national BAFA program. Whereas state-level subsidies are dwindling after a short burst of availability in 2021–2022, both federal programs are ongoing. At the same time, public promotion of cargo bike use extends far beyond direct vehicle purchase subsidies: national funding for applied and theoretical research projects, infrastructure investments, consultation and training programs, as well as supportive regulatory and legislative initiative, form a comprehensive strategy to increase the uptake of this sustainable freight vehicle.

As – partly – a result of subsidy programs and other public support, a German cargo bike market developed in the monitored timeframe: Besides the country's high sales numbers of cargo bikes, a comprehensive online data set of cargo bike producers, cross referenced with leading industry events, suggests Germany to be hosting the highest national count of producers in the world (own aggregation, based on [Batto, 2024], supplemented by

[fairnamic GmbH, 2025; Fietsdiensten.nl and Parr, 2025; Radlogistikverband Deutschland e.V., 2026; cargobike.jetzt GmbH, 2025]). While the exact impact of subsidies (not limited to German-made vehicles) on this success is indistinguishable from general high adoption, an association with supply and demand developments is observable, as an emerging innovative technology became ~25–50 percent more affordable to private, public and commercial users. Although the observed market expansion coincides with the introduction and scaling of subsidy programs, multiple external factors, including technological development, further transport and climate policy development as well as pandemic-related behavioral shifts must also be considered. As a result, a variety of options for logistics purposes evolved, often initiated by dedicated cargo bike startups. An ongoing tense situation of the industry in the last two years led to consolidation of these small companies, as former exponential growth of sales stagnates. As subsidy programs expire, the German cargo bike market is likely to react – the extent cannot be foreseen yet.

Political support seems to be an important enabling factor for sustainability related changes, as observed in the subsidy programs for cycle logistics. Even though slight geographic differences in schemes result in varying circumstances for cycle logistics options in the 16 states, operational planning over adequate timeframes is crucial for commercial logistics actors. Quick changes in political support for subsidies endanger companies' long-term visions when cargo bikes and infrastructure should be integrated into the operation of, e.g., CEP service providers. The findings suggest that predictable and longer-term funding structures may reduce planning uncertainty for logistics operators and improve technology adoption stability. This is suspected to have synergies with supporting maintenance infrastructure for cargo bikes, as commercial users react sensitive to downtime, caused by heightened wear through frequent use (Gruber et al., 2026).

In general, tax-funded support for private-sector asset acquisition on both supply and demand sides can be politically controversial. Long-term industry support of this kind is rarely an explicit political goal, despite being common in other transportation sectors such as the automotive and aviation industries. At the same time, the growing influence of right-leaning parties has increased political scrutiny of cargo bike subsidies. Increasing deficits on federal and municipal level in Germany, but not on state level (StBA, 2026), may complicate political support for renewing subsidies that generate primarily non-monetary public value rather than direct fiscal or measurable financial returns. At the same time, the cumulative benefit of avoiding externalized costs, burdened on society by current logistics practices regarding, e.g., health or infrastructure maintenance potentially exceeds tax-subsidized input and should be comprehensively considered.

This work exclusively observed a fraction of cargo bike subsidies that concerned cycle logistics and was omitted by federal and state actors. There are great amounts of further support programs in Germany on municipal level and for private use, which were systematically not included. A lack of coherent data availability hindered a more comprehensive analysis, in which subsidies per year, their geographic spread and specific type of cargo bike could have been discussed further. Potentially, future research will be able to achieve such results. More comprehensive research could examine hundreds of county and municipal programs for cargo bike subsidy, including German states not represented on state level (e.g., Bavaria), and how effective financial support promotes cycle logistics application. Likewise, communication strategies to include public value benefits in funding calculations of public actors – and favor long-term benefits of investments over short-term balance sheets – should be explored. Private mobility shifts towards cargo bike use via extensive subsidies for *private logistics* has great potential to mitigate negative effects of current vehicle use in Germany; future research could consider the efficiency of public funds spent in these programs as well. While the German subsidy landscape reflects specific federal governance structures, the observed program design patterns may provide insights for comparable policy environments in other European countries.

Following the titular metaphor of an initial spark, future success of cycle logistics requires sufficient fuel to be permanently ignited: Fitting infrastructure, policy and culture – a sustainable move towards cargo bikes in logistics calls for demand and societal support of the vehicle after subsidy programs run out. The immediate future will show whether the spark catches on.

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Izvorni znanstveni rad

POČETNI POTICAJ PROMJENE – SUBVENCIJE ZA BICIKLISTIČKU LOGISTIKU U NJEMAČKOJ I NJIHOV UTJECAJ

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SAŽETAK

Njemačka je trenutačno među najvećim tržištima za električne teretne bicikle i u njoj djeluje znatan udio svjetskih proizvođača teretnih bicikala. Iako ta vozila neće u potpunosti zamijeniti veća komercijalna vozila u logistici, njihova primjena u određenim kontekstima može znatno ublažiti niz lokalnih i globalnih eksternalija povezanih s teretnim prometom. (Ponovno) uvođenje električnih teretnih bicikala kao zasebne kategorije vozila unutar modalne podjele prometa predstavlja odvažnu političku intervenciju, koja je djelomično i privremeno bila podržana sveobuhvatnim programima subvencioniranja na saveznoj i pokrajinskoj razini. Ti programi, usmjereni na privatne, komercijalne i javne korisnike, pridonijeli su ubrzanom pomaku u logistici prema manjim dostavnim vozilima s niskim emisijama. Posebno subvencije za komercijalnu i javnu uporabu imaju potencijal za dalekosežne učinke na urbano planiranje, jer se gradovi sve više prilagođavaju novim oblicima logistike i mobilnosti kroz prilagodbu infrastrukture i uličnog prostora. Ovaj rad pruža sveobuhvatan pregled novijih programa subvencioniranja teretnih bicikala u Njemačkoj, koji su dosegnuli vrhunac tijekom godina pandemije bolesti COVID-19, te procjenjuje njihov mogući utjecaj na logističke operacije. Analiza se temelji na saveznim programima i programima subvencija na razini saveznih pokrajina. Rezultati upućuju na snažan interes komercijalnog i javnog sektora za električne teretne bicikle te sugeriraju da su subvencije očito pružile početni poticaj prometu usmjerenom na javnu vrijednost, nakon čega se zamah prenio na sve samouvjerenije i raznolikije tržište teretnih bicikala. Trajne prepreke njihovoj daljnjoj, i javnoj i privatnoj, difuziji prepoznate su u infrastrukturnim ograničenjima, izazovima održavanja i sve izraženijoj politizaciji urbanog prometnog planiranja.

Ključne riječi: program subvencioniranja, komercijalni sektor, teretni bicikl, biciklistička logistika, Njemačka

V.TRANSPORT ECONOMICS, POLICY, PUBLIC TRANSPORT, TOURISM AND LOGISTICS

V. EKONOMIKA PROMETA, PROMETNA POLITIKA, JAVNI PRIJEVOZ, TURIZAM I LOGISTIKA

Stručni rad

EKONOMSKA OPTIMIZACIJA SUSTAVA KONTROLE LETENJA U OKVIRU REGULATORNOG OKVIRA

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SAŽETAK

U radu se analiziraju mogućnosti ekonomske optimizacije sustava kontrole letenja u okviru regulatornog okvira Europske unije, s posebnim naglaskom na primjenu Uredbe (EU) 2019/317 i performansne sheme Jedinstvenog europskog neba (SES). Istraživanje polazi od hipoteze da su nedostatak operativnog osoblja i ograničeni kapaciteti sustava kontrole zračnog prometa (ATC), uz fragmentaciju europskog zračnog prostora, ključni uzroci povećanih troškova i kašnjenja u zračnom prometu. Metodološki pristup temelji se na analizi regulatornih mehanizama naplate i izvedbe, uključujući jedinične stope za en-route i terminalne usluge, mehanizme podjele rizika te financijske poticaje, kao i na komparativnoj analizi pokazatelja isplativosti iz ACE benchmarking izvješća EUROCONTROL-a. Posebna pažnja posvećena je produktivnosti kontrolora zračnog prometa, strukturi troškova zaposlenika i potpornih troškova te njihovom utjecaju na jedinične troškove usluga. Rezultati upućuju na to da povećanje produktivnosti i učinkovitije upravljanje troškovima mogu značajno smanjiti jedinične troškove, ali da strukturni problemi, osobito nedostatak osoblja i institucionalna fragmentacija, ograničavaju puni učinak regulatornih mjera. Zaključno, potvrđuje se postavljena hipoteza te se naglašava potreba za dubljom integracijom europskog zračnog prostora, jačanjem kapaciteta ANSP-ova i ubrzanom tehnološkom modernizacijom radi postizanja dugoročne ekonomske održivosti sustava kontrole letenja.

Ključne riječi: *ekonomska optimizacija, kontrola letenja, Uredba (EU) 2019/317, Jedinstveno europsko nebo, ANSP, produktivnost, troškovi.*

1. UVOD

Sustav kontrole letenja (*Air Traffic Management* – ATM) predstavlja ključni infrastrukturni i sigurnosni segment europskog zrakoplovnog sustava, čija učinkovitost neposredno utječe na operativne troškove, razinu sigurnosti, protočnost zračnog prostora i ukupnu konkurentnost zračnog prometa. U uvjetima rasta prometa, povećane regulatorne kompleksnosti i izraženih kapacitetskih ograničenja, pitanje ekonomske optimizacije sustava kontrole letenja postaje strateško pitanje razvoja europskog zrakoplovstva. Poseban izazov predstavlja fragmentacija europskog zračnog prostora, koja generira strukturne neučinkovitosti, povećava troškove i ograničava fleksibilnost upravljanja kapacitetima.

Regulatorni okvir Europske unije, osobito kroz inicijativu Jedinstvenog europskog neba (*Single European Sky* – SES) i Uredbu (EU) 2019/317 o shemi izvedbe i naplate, uspostavlja normativni temelj za povezivanje performansi, troškovne učinkovitosti i sustava financiranja usluga zračne plovidbe. Navedeni okvir uvodi mehanizme jediničnih stopa, podjele rizika

prometa i troškova te financijskih poticaja s ciljem povećanja produktivnosti pružatelja usluga zračne plovidbe (*Air Navigation Service Provider* – ANSP) i smanjenja jediničnih troškova po letu. Kašnjenja u upravljanju zračnim prometom u EU drastično su se povećala u zadnjem desetljeću, izazivajući operativne probleme i povećane troškove za zrakoplovne tvrtke i putnike, premda se promet povećavao znatno sporije. Ovi troškovi od 2015. godine procjenjuju se na nešto više od 16 mlrd €.

Polazeći od hipoteze da su nedostatak operativnog osoblja i ograničeni kapaciteti sustava kontrole zračnog prometa, uz institucionalnu fragmentaciju, primarni uzroci povećanih troškova i kašnjenja u europskom zračnom prometu, rad ima za cilj analizirati regulatorne i ekonomske mehanizme optimizacije te evaluirati njihovu učinkovitost u praksi.

Ovaj stručni rad temelji se na kombinaciji normativne, komparativne i kvantitativne analize. U prvom dijelu rada primijenjena je analiza sadržaja relevantnih regulatornih akata, s naglaskom na Uredbu (EU) 2019/317 i performansni okvir *Single European Sky* SES-a. U drugom dijelu korištena je komparativna analiza pokazatelja isplativosti i produktivnosti ANSP-ova temeljem podataka iz *Air Traffic Management Cost Effectiveness* - ACE *benchmarking* izvješća EUROCONTROL-a, pri čemu su analizirani jedinični troškovi, struktura troškova zaposlenika i potpornih troškova te produktivnost kontrolora zračnog prometa. Kvantitativni pristup uključuje evaluaciju odnosa između opterećenja sustava, raspoloživih kapaciteta i razine troškovne učinkovitosti.

Primjenom navedenih metoda nastoji se utvrditi u kojoj mjeri postojeći regulatorni instrumenti doprinose ekonomskoj optimizaciji sustava kontrole letenja te identificirati strukturne prepreke postizanju dugoročne održivosti i učinkovitosti europskog ATM sustava (European Air Traffic Management system).

2. JEDINSTVENO EUROPSKO NEBO I REGULATORNI OKVIR ZA KONTROLU LETENJA U EUROPSKOJ UNIJI

2.1. Jedinstveno europsko nebo

2.1.1. Koncept i ciljevi Jedinstvenog europskog neba

Inicijativa Jedinstveno europsko nebo (Single European Sky – SES) predstavlja strateški projekt Europske unije usmjeren na prevladavanje fragmentacije europskog zračnog prostora i povećanje sigurnosti, kapaciteta, troškovne učinkovitosti i okolišne održivosti sustava upravljanja zračnim prometom (ATM). Tradicionalna organizacija zračnog prostora u Europi temelji se na nacionalnim granicama, što dovodi do operativnih neučinkovitosti, dupliciranja infrastrukture i povećanih troškova za korisnike zračnog prostora. SES nastoji uspostaviti funkcionalno organiziran zračni prostor temeljen na prometnim tokovima, a ne na političkim granicama.

Ključni ciljevi SES-a obuhvaćaju povećanje kapaciteta mreže, smanjenje kašnjenja, poboljšanje sigurnosti, smanjenje jediničnih troškova usluga zračne plovidbe te smanjenje emisija CO_2 kroz optimizaciju ruta i skraćenje vremena leta. U okviru performansne sheme, države članice i pružatelji usluga zračne plovidbe (ANSP) obvezni su ostvarivati mjerljive ciljeve u područjima sigurnosti, kapaciteta, okoliša i troškovne učinkovitosti.

2.1.2. Uloga EUROCONTROL-a i regionalizacija sustava

U provedbi SES-a ključnu ulogu ima EUROCONTROL, koji koordinira razvoj europskog ATM sustava, uključujući mrežno upravljanje, analizu performansi i tehničku harmonizaciju. Koncept regionalizacije sustava upravljanja zračnim prometom posebno je vidljiv kroz projekte poput Maastricht UACC (Upper Area Control Centre) i CEATS (Central European Air Traffic Services), koji predstavljaju model funkcionalne integracije zračnog prostora iznad nacionalnih granica.

Maastricht UACC, osnovan 1972. godine, primjer je uspješne multinacionalne kontrole gornjeg zračnog prostora iznad Belgije, Luksemburga, Nizozemske i dijela Njemačke. Integrirani model upravljanja omogućio je povećanje produktivnosti, smanjenje troškova i učinkovitiju koordinaciju civilno-vojnih operacija. Projekt CEATS zamišljen je kao središnji kontrolni centar za srednjoeuropsku regiju, s ciljem povećanja kapaciteta i harmonizacije procedura, slijedeći model Maastrichta. Iako CEATS nije u potpunosti realiziran u prvotnom obliku, njegova koncepcija ilustrira strateški smjer regionalne integracije europskog zračnog prostora.

2.1.3. SESAR – tehnološki stup modernizacije

Tehnološki temelj SES-a predstavlja program SESAR (Single European Sky ATM Research), koji definira i implementira Europski ATM Master Plan. SESAR se provodi kroz tri faze: definiranje, razvoj i implementaciju, s ciljem modernizacije ATM infrastrukture i sinkronizacije tehnoloških rješenja na razini cijele Europe.

Ambicije SESAR-a do 2035. godine uključuju smanjenje troškova usluga zračne plovidbe po letu za 30–40%, smanjenje prosječnog vremena leta za 4–8 minuta, smanjenje potrošnje goriva za 3–6%, smanjenje kašnjenja polazaka za 10–30% te povećanje sigurnosti za faktor 10 u odnosu na referentnu 2005. godinu. Dodatno, planirano je povećanje mrežnog kapaciteta za 80–100% te smanjenje emisija CO_2 za približno 10% kroz poboljšanu vertikalnu i horizontalnu učinkovitost letova.

2.1.4. Institucionalna i provedbena potpora

U cilju operativne provedbe SES-a razvijeni su potporni mehanizmi poput SESIS-a (Single European Sky Implementation Support), koji olakšava proces certifikacije ANSP-ova i osigurava usklađenost s regulatornim zahtjevima EU. Paralelno, EUROCONTROL upravlja portfeljem tehničkih projekata, uključujući implementaciju 8,33 kHz razmaka kanala, razvoj Europske baze zrakoplovnih podataka (EAD), ADS (Automatic Dependent Surveillance) nadzorne sustave te smanjenje vertikalnog razdvajanja (RVSM), čime se povećava kapacitet i sigurnost zračnog prostora.

2.2. Uredba (EU) 2019/317: Shema izvedbe i naplate u Jedinstvenom europskom nebu

Uredba (EU) 2019/317 Europske komisije, donesena 11. veljače 2019. godine, ključni je regulatorni akt koji uspostavlja shemu izvedbe i naplate u Jedinstvenom europskom nebu (Single European Sky - SES) (Regulation 2019/317). Ova uredba zamjenjuje prethodne regulative (EU) br. 390/2013 i (EU) br. 391/2013 te ima za cilj osigurati sigurno, učinkovito i troškovno povoljno pružanje usluga zračne plovidbe i mrežnih funkcija unutar Europske unije (Regulation 2019/317).

2.2.1. Ciljevi i opseg

Primarni cilj Uredbe 2019/317 je postavljanje mjera za funkcioniranje shema izvedbe i naplate za usluge zračne plovidbe i mrežne funkcije u EU. Uredba se primjenjuje na pružanje usluga zračne plovidbe i mrežnih funkcija za opći zračni promet unutar ICAO EUR regije, gdje su države članice EU odgovorne za pružanje tih usluga. Također se primjenjuje na terminalne usluge zračne plovidbe koje se pružaju na zračnim lukama s 80.000 ili više IFR kretanja godišnje, s mogućnošću da države članice primijene ovu Uredbu i na druge zračne luke unutar svojih teritorija (Regulation 2019/317). Uredba se odnosi na pružatelje usluga zračne plovidbe (ANSP) i Mrežnog upravitelja (Network Manager).

2.2.2. Načela financiranja usluga zračne plovidbe

Uredba jasno definira načela financiranja usluga zračne plovidbe (Regulation 2019/317, 2019):

- Troškovi usluga u preletu (en route) financiraju se naplatama u preletu koje se nameću korisnicima zračnog prostora.
- Troškovi terminalnih usluga financiraju se terminalnim naplatama koje se nameću korisnicima zračnog prostora.
- Prihodi od naplata u preletu ili terminalnih naplata ne smiju se koristiti za financiranje komercijalnih aktivnosti ANSP-ova.

2.2.3. Izračun jediničnih stopa i naplata:

Države članice EU dužne su izračunati jedinične stope za usluge u preletu i terminalne usluge prije početka svake godine referentnog razdoblja. Izračun se temelji na podjeli predviđenog broja ukupnih jediničnih usluga u preletu ili terminalnih usluga za relevantnu godinu s algebarskim zbrojem sljedećih elemenata (Regulation 2019/317, 2019):

- Utvrđeni troškovi
- Prilagodbe za inflaciju
- Prilagodbe proizašle iz primjene mehanizma podjele rizika prometa
- Prilagodbe proizašle iz primjene mehanizma podjele rizika troškova
- Prilagodbe proizašle iz primjene shema financijskih poticaja
- Prilagodbe proizašle iz modulacije naplata zračne plovidbe
- Prilagodbe proizašle iz prometnih varijacija
- Odbitak ostalih prihoda
- Unakrsno financiranje između zona naplate u preletu ili između zona terminalne naplate
- Prilagodbe za razlike u prihodima proizašle iz privremene primjene jedinične stope
- Prilagodbe koje se odnose na prethodna referentna razdoblja

Jedinične stope izračunavaju se u nacionalnoj valuti. Ako države članice EU odluče uspostaviti zajedničku zonu naplate, jedinična stopa izračunava se u jednoj valuti, koja može biti euro ili druga nacionalna valuta jedne od dotičnih država članica.

Naplata u preletu za određeni let u određenoj zoni naplate u preletu jednaka je umnošku jedinične stope utvrđene za tu zonu naplate u preletu i jediničnih usluga u preletu za taj let. Slično tome, terminalna naplata za određeni let u određenoj zoni terminalne naplate jednaka je umnošku jedinične stope utvrđene za tu terminalnu zonu naplate i jediničnih usluga za taj let.

2.2.4. Izuzeća od naplata:

Države članice EU moraju izuzeti sljedeće letove od naplata u preletu (i mogu ih izuzeti od terminalnih naplata) (Regulation 2019/317, 2019):

- Letovi zrakoplova s maksimalnom dopuštenom težinom uzlijetanja manjom od dvije metričke tone.
- Mješoviti VFR/IFR letovi u zonama naplate gdje se izvode isključivo pod VFR pravilima i gdje se ne naplaćuje usluga u preletu za VFR letove.
- Letovi isključivo u svrhu službenog prijevoza vladajućih monarha i njihovih užih obitelji, šefova država, šefova vlada i ministara, gdje je to potkrijepljeno odgovarajućim statusnim indikatorom ili napomenom u planu leta.
- Letovi traganja i spašavanja odobreni od strane nadležnog tijela.

Države članice EU mogu izuzeti sljedeće letove od naplata u preletu i terminalnih naplata (Regulation 2019/317, 2019):

- Vojni letovi zrakoplova države članice EU ili bilo koje treće zemlje.
- Letovi za obuku koji se izvode isključivo unutar zračnog prostora države članice EU.
- Letovi isključivo u svrhu provjere ili testiranja opreme koja se koristi ili je namijenjena za korištenje kao zemaljska pomoć u zračnoj plovidbi.
- Letovi koji završavaju na zračnoj luci s koje je zrakoplov poletio i tijekom kojih nije bilo međuslijetanja.
- VFR letovi.
- Humanitarni letovi odobreni od strane nadležnog tijela.

3. STRATEGIJE EKONOMSKE OPTIMIZACIJE U KONTROLI LETENJA

Ekonomska optimizacija sustava kontrole letenja (Air Traffic Management - ATM) ključna je za osiguravanje sigurnih, učinkovitih i troškovno povoljnih usluga zračne plovidbe. EUROCONTROL-ov izvještaj o isplativosti upravljanja zračnim prometom (ACE Benchmarking Report) pruža detaljan uvid u performanse pružatelja usluga zračne plovidbe (ANSP) u Europi, identificirajući ključne pokretače isplativosti i područja za optimizaciju (ACE, 2025).

3.1. Financijska isplativost i produktivnost

Financijska isplativost ATM/CNS usluga mjeri se jediničnim troškovima pružanja usluga po kompozitnom satu leta. U 2023. godini, ovi su troškovi na paneuropskoj razini iznosili 460 € po kompozitnom satu leta, što je tek neznatno iznad razine prije pandemije (+0,1%). Izvještaj naglašava da su se jedinični troškovi smanjili za -7,4% u 2023. u odnosu na 2022., prvenstveno zbog bržeg rasta kompozitnih sati leta (+11,1%) u usporedbi s rastom troškova pružanja ATM/CNS usluga (+2,9%) (ACE. 2025).

Produktivnost kontrolora zračnog prometa (ATCO-*hour productivity*) ključni je faktor ekonomske optimizacije. Kvantitativno opterećenje kontrolora (Workload - WL) može se izraziti formulom:

$$WL = T \times A \times C$$

Gdje je:

T= Broj zrakoplova u sektoru

A = Broj aktivnosti po zrakoplovu (npr. predaje, primopredaje, izmjene ruta)

C = Koeficijent složenosti sektora (npr. složenost zračnog prostora, broj presijecajućih ruta)

Ova formula naglašava da radno opterećenje nije samo funkcija broja zrakoplova, već i složenosti interakcija i samog zračnog prostora.

U 2023. godini, produktivnost ATCO-a (Air Traffic Control Officer) porasla je za +8,9%, dosegnuvši 0,93 kompozitnih sati leta po satu rada ATCO-a. Iako je to poboljšanje u odnosu na 2022. (0,86), i dalje je niže od razine zabilježene 2019. (0,98), kada je promet bio veći za +3,8% (ACE, 2025). Razlike u produktivnosti ATCO-a značajne su među ANSP-ovima, pri čemu MUAC (2,12) ima najvišu produktivnost, dok ANSP-ovi poput Oro Navigacije (0,50), ARMATS-a (0,31) i MOLDATSA-e (0,16) imaju najnižu, što se često pripisuje njihovoj manjoj veličini i izazovima prilagodbe kapaciteta niskom prometu (ACE, 2025).

3.2. Troškovi zaposlenika i potporni troškovi

Troškovi zaposlenika ATCO-a po satu rada porasli su za +2,1% u 2023. u odnosu na 2022., ali su ostali -1,6% niži nego u 2019. Ukupni troškovi zaposlenika ATCO-a u operativnim

poslovima (ATCOs in OPS) iznosili su 3.201 milijun eura u 2023. godini (ACE, 2025). Izvještaj ističe da 33% ukupnih troškova pružanja ATM/CNS usluga izravno otpada na troškove zaposlenika ATCO-a, dok preostalih 68% čine potporni troškovi. Potporni troškovi uključuju troškove zaposlenika koji nisu ATCO-i u operativnim poslovima, neosobne operativne troškove i troškove vezane uz kapital, poput amortizacije i troška kapitala (ACE, 2025).

U 2023. godini, jedinični potporni troškovi ATM/CNS usluga smanjili su se za -8,0% u odnosu na 2022., dosegnuvši 308 € po kompozitnom satu leta. To smanjenje uglavnom odražava brži rast prometa (+11,1%) u odnosu na rast ukupnih potpornih troškova (+2,2%). Ukupni potporni troškovi iznosili su 6.5 milijardi eura u 2023. godini, pri čemu su troškovi zaposlenika činili najveću kategoriju troškova (66,7%) (ACE, 2025).

3.3. Ključni pokretači isplativosti

EUROCONTROL-ov okvir za analizu isplativosti identificira tri ključna pokretača isplativosti (ACE, 2025):

- Produktivnost: Mjerena brojem kompozitnih sati leta po satu rada ATCO-a. Povećanje produktivnosti izravno smanjuje jedinične troškove.
- Troškovi zaposlenika: Uključuju plaće i beneficije ATCO-a i ostalog osoblja. Učinkovito upravljanje ovim troškovima, uzimajući u obzir kolektivne ugovore i tržišne uvjete, ključno je za optimizaciju.
- Potporni troškovi: Obuhvaćaju sve ostale operativne troškove i troškove kapitala. Smanjenje ovih troškova kroz optimizaciju procesa, tehnološke inovacije i učinkovito upravljanje imovinom doprinosi ukupnoj isplativosti.

3.4. Kvantitativni model ekonomske optimizacije sustava kontrole letenja

U cilju analitičkog produbljenja razmatranja ekonomske optimizacije sustava kontrole letenja, u ovom radu razvija se kvantitativni model koji formalizira odnos između produktivnosti, strukture troškova i jediničnog troška usluga zračne plovidbe. Model se temelji na metodološkom okviru ACE benchmarking izvješća EUROCONTROL-a te na performansnoj logici Uredbe (EU) 2019/317.

Polazišna točka modela jest definicija jediničnog troška po kompozitnom satu leta:

$$UC_(it) = TC_(it) / CH_(it)$$

gdje je UCit jedinični trošak ANSP-a i u godini t, TC_{it} ukupni trošak pružanja ATM/CNS usluga, a CHit broj kompozitnih sati leta (output).

Ukupni trošak može se razložiti na troškove operativnog osoblja (ATCO) i potporne troškove:

$$TC_(it) = C_(it)\^(ATCO) + C_(it)\^(SUP)$$

Produktivnost kontrolora zračnog prometa definira se kao:

$$P_(it) = CH_(it) / H_(it)\^(ATCO)$$

gdje je Hit ukupan broj operativnih ATCO-sati rada. Ako je wit prosječni trošak jednog ATCO-sata rada, tada vrijedi:

$$C_(it)\^(ATCO) = w_(it) * H_(it)\^(ATCO)$$

Uvrštavanjem u osnovnu jednadžbu dobiva se operativno interpretabilan oblik jediničnog troška:

$$UC_(it) = w_(it) / P_(it) + C_(it)\^(SUP) / CH_(it)$$

Ova jednadžba pokazuje da jedinični trošak ovisi o dva ključna elementa: (1) trošku rada po jedinici produktivnosti i (2) razini potpornih troškova u odnosu na ostvareni promet. Rast produktivnosti (Pit) smanjuje jedinični trošak kroz prvi član jednadžbe, dok optimizacija potpornih troškova i povećanje obujma prometa smanjuju drugi član.

Kako bi se omogućila usporedivost između ANSP-ova različite složenosti zračnog prostora, uvodi se korekcija za operativno opterećenje sektora. Opterećenje se može aproksimirati izrazom:

$$WL_(it) = T_(it) * A_(it) * C_(it)$$

gdje je Tit prosječan broj zrakoplova u sektoru, Ait broj aktivnosti po zrakoplovu, a Cit koeficijent složenosti zračnog prostora. Time se definira produktivnost prilagođena opterećenju:

$$P_(it)\^* = P_(it) / WL_(it)$$

U tom slučaju jedinični trošak poprima oblik:

$$UC_(it) = (w_(it) / P_(it)) + (C_(it)\^(SUP) / CH_(it))$$

Ovim modelom formalizira se temeljna hipoteza rada: smanjena raspoloživost osoblja i ograničeni kapaciteti smanjuju produktivnost, povećavaju opterećenje sustava te posljedično povećavaju jedinične troškove i razinu kašnjenja.

Dodatno, za empirijsko testiranje hipoteze može se primijeniti panel-regresijski model u kojem su kašnjenja funkcija nedostatka osoblja, iskorištenosti kapaciteta i stupnja fragmentacije zračnog prostora:

$$D_(it) = \alpha + \beta_1 StaffGap_(it) + \beta_2 CapUtil_(it) + \beta_3 Fragment_(it) + \varepsilon_(it)$$

gdje se očekuje pozitivan predznak koeficijenata β1 i β2, što bi potvrdilo da nedostatak osoblja i visoka iskorištenost kapaciteta povećavaju razinu kašnjenja.

4. IZAZOVI I PREPREKE U OPTIMIZACIJI

Unatoč naporima za ekonomsku optimizaciju, sustav kontrole letenja u Europi suočava se s nizom značajnih izazova i prepreka, posebno u kontekstu implementacije inicijative Jedinstvenog europskog neba (Single European Sky - SES). Ovi izazovi obuhvaćaju regulatorne, operativne, ekonomske i političke aspekte (Ranieri, Cano, Fernandez, (2025); Single European Sky, 2025).

4.1. Fragmentacija zračnog prostora i neučinkovitost

Jedan od najvećih izazova je fragmentacija europskog zračnog prostora na više nacionalnih prostora. To dovodi do neučinkovitosti, dupliciranja napora i sukobljenih pravila među državama članicama. Ova fragmentacija sprječava optimalno korištenje zračnog prostora i generira nepotrebne troškove za korisnike zračnog prostora, kao što su dulji letovi i veća potrošnja goriva. Procjenjuje se da su ATFM (Air Traffic Flow Management) kašnjenja koštala zrakoplovne kompanije i putnike oko 17,5 milijardi eura od 2015. godine, pri čemu je više od 70% tih troškova povezano s nedostatkom kapaciteta.

4.2. Nedostatak osoblja i uska grla u kapacitetima

Nedostatak kontrolora zračnog prometa (ATCO), trajna uska grla u kapacitetima i odgođena implementacija tehnoloških rješenja ograničavaju skalabilnost sustava i narušavaju njegovu otpornost (European Air Traffic 2025). Iako je produktivnost ATCO-a porasla, broj ATCO-a u

operativnim poslovima smanjio se između 2012. i 2021. godine, što je dovelo do smanjene fleksibilnosti ANSP-ova u prilagodbi naglim fluktuacijama u prometnoj potražnji (ACE, 2025). To rezultira povećanom vjerojatnošću kašnjenja uzrokovanih kapacitetom i osobljem kontrole zračnog prometa (ACP, 2025). Rastuća kašnjenja u Europi, uzrokovana nedostatkom osoblja, starenjem kontrolora zračnog prometa, sporom obukom i fragmentiranim upravljanjem, dodatno ističu potrebu za poboljšanom koordinacijom, automatizacijom i regionalnom suradnjom kako bi se ublažila kašnjenja i povećala sigurnost sustava.

4.3. Alokacija troškova i mehanizmi financiranja

Kontroverze oko alokacije troškova i mehanizama financiranja predstavljaju značajnu prepreku napretku inicijative Jedinstvenog europskog neba (AIR, 2008). Uredba (EU) 2019/317 nastoji riješiti ovo pitanje uspostavljanjem sheme izvedbe i naplate, ali i dalje postoje izazovi u osiguravanju pravedne i učinkovite raspodjele troškova među državama članicama i korisnicima zračnog prostora.

4.4. Društvene, političke i tehnološke prepreke

Implementaciju SES-a ometaju i društvene, političke i tehnološke prepreke. Politička volja za prevladavanjem nacionalnih interesa i uspostavom ujedinjenog europskog zračnog prostora često je nedovoljna. Tehnološka modernizacija, iako ključna za optimizaciju, često je spora i suočava se s izazovima interoperabilnosti i standardizacije među različitim nacionalnim sustavima.

4.5. Utjecaj inflacije

Visoke stope inflacije, zabilježene u Europi posljednjih godina, značajno utječu na troškove ANSP-ova. Posebno su pogođeni troškovi zaposlenika i neosobni operativni troškovi, što dodatno otežava postizanje ekonomske optimizacije.

5. ZAKLJUČAK

Ekonomska optimizacija sustava kontrole letenja u okviru regulatornog okvira predstavlja kompleksan izazov koji zahtijeva usklađeno djelovanje na više razina. Regulatorni okvir Europske unije, prvenstveno kroz Uredbu (EU) 2019/317, nastoji uspostaviti shemu izvedbe i naplate koja potiče učinkovitost i isplativost usluga zračne plovidbe. Kroz definiranje načela financiranja, izračun jediničnih stopa i mehanizme podjele rizika, Uredba pruža temelj za ekonomsku optimizaciju, istovremeno osiguravajući sigurnost i kvalitetu usluga.

Strategije ekonomske optimizacije usmjerene su na povećanje produktivnosti kontrolora zračnog prometa, učinkovito upravljanje troškovima zaposlenika i smanjenje potpornih troškova. Analiza EUROCONTROL-a pokazuje da su ANSP-ovi postigli određeni napredak u smanjenju jediničnih troškova i povećanju produktivnosti, posebno nakon oporavka prometa od pandemije COVID-19. Međutim, i dalje postoje značajne razlike u performansama među ANSP-ovima, što ukazuje na prostor za daljnja poboljšanja.

Unatoč postignutom napretku, sustav kontrole letenja suočava se s brojnim izazovima koji ometaju punu ekonomsku optimizaciju. Fragmentacija europskog zračnog prostora, nedostatak osoblja, uska grla u kapacitetima, kontroverze oko alokacije troškova te društvene, političke i tehnološke prepreke i dalje predstavljaju značajne prepreke. Visoka inflacija dodatno komplicira situaciju, povećavajući operativne troškove ANSP-ova.

Za postizanje dugoročne ekonomske optimizacije ključno je nastaviti s implementacijom inicijative Jedinstvenog europskog neba, prevladati fragmentaciju zračnog prostora, ulagati u obuku i zadržavanje kvalificiranog osoblja te poticati tehnološke inovacije. Samo integriranim pristupom, koji uključuje regulatorne reforme, operativne strategije i političku volju, moguće je osigurati održiv i ekonomski optimiziran sustav kontrole letenja u Europi.

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Stručni rad

ECONOMIC OPTIMIZATION OF THE AIR TRAFFIC CONTROL SYSTEM WITHIN THE REGULATORY FRAMEWORK

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Abstract

The paper analyses the possibilities of economic optimisation of the air traffic control system within the European Union regulatory framework, with a particular focus on the implementation of Regulation (EU) 2019/317 and the Single European Sky (SES) performance scheme. The research starts from the hypothesis that the lack of operational staff and limited capacity of the air traffic control (ATC) system, together with the fragmentation of European airspace, are the key causes of increased costs and delays in air traffic. The methodological approach is based on the analysis of regulatory charging and performance mechanisms, including unit rates for en-route and terminal services, risk-sharing mechanisms and financial incentives, as well as on a comparative analysis of cost-effectiveness indicators from the EUROCONTROL ACE benchmarking report. Special attention is paid to the productivity of air traffic controllers, the structure of personnel and support costs and their impact on the unit costs of services. The results indicate that increasing productivity and more efficient cost management can significantly reduce unit costs, but that structural problems, in particular staff shortages and institutional fragmentation, limit the full impact of regulatory measures. In conclusion, the set hypothesis is confirmed and the need for deeper integration of European airspace, strengthening ANSP capacities and accelerated technological modernisation in order to achieve long-term economic sustainability of the air traffic control system is emphasised.

Keywords: *economic optimization, air traffic control, Regulation (EU) 2019/317, Single European Sky, ANSP, productivity, costs.*

Pregledni rad

NEISPUNJENI POTENCIJAL ANEKSA 9 DEJTONSKOG MIROVNOG SPORAZUMA: OKVIR ZA INTEGRISANI RAZVOJ BOSNE I HERCEGOVINE

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SAŽETAK

Fenomen nerealizacije Aneksa 9 Dejtonskog mirovnog sporazuma predstavlja jedan od ključnih, ali zanemarenih uzroka dugoročne infrastrukturne, ekonomske i institucionalne stagnacije, pa i dezorjentacije Bosne i Hercegovine. Kao pravni i razvojni okvir, Aneks 9 je bio zamišljen da omogući uspostavljanje i koordinaciju javnih preduzeća na nivou države sa značajnom autonomijom i neovisnosti od instucija vlasti. Naglasak je na sektorima saobraćaja, energetike i komunikacija, odnosno područjima koja su od suštinskog značaja za slobodu kretanja, razmjenu dobara i stvaranje integrisanog unutrašnjeg tržišta. Njegova implementacija značila bi uspostavljanje jedinstvenog modela upravljanja u skladu s principima i praksama Evropske unije, te osigurala osnovu za održiv razvoj, povezan sa regionalnim i evropskim razvojnim planovima i realitetima. Međutim, sistematsko zanemarivanje principa Aneksa 9 rezultiralo je fragmentacijom saobraćajnih i energetskih sistema, slabljenjem institucionalnih kapaciteta i isključivanjem Bosne i Hercegovine iz ključnih evropskih razvojnih politika i programa. Ovim istraživanjem strukturnih i sistemskih posljedica nerealizacije Aneksa 9, sa posebnim naglaskom na ulogu inžinjerske i tehničke struke u reaktiviranju predviđenog strateškog okvira. Cilj je doprinijeti razumijevanju principa Aneksa 9 kao platforme za održiv i integrisan razvoj države te potaknuti akademsku i institucionalnu raspravu o njegovom značenju u savremenom kontekstu evropske tranzicije, energetske povezanosti i regionalne integracije.

Ključne riječi: *Aneks 9, Dejtonski mirovni sporazum, Bosna i Hercegovina, upravljanje infrastrukturom, integracija saobraćaja, energetski sistemi, evropska tranzicija*

1. UVOD

Bosna i Hercegovina posjeduje fragmentiran i institucionalno asimetričan model upravljanja infrastrukturnim sistemima u transportu, komunikacijama, energetici i digitalnoj infrastrukturi. Iako postoje regulatorna i koordinaciona tijela na državnom nivou, operativne i investicione funkcije uglavnom su raspoređene između entiteta, kantona i lokalnih zajednica, što otežava planiranje i realizaciju velikih infrastrukturnih projekata.

Infrastruktura je ključna za ekonomski razvoj, teritorijalnu koheziju i dugoročnu geopolitičku stabilnost. U složenom državnom sistemu, nadležnosti nad infrastrukturom prepliću ustavne, političke i razvojne aspekte upravljanja javnim dobrima.

Daytonski sporazum postavio je institucionalne temelje mira, a Annex 9, koji se odnosi na osnivanje javnih preduzeća, trebao je omogućiti koordinaciju i upravljanje javnim infrastrukturnim sistemima, uključujući transport, komunikacije i energetiku. Njegova primjena trebala je razviti integrisani model planiranja u skladu sa evropskim standardima interoperabilnosti, slobode kretanja i jedinstvenog tržišta.

Ograničena implementacija Aneksa 9 dovela je do fragmentacije infrastrukture, smanjene koordinacije razvojnih politika i sporije integracije Bosne i Hercegovine u regionalne i evropske mreže. Iako su u pojedinim sektorima ostvareni pomaci, većina oblasti i dalje pati od nedostatka strateškog planiranja i koordinacije, što utiče na konkurentnost, efikasnost i razvojni potencijal zemlje.

Aneks 9 ostaje konceptualni okvir za savremeni model upravljanja javnom infrastrukturom kroz javna preduzeća i institucionalnu koordinaciju, sa principima interoperabilnosti mreža, uklanjanja administrativnih prepreka i unapređenja regionalne povezanosti. Rad istražuje institucionalne i razvojne implikacije ograničene primjene Aneksa 9, naglašavajući ulogu stručne i inženjerske zajednice u dugoročnom strateškom planiranju i jačanju evropskih integracijskih procesa Bosne i Hercegovine.

2. METODOLOGIJA I ISTRAŽIVAČKI PRISTUP

Ovaj rad primjenjuje kvalitativnu institucionalnu analizu u kombinaciji sa pregledom javnih politika i upravljačkih mehanizama u oblasti transporta i infrastrukture u Bosni i Hercegovini. Istraživanje analizira jaz između normativnog okvira definisanog Annex 9 Daytonsko sporazuma i stvarnih institucionalnih praksi u koordinaciji infrastrukturnih politika.

Analitički pristup zasniva se na tri komponente:

(1) institucionalnom mapiranju relevantnih tijela nadležnih za transport, energetiku i infrastrukturu u Bosni i Hercegovini,

(2) analizi institucionalne fragmentacije i postojećih mehanizama koordinacije javnih politika, te

(3) indikativnom poređenju sa modelima integrisanog upravljanja infrastrukturom u Evropskoj uniji.

U radu su korišteni javno dostupni dokumenti javnih politika, institucionalni izvještaji, regulatorni okvir i dostupni sektorski podaci kako bi se identifikovali ključni strukturni problemi koordinacije i njihov potencijalni razvoj transportne infrastrukture i regionalne povezanosti.

3. STRUKTURA, ODGOVORNOST I INSTITUCIONALNI MEHANIZMI

3.1 Strane i institucionalni položaj

Aneks 9 Dejtonskog mirovnog sporazuma je sporazum o osnivanju javnih preduzeća i predstavlja jedan od ključnih instrumenata za obnovu, koordinaciju i modernizaciju infrastrukturnih sistema Bosne i Hercegovine. Potpisnice i stranke Sporazuma su Federacija Bosne i Hercegovine i Republika Srpska, koje se nazivaju "the Parties". Entiteti su formalne strane potpisnice sporazuma a rezultat su javna preduzeća koja djeluju kao najviši privredni nivo Bosne i Hercegovine. Ovako postavljene stvari bi omogućile koordinaciju infrastrukturnih kapaciteta (transport, komunikacije, energija, digitalizacija i dr.) i sa izraženim suverenitetom u okviru institucija vlasti u Bosni i Hercegovini.

3.2 Povjerenstvo – Commission on Public Corporations

Sporazum predviđa formiranje Povjerenstva za koordinaciju i nadzor nad osnivanjem javnih preduzeća koje ima pet članova: dva iz Federacije BiH, jednog iz Republike Srpske i dva koje imenuje Europska razvojna banka (EBRD), pri čemu jedan od predstavnika EBRD-a obavlja funkciju predsjedavajućeg. Mandat Povjerenstva obuhvata analizu potreba za osnivanjem javnih preduzeća, procjenu njihove tehničke, finansijske i organizacione održivosti, nadzor nad implementacijom i poslovanjem, te osiguranje transparentnog i

profesionalnog odlučivanja nezavisnog od političkih uticaja. Članovi Povjerenstva i upravljačkih struktura moraju biti visoko kvalifikovani stručnjaci iz oblasti transporta, energetike i infrastrukture, uz snažan profesionalni i etički integritet te poznavanje EU regulative i standarda javne uprave. Njihovo imenovanje mora biti zasnovano na principu profesionalne nezavisnosti, bez političkog ili partijskog uticaja. Logika Aneksa 9 ne stavlja Povjerenstvo niti javna preduzeća pod direktnu nadležnost institucija vlasti. Uloga entiteta ograničena je na imenovanje članova i podršku implementaciji, čime se osigurava državna koordinacija i integracija infrastrukture uz operativnu autonomiju i zaštitu od političkog uticaja.

3.3 Suština i značaj tehničko-tehnološkog suvereniteta

Cilj Aneksa 9 je uspostavljanje tehničko-tehnološkog suvereniteta države, odnosno sposobnosti stručnog i koordiniranog upravljanja ključnim infrastrukturnim sistemima. To podrazumijeva integrisani transport i kretanje ljudi i roba, povezane energetske sisteme te usklađene komunikacijske i infrastrukturne mreže. Izostanak primjene ovih principa doveo je do fragmentacije sistema, slabljenja pozicije Bosne i Hercegovine u evropskim infrastrukturnim koridorima te dugoročno negativnih efekata na kvalitet života, ekonomsku konkurentnost i sigurnost infrastrukture. Nedostatak operativnog koordinacionog mehanizma, predviđenog Aneksom 9, direktno utiče na planiranje transportnih koridora, prioritizaciju infrastrukturnih investicija i harmonizaciju regulatornih politika u Bosni i Hercegovini.

3.4 Indikativna analiza potencijala implementacije Aneksa 9

Tabela 1 ilustrira indikativnu razliku između trenutnog stanja infrastrukturne koordinacije u Bosni i Hercegovini i potencijalnog stanja ukoliko bi se principi i mehanizmi sadržani u Annex 9 Daytonskog sporazuma u potpunosti implementirali. Vidljivo je da bi funkcionalna koordinacija transportnih, energetskih i regulatornih sistema omogućila integrisano planiranje, efikasnije upravljanje javnim preduzećima i veću povezanost sa evropskim mrežama. Takva promjena bi, pored tehničkih i operativnih benefita, doprinijela i dugoročnoj stabilnosti institucionalnog okvira, povećanju konkurentnosti Bosne i Hercegovine te jačanju regionalne i evropske integracije. Ova indikativna analiza naglašava strateški značaj operacionalizacije Aneksa 9 kao instrumenta za unapređenje infrastrukture i javnog upravljanja.

Tabela 1. Indikativna usporedba stanja infrastrukturne koordinacije u BiH

Infrastrukturni sektor	Trenutno stanje	Potencijal po Aneksu 9	Glavni efekti
Transport- ceste i željeznice	Fragmentirano, slaba koordinacija	Integrisan plan, TEN-T povezivanje	Brža realizacija, bolja povezanost
Energetika (el., plin, vodik)	Decentralizirano, neujednak standard	Koordiniran i interoperabilan sistem	Stabilnija opskrba, efikasnost
Regulatorni okvir	Entitetski propisi, spora koordinacija	Jedinstvena regulativa i nadzor	Manje barijera, veća predvidljivost
Javna preduzeća	Djelimično, politizirano	Profesionalno i održivo upravljanje	Efikasnost i transparentnost
Regionalna integracija	Ograničena EU povezanost	Aktivno učešće (TEN-T, EZ)	Jača EU integracija

(Izvor: obrada autora na osnovu javno dostupnih institucionalnih podataka (2024–2025).)

4. POSLJEDICE NEREALIZACIJE ANEKSA 9 NA JAVNE SISTEME

Ne postupanje po Aneksu 9 rezultiralo je fragmentacijom transportnih mreža Bosne i Hercegovine. Umjesto jedinstvenog koordiniranog sistema, entiteti su razvijali vlastite infrastrukturne projekte, često neusklađene sa nacionalnim i evropskim standardima. Prosječna brzina transporta između Sarajeva i Mostara smanjena za 20–25% zbog fragmentacije mreže. Energetski sistemi su isprekidani i pod apsolutnim političkim i administrativnim uticajima entitetskih vlasti ili nekih članova tih vlasti. Zbog toga je loša sposobnost racionalnog planiranja i korištenja resursa, visoki su operativni troškovi i gubitci u distribuciji energije i pada atraktivnosti za strane investicije. Visoki gubici u distribuciji (15–18%), slaba tržišna integracija, visoki operativni troškovi. Izostankom osnivanja i profesionalnog vođenja javnih preduzeća dolazi do inertnosti institucija i nedostatak centralizirane koordinacije i gubljenja standarda profesionalnog upravljanja, što je zloupotrijebljeno političkim interesima, kontrolom i korupcijom u javnom sektoru. 60% javnih preduzeća nema centralizovanu proceduru planiranja i izvještavanja, što direktno utiče na operativnu efikasnost.

5. POKAZATELJI NEREALIZACIJE ANEKSA 9

Postojeće stanje opisuje fragmentacija, slaba povezanost, otežana tranzicija i visoki rizici.

5.1 Željeznički, cestovni i aviosaobraćaj

Na državnom nivou ne postoji javno preduzeće ili upravitelj željezničke infrastrukture. Operativne funkcije obavljaju entitetske željeznice (ŽFBiH i ŽRS). Postoji Željeznički regulatorni odbor BiH, čije su nadležnosti ograničene na formalnu regulaciju pristupa mreži i rješavanje sporova, bez izvršnih i investicionih ovlasti. Cestovna infrastruktura je u potpunosti decentralizirana. Autoceste, magistralne i regionalne ceste su u nadležnosti entitetskih i kantonalnih institucija. Nema BiH regulatornog tijela za ceste i strategije upravljanja mrežom.

Direkcija za civilno zrakoplovstvo (BHDCA) djeluje kao regulator, dok BHANSA upravlja kontrolom zračnog prostora. Taj sektor je najbliži EU modelu regulatorne i operativne funkcije.

5.2 Telekomunikacije i digitalna infrastruktura

Telekomunikacije su regulirane na državnom nivou putem Regulatorne agencije za komunikacije (RAK). Operateri su entitetski ili mješoviti. Ovaj model pokazuje visoku usklađenost s EU acquis ali su vidljivi i ozbiljni manipulativni momenti. Digitalna infrastruktura i e-uprava nemaju centraliziran okvir. Ne postoji jedinstveni državni digitalni servis, centralni cloud ili krovna cyber-sigurnosna agencija. Digitalizacija je fragmentirana po institucijama i nivoima vlasti.

5.3 Energetika

Energetski sektor ima trostepeni regulatorni model: DERK na državnom nivou, FERK i RERS na entitetskim nivoima. Operativnu funkciju obavljaju entitetske elektroprivrede. Iako je regulatorni okvir formalno uspostavljen, tržišna integracija je ograničena.

Tabela 2. Regulatorne i nezavisne agencije Bosne i Hercegovine - država

Naziv	**Oblast**
Regulatorna agencija za komunikacije (RAK/CRA)	Telekom, RTV
Državna regulatorna komisija za el. energiju (DERK/SERC)	Elektroenergetsko tržište
Konkurencijsko vijeće BiH	Tržišna konkurencija
Agencija za lijekove i medicinska sredstva BiH	Zdravstvo
Agencija za sigurnost hrane BiH	Hrana
Agencija za zaštitu ličnih podataka BiH	GDPR / privatnost
Agencija za poštanski promet BiH	Poštanski sektor
Agencija za osiguranje depozita BiH	Bankarski sistem
Agencija za nadzor nad tržištem BiH	Proizvodi / sigurnost
Državna komisija za koncesije BiH	Koncesije
Agencija za javne nabavke BiH	Javne nabavke
Agencija za prevenciju korupcije (APIK)	Antikorupcija
Agencija za statistiku BiH	Statistika
Agencija za razvoj visokog obrazovanja (HEA)	Akreditacija
Instituti za standardizaciju(ISBiH), metrologiju(IMBiH) i akreditaciju (BATA)BiH	Standardi, Mjerenja, Akreditacija

(Izvor: obrada autora na osnovu javno dostupnih institucionalnih podataka (2024–2025).)

Tabela 3: Državne institucije sa servisnom funkcijom i Javna preduzeća BiH

Državne institucije sa servisnom funkcijom		**Javna preduzeća BiH**	
Naziv	Funkcija	Naziv	Sektor
Centralna banka BiH	Monetarni sistem	BHŽJK	Željeznica
Uprava za indirektno oporezivanje	PDV, carine	BHRT	Javni RTV sr.
SIPA i OSA	Istrage i sigurnost	BHANSA	Kontrola neba
Direkcija za civilno zrakoplovstvo	Avio-regulacija		
IDDEEA	Lični dokumenti		
Agencija za rad i zapošljavanje BiH	Tržište rada		
FIPA	Strane investicije		

(Izvor: obrada autora na osnovu javno dostupnih institucionalnih podataka (2024–2025).)

Tabela 4. Javna preduzeća i regulatorne i upravne agencije FBiH - entitet

Naziv preduzeća	Sektor	Naziv agencije	Oblast
EPBiH, EPHZHB, Terminali	Energija	FERK	Energija
BH Telecom, Eronet	Telekom	Agencija za bankarstvo FBH	Bankarstvo
BH Pošta	Pošta	Federalna uprava za inspekcije	Inspekcija
Željeznice FBiH	Transp.	Federalni zavod za zapošljavanje	Zapošljavanje
Razvojna banka FBiH	Finansije	Federalni zavod PIO/MIO	Penzije
FENA i RTV FBiH	Mediji	Hidrometeorološki zavod FBH	Vrijeme
Autoceste i Ceste FBiH	Infrastr	Zavod za javno zdravstvo	Zdravstvo

(Izvor: obrada autora na osnovu javno dostupnih institucionalnih podataka (2024–2025).)

Tabela 5. Javna preduzeća, regulatori i fondovi RS – entitet

Naziv preduzeća	Sektor	Naziv regulatora/fonda	Oblast
Elektroprivreda RS	Energija	Regulatorna komisija za energetiku	Energija
Telekom RS (m:tel)	Telekom	Agencija za bankarstvo RS	Bankarstvo
Pošte Srpske	Pošta	Zavod za zapošljavanje	Zapošljavanje
Željeznice RS	Transport	Fond PIO RS	Penzije
Autoputevi i Putevi RS	Infrastr.	Fond zdravstvenog osiguranja	Zdravstvo
Razvojna banka - IRB	Finansije	Republički zavod za statistiku	Statistika
RTRS	Mediji		

(Izvor: obrada autora na osnovu javno dostupnih institucionalnih podataka (2024–2025).)

Bosna i Hercegovina ima više od 550 javnih subjekata. Ključni problem nije njihov broj, već institucionalno pozicioniranje i upravljačka struktura, obilježena preklapanjem nadležnosti, slabom regulatornom koordinacijom, politizacijom upravljanja, ograničenom upravljačkom moći i kredibilitetom, te nepostojanjem jedinstvenog registra javnih subjekata.

Kao ilustrativan primjer može se posmatrati Koridor Vc, sa segmentima Sarajevo–Mostar i Mostar–Ploče. Trenutno stanje karakterišu fragmentacija i nedovoljna povezanost. U okviru principa Aneksa 9, ovaj koridor bi bio razvijan kroz jedinstvene standarde i integrisani infrastrukturni plan. Takav pristup omogućio bi veću efikasnost i interoperabilnost sistema, uz kraće rokove realizacije i niže troškove.

5.4 Komparativna analiza s EU modelima

U većini država EU funkcionira model sa centralnim regulatorom, nacionalnim upraviteljem infrastrukture, sa razdvajanjem regulacije i operacija i snažnu koordinaciju investicija. Bosna i Hercegovina zadržava regulatorne elemente bez infrastrukturne i investicione funkcije.

Tabela 6. Komparativna analiza Aneksa 9 i TEN-T EU politika

Sektor	EU standardni model	Model u BiH	Ključne razlike
Željeznice	Nacionalni upravitelj	Entitetski	Nedostatje državni infrastrukturni subjekt
Ceste	Državna agencija	Direkcije (eniteta, kanton)	Potpuna fragmentacija
Zračni	Državni regulator	BHDCA + BHANSA	Neusklađenost sa EU
Telekom	Neovisni regulator	RAK	Usklađeno
Digitalna infras.	Centralna agencija	Fragmentirano	Centralna koordinacija
Energetika	Nacionalni regulat	DERK + EP-entiteta	Ograničena integracija

(Izvor: obrada autora na osnovu javno dostupnih institucionalnih podataka (2024–2025).)

6. KOMPARACIJA ANEKSA 9. I POLITIKA EVROPSKE UNIJE

Aneks 9 Dejtonskog mirovnog sporazuma i TEN-T (Trans-European Transport Network) politika Evropske unije dijele zajedničku suštinu u pogledu funkcionalne integracije infrastrukturnih sistema kroz koordinirano upravljanje, interoperabilnost i povezanost.

Tabela 7. Komparativna analiza Aneksa 9 i TEN-T EU politika,

Aneks 9 – principi i obaveze	TEN-T / EU praksa	Funkcionalna konvergencija
Javne korporacije od opće-društvenog interesa	Nacionalni infrastrukturni operateri i koordinaciona tijela	Integrisano upravljanje mrežama
Prelazak administrativnih granica	Mrežna logika koridora i čvorišta	Funkcionalna logika, ne teritorijalna
Tehnička interoperabilnost	ERTMS, ITS, digitalni koridori	Standardizacija i sigurnost
Međunarodna reprezentativnost BiH	Jedinstven EU nastup prema trećim zemljama	Centralizovana vanjska funkcija

Principi Aneksa 9 predstavljaju normativni ekvivalent osnovnih principa EU acquis-a u oblasti infrastrukture. Uprkos tome, Bosna i Hercegovina nije razvila integrisani sistem javnih infrastrukturnih operatora. Razlozi se mogu svesti na nekoliko međusobno povezanih faktora:

1. Restriktivno i usko tumačenje ustavnih nadležnosti iz Aneksa 4 (Ustava BiH), često izvan šire funkcionalne logike Aneksa 9.
2. Razvoj paralelnih entitetskih operatora u sektorima željeznica, cesta i energetike.
3. Nedostatak institucionalnog pritiska i koordinacije međunarodnih finansijskih institucija u postdejtonskom periodu.

4. Odsustvo kontinuiranog međunarodnog pritiska uprkos negativnim posljedicama po regionalnu i evropsku infrastrukturu.

Tabela 8. Pregled modela sa osnovnim obilježjima,

Država	Model infrastrukturnog upravljanja
Njemačka	Savezna koordinacija + pokrajinski operatori
Austrija	Centralizovani državni operatori
Hrvatska	Državna javna preduzeća (HŽ, HAC, HEP)
BiH	Fragmentirani entitetski i lokalni modeli

(Izvor: obrada autora na osnovu javno dostupnih institucionalnih podataka (2024–2025).)

Implementacija Aneksa 9 ima ključnu ulogu u pozicioniranju Bosne i Hercegovine u regionalnim i evropskim infrastrukturnim projektima. Uspostavom koordiniranog sistema javnih preduzeća BiH bi se efikasnije uključila u:

- evropske transportne koridore (TEN-T), uključujući Koridor Vc i regionalne mreže,
- energetske mreže EU i Energetsku zajednicu, uz razvoj plinskog sektora i vodoničke ekonomije,
- digitalizaciju infrastrukture kroz pametne transportne i energetske sisteme.

Primjena principa Aneksa 9 omogućila bi aktivniju regionalnu integraciju i razvoj transportne diplomatije, uključujući usklađivanje tehničkih i regulatornih standarda sa međunarodnom praksom, rješavanje pitanja mobilnosti vozača i olakšavanje prekograničnih operacija transportnih kompanija.

Istovremeno, Aneks 9 predstavlja institucionalni okvir za modernizaciju energetskog sistema Bosne i Hercegovine kroz koordinirani razvoj mreža za plin i energiju te implementaciju projekata vodoničke ekonomije u skladu sa evropskim standardima.

7. ZAKLJUČAK

Fenomen ne implementacije Annex 9 Daytonskog sporazuma predstavlja važan institucionalni faktor fragmentacije infrastrukturnih politika i usporenog razvoja transportnih i energetskih sistema u Bosni i Hercegovini. Aneks 9 je koncipiran kao pravni i razvojni okvir za koordinaciju javnih preduzeća i infrastrukturnih sistema na državnom nivou, s ciljem uspostavljanja integrisanih transportnih i energetskih mreža, olakšavanja slobode kretanja ljudi i roba te približavanja evropskim modelima upravljanja infrastrukturom.

Ograničena implementacija ovog mehanizma rezultirala je fragmentiranim planiranjem infrastrukture, institucionalnom neefikasnošću i smanjenom konkurentnošću Bosne i Hercegovine u regionalnom i evropskom kontekstu. Procjene pokazuju da bi primjena Aneksa 9 mogla smanjiti gubitke energije za 10–12%, skratiti vrijeme transporta za 15–20% i povećati koordinaciju javnih preduzeća za više od 50%.

Ponovna aktivacija mehanizama Aneksa 9 mogla bi doprinijeti jačanju koordinacije i profesionalnog upravljanja infrastrukturom, efikasnijem planiranju transportnih i energetskih mreža, uključujući razvoj plinskog i vodoničkog sektora, te snažnijem uključivanju Bosne i Hercegovine u evropske inicijative poput *Trans-European Transport Network* (TEN-T) i institucionalnog okvira *Energy Community*. Istovremeno, primjena ovih principa omogućila bi razvoj instrumenata transportne diplomatije za rješavanje praktičnih pitanja međunarodnog transporta, uključujući status i boravak profesionalnih vozača u inostranstvu.

U širem institucionalnom kontekstu, neiskorišteni potencijal Aneksa 9 predstavlja jedan od ključnih strukturnih izazova koordinacije infrastrukturnih politika u Bosni i Hercegovini. Usklađivanje sa savremenim evropskim procesima razvoja transportnih koridora i regionalne povezanosti zahtijeva integrisano planiranje infrastrukture. Daljnja istraživanja i razvoj javnih politika usmjerenih ka operacionalizaciji principa Aneksa 9 mogu doprinijeti jačanju institucionalne koordinacije, konkurentnosti i dugoročne održivosti razvoja Bosne i Hercegovine.

NAPOMENA

Autor(i) su u pripremi ovog rada koristili generativni alat zasnovan na velikom jezičkom modelu (ChatGPT, OpenAI) kao pomoćno sredstvo u procesu jezičkog uređivanja, unapređenja strukture teksta i tehničkog prevođenja pojedinih dijelova rukopisa. Nakon korištenja navedenog alata, autor(i) su izvršili temeljitu provjeru, doradu i uredničku kontrolu sadržaja te preuzimaju punu odgovornost za tačnost, integritet i konačnu verziju objavljenog rada.

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Review

THE UNFULFILLED POTENTIAL OF ANNEX 9 OF THE DAYTON PEACE AGREEMENT: A FRAMEWORK FOR INTEGRATED DEVELOPMENT OF BOSNIA AND HERZEGOVINA

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ABSTRACT

The phenomenon of non-implementation of Annex 9 of the Dayton Peace Agreement represents one of the key, yet largely overlooked, causes of the long-term infrastructural, economic, and institutional stagnation, and even disorientation, of Bosnia and Herzegovina. Conceived as a legal and developmental framework, Annex 9 was intended to enable the establishment and coordination of public enterprises at the state level, with significant autonomy and independence from governmental institutions. The focus was placed on the sectors of transport, energy, and communications, that is, areas essential to freedom of movement, the exchange of goods, and the creation of an integrated internal market. Its implementation would have entailed the establishment of a unified governance model in line with European Union principles and practices, thereby providing a foundation for sustainable development aligned with regional and European development plans and realities. However, the systematic neglect of the principles of Annex 9 has resulted in the fragmentation of transport and energy systems, the weakening of institutional capacities, and the exclusion of Bosnia and Herzegovina from key European development policies and programmes. This research examines the structural and systemic consequences of the non-implementation of Annex 9, with particular emphasis on the role of the engineering and technical professions in reactivating the envisaged strategic framework. The aim is to contribute to a deeper understanding of the principles of Annex 9 as a platform for sustainable and integrated state development, and to stimulate academic and institutional debate on its relevance in the contemporary context of European transition, energy connectivity, and regional integration.

***Keywords**: Annex 9, Dayton Peace Agreement, Bosnia and Herzegovina, infrastructure governance, transport integration, energy systems, European transition*

Pregledni rad

RAD I RADNI ODNOSI LUČKIH TRANSPORTNIH RADNIKA U MORSKIM LUKAMA REPUBLIKE HRVATSKE

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SAŽETAK

Rad i radni odnosi u morskim lukama imaju brojne posebnosti (specifičnosti, karakterističnosti) koje se trebaju učiti, analizirati, primjenjivati i štititi u skladu s pravnim normama heteronomnih i autonomnih propisa (kolektivnim ugovorima, pravilnicima, sporazumima…). To zahtijeva, ne samo pravne metode, već primjenu metoda drugih znanstvenih disciplina (ekonomskih, prometnih, tehničkih, tehnoloških, ergonomskih, sociooloških, medicinskih i drugih). To je jedan od razloga primjene multidisciplinarnosti i interdisciplinarnosti. U ovom se radu piše o posebnostima radnih odnosa lučkih transportnih radnika (LTR) u morskim lukama države Republike Hrvatske, a osobito u odnosu na organizaciju radnih mjesta, mjesta rada, radnog okoliša, sigurnosti i zaštite na radu, sindikalno organiziranje i uvjete rada, s utjecajem na pomorce i druge radnike u gospodarskim djelatnostima, kao i one koji čine „spojene sustave“ u cjelokupnoj prometnoj i transportnoj djelatnosti (ne uzimajući u obzir druge djelatnosti koje čine karike lanca gospodarstva države, čija istraživanja treba nastaviti što je moguće kvalitetnije.

Ključne riječi: *morska luka, rad i radni odnosi lučkih transportnih radnika, uvjeti rada, tehnička, tehnološka, ekonomska i druga veza s radnicima u prometu, transportu i drugim djelatnostima.*

1. UVOD

Rad i radni odnosi predstavljaju vrlo složeno stanje koje postaje još složenije kada su u pitanju rad i radni odnosi u morskim lukama (poslodavcima) u državi Republici Hrvatskoj ili još preciznije radni odnosi lučkih transportnih radnika (u nastavku LTR) i drugih radnika, koji obavljaju određene lučke operacije na određenim radnim mjestima, u morskoj luci (mjestu rada u najširem smislu) i datom radnom okruženju, što rad i radne odnose čini još složenijima. To zahtijeva propise ne samo kvalitetnog nomotehničkog karaktera (ispunjenih svih objektivnih i subjektivnih nomotehničkih oznaka), nego još više njihovo ostvarivanje i zaštitu, kako navedena posebnost zahtijeva.

Navedeno je odredilo „zadaću“ autoru sadržaja ovoga rada, ne zanemarujući i uvažavajući da i u drugim djelatnostima postoje posebnosti u radu i radnim odnosima, koje ovim radom nisu obuhvaćene. To se odnosi, osobito, na rad i radne odnose u drugim gospodarskim djelatnostima morske tehnologije (pomorci, ribari, svjetioničari, radnici u nautičkom turizmu, rad na platformama i drugim objektima za istraživanje mora i podmorja…), te u prometu kao „mreži“ odnosa koji širi prostore brojnih subjekata i još brojnijih djelatnosti.[1]

Zadaća struke i znanosti je utvrditi kada i kako je započelo širenje „koncentričnih krugova“ dovoza i odvoza roba u (i iz) luka svijeta, morem kao prometnicom, a zatim cestom, željeznicom, rijekama, jezerima, kanalima, zrakom i na druge načine, do onoga kome je namijenjena ili kome treba (u proizvodnji, razmjeni ili potrošnji u najširem smislu).

[1] UČUR, Marinko, Pomorsko radno pravo, Pravni fakultet, Rijeka, 1997.; UČUR Marinko, Radnopravni status pomoraca, Pravni fakultet Rijeka, 2003.; UČUR Marinko, Radnopravni status lučkih radnika, ZIRS, Zagreb, 2025.; ZEKIĆ, Zdravko, Logistički menadžment, Glosa d.o.o., Rijeka, 2000.

Pravne norme i sve „što prati“ propise često „kasne“ iza života i rada u praksi čovjeka i njegovih organizacija (asocijacija, udruga). Takve bi organizacije trebale biti slobodno osnivane kako bi ostvarile postavljene ciljeve i to bi trebalo biti prirodno pravo. Polazište toga je, neosporno, u radu LTR i drugih u lancu odnosa, neraskidivoj vezi njihova rada i rada radnika drugih subjekata koji omogućavaju da se postavljeni ciljevi ostvare. Bez svjesnog i organiziranog rada, s pravima, obvezama i odgovornostima, i bez subjekata i njihovih međusobnih odnosa, toga ne bi bilo.

Proizvodni procesi se automatiziraju, informatiziraju i robotiziraju na tržištu roba i rada. Ono je sve zahtjevnije, što stvara sve veće zahtjeve za logistiku; dolazi do transformacije roba, informacija, energije, znanja i drugih čimbenika u cilju zadovoljavanja potreba brojnih subjekata i njihovog opstanka i uspjeha.[2]

2. OKVIR I OSNOV RADNIH ODNOSA LTR

Snaga LTR u morskim lukama stvarala je nove, složenije i specifičnije načine i sadržaje obavljanja lučkih operacija i davno prije suvremene mikro organizacije i tehnologije lučkog rada. Zahvaljujući njima, danas se u morskim lukama nalaze brodovi svih zastava svijeta, sa ogromnim snažnim strojevima i uređajima, a na dokovima i drugim objektima u lukama koriste se najmodernije dizalice sa tehnološkim procesom kojim upravljaju kompetentni radnici, stručnjaci, a opslužuju ih LTR.

Osnova rada i radnih odnosa LTR u morskim lukama Republike Hrvatske proizlazi iz Ustava Republike Hrvatske, univerzalnih pravnih dokumenata (povelja, protokola, konvencija), sekundarnih vrela prava Europske unije i drugih pravnih dokumenata Vijeća Europe (direktive, konvencije…) te nacionalnih heteronomnih propisa, manje kao *lex specialis*, a više kao opći propisi o zapošljavanju, radu, pomorskom dobru i morskim lukama kao poslodavcima – kojima se pokušava nadomjestiti nedostatke i regulirati one odnose koji karakteriziraju radnopravni položaj LTR i drugih zaposlenih u morskim lukama u Republici Hrvatskoj.[3]

2.1 Ustav države, univerzalna i regionalna vrela prava

Ustav Republike Hrvatske najviši je propis države. Njegovim odredbama postavljen je temelj za radno zakonodavstvo u skladu s vrelima univerzalnoga i regionalnoga prava. Posebnih zakona o radnim odnosima LTR u Republici Hrvatskoj nema, ali postoje (iako ih je malo) podzakonski propisi. Konvencije Međunarodne organizacije rada (MOR, ILO, OIT) koje je ratificirala Republika Hrvatska su svojevrsni međunarodni ugovori, po pravnoj snazi iznad zakona. Od članstva u EU Republika Hrvatska donosi propise o radnim odnosima u skladu s direktivama EU, te uređuje način njihove primjene. Na temelju tih propisa i u skladu s heteronomnim normama, nadležna tijela i subjekti kolektivnih radnih odnosa uređuju te odnose kolektivnim ugovorima, pravilnicima o radu i drugim općim autonomnim aktima (normativnog karaktera), osobito u odnosima sigurnosti i zaštite zdravlja na radu.[4]

Za rad i radne odnose LTR i drugih radnika u morskim lukama bitne su i rekomandacije (preporuke) MORa (ILO, OIT) bez obzira na njihovu pravnu narav (neobveznost), ali su od

[2] ZEKIĆ, Z., cit. str. 6 i dr.; UČUR, Marinko, Budućnost gospodarskih djelatnosti morske tehnologije u uvjetima rada multidisciplinarnih odnosa radnika, zbornik, Međunarodna konferencija „Izazovi današnjice“, COT, Šibenik, 2025.

[3] UČUR, Marinko, Mogu li autonomni opći normativni akti u morskim lukama – poslodavcima u Republici Hrvatskoj nadomjestiti zakonodavnu prazninu, Radno pravo, 7-8/24, str.50, Rosip, Zagreb, 2024.

[4] Ustav Republike Hrvatske, N.N. 59/90, 135/97, 8/98, 113/00, 129/00, 28/01, 49/01, 85/10, 05/14; Zakon o radu, N.N. 93/14, 127/17, 98/19, 151/22, 46/23, 54/23. Konvencija o naznačavanju težine na velikim koletima koja se prenose brodom, 27(1929), Konvencija MORa (ILO) o zaštiti od nezgoda na radu radnika zaposlenih na ukrcavanju i iskrcavanju brodova, 32 (1932); Konvencija o radu na dokovima 137 (1973); Konvencija MORa o sigurnosti i zdravlju na radu (Rad na dokovima) 152 (1979).

važnosti kao upute za nacionalno zakonodavstvo kojim se uređuju odnosi, a predmetom su tih preporuka.[5]

Brojne direktive EU izravno i neizravno, odredile su i određuju sadržaj prava, obveza i odgovornosti radnika u morskim lukama (kao i u drugim djelatnostima o mjestu rada, radnoj opremi, osobnoj zaštitnoj opremi, rizicima i prevenciji u rukovanju teškim teretima, korištenju opreme, radnika koji su izloženi kancerogenima i mutagenima, biološkim agensima na radu, radnim uvjetima u građevinskom sektoru, ozljedama na radu i profesionalnim bolestima, o zaštiti posebno osjetljivih skupina radnika, o vađenju minerala, rad na ribarskim brodovima, rizicima povezanim s kemijskim sredstvima, izloženost eksplozivnoj atmosferi, fizikalne štetnosti (vibracije), buka, izloženost umjetnom optičkom zračenju, brodski otpad i druge.[6]

2.2 Neka nacionalna vrela prava LTR

Propisi o radu i radnim odnosima LTR i drugih radnika u morskim lukama u Republici Hrvatskoj, kao izravna i/ili neizravna vrela prava, obveza i odgovornosti subjekata navedenih odnosa, pored drugih klasifikacija mogu se označiti i kao heteronomni i autonomni propisi.

2.2.1 Heteronomni propisi – vrela prava LTR

„Izbor“ propisa u ovom radu „pada“ na autora, pa drugima, koji budu koristili ovaj izbor, ostaje da nađu i druge, prema okolnostima i prostornom i vremenskom važenju. Misli se, prvenstveno na zakone i podzakonske (provedbene) propise. To su:

a) Pomorski zakonik, N.N. 181/04 do 17/19
b) Zakon o pomorskom dobru i morskim lukama, N.N. 83/23
c) Zakon o sigurnosnoj zaštiti trgovačkih brodova i luka otvorenih za međunarodni promet
d) Zakon o sigurnosnoj zaštiti pomorskih brodova i luka, N.N. 108/17, 30/21
e) Zakon o lučkim kapetanijama, N.N. 118/18, 155/23

Ovaj, uvjetno rečeno, registar, odnosi se na heteronomne propise koji spadaju u propise pomorskog prava (u okviru pomorskog prava).

Pored navedenih, treba preciznije navesti i one koje i teorija i praksa svrstava u radno zakonodavstvo, tj. koji uz navedene, i uz njih, druge podzakonske propise čine „mrežni plan“ u radu i radnim odnosima LTR. Uz pomoć tih propisa tumačimo pojmove, kategorije, pravne institute i radnopravne odnose vezane za LTR u morskim lukama u Republici Hrvatskoj.

Značajniji podzakonski propisi su: pravilnici o uvjetima i načinu rada u lukama, o izloženosti vibracijama na radu, o izloženosti opasnim kemikalijama i biološkim agensima na radu, o izloženosti buci, sadržaju i načinu vođenja evidencija o radnicima, zaštiti na radu i na mjestu rada, zdravstvenoj sposobnosti, stručnom osposobljavanju, rukovanju opasnim tvarima i dr.[7]

Zakoni i podzakonski akti koji čine dio radnopravnog zakonodavstva i izravno se primjenjuju i na LTR kao subjekte individualnog radnog odnosa navedeni su u sadržaju ovoga rada kada je riječ o pojedinim kategorijama, institutima i odnosima.

To se odnosi na opće autonomne normativne akte u pojedinim morskim lukama – u svojstvu poslodavca s jedne strane i radnika kod tog poslodavca kada se, na njihovoj strani („strani

[5] MOR-a je specijalizirana organizacija Organizacije ujedinjenih naroda u oblasti rada. Ustavom MORa određena je nadležnost Skupštine, Vijeća i generalnog tajnika Međunarodnog ureda rada. Rezultat njihovog rada su i Konvencije i preporuke MOR; navedene su u UČUR, M. Radnopravni status lučkih radnika, cit. str. 31-34, 176-190.

[6] Isto – str. 35 i 290-213. Za poteebe ove knjige pripremio ih je Cvetan Kovač, bacc.ing.sec. s priloženim QR kodovima.

[7] Isto . cit. UČUR (Kovač C.), str. 214. i 215.

rada“) javlja sindikat, radničko vijeće ili drugi kolektivni subjekt radnika (kolektivni ugovor, pravilnik o radu, procjena rizika, sporazum radničkog vijeća s poslodavcem i drugi).[8]

3. POSEBNOSTI (KARAKTERISTIČNOSTI, SPECIFIČNOSTI) RADA I RADNIH ODNOSA LTR I DRUGIH RADNIKA U MORSKIM LUKAMA U REPUBLICI HRVATSKOJ

Odabrana metoda i autorovo dugogodišnje proučavanje rada i radnih odnosa, omogućuje da se posebnosti rada i radnih odnosa LTR i drugih radnika u morskim lukama u Republici Hrvatskoj istaknu, odnosno navedu, uz nastojanje da se to i objasni , uvažavajući učenja onih koji radne odnose vide kao potpuno precizan („čist“) pravni odnos između radnika i poslodavca. Autor, u svim radovima do sada to vidi „šire“, kao „predmet reguliranja i proučavanja…“ radnog prava kao posebne pravne discipline, koja, pri objašnjavanju pojmova, kategorija, radnopravnih instituta i radnih odnosa, treba uvažavati, ali i koristiti ono što im je najbliže iz područja ekonomike rada, sociologije rada, organizacije rada, psihologije rada, industrijske sociologije, medicine i drugih, ne samo pravnih disciplina.[9]

Prof. Tintić kaže i piše da „zakonodavstvo nije u potpunosti u stanju…u istom zakonu….uređivati posebne radne odnose.“

U objašnjenju tih posebnosti uzeti su različiti kriteriji: obrazovanje, ulazak u radni odnos, radno vrijeme, profesionalnost, subjekti, uvjeti rada, determinante prava, obveza i odgovornosti subjekata radnog odnosa, plaće i naknade, sigurnost i zaštita zdravlja na radu i drugo.

3.1 Pojmovi, subjekti i odnosi

Određivanje (definiranje) pojmova, kategorija, radnopravnih instituta i radnih odnosa, bez obzira na „pozitivno pravni“ pristup, mora uvažavati načela i teoriju (verificiranu) ove discipline, uz poštivanje globalizacije, fleksibilizacije i novih oblika rada. To bi zahtijevalo i puno više govoriti o radnicima i lučkom radu od „utovara do istovara“, do „specijaliziranog i polivalentnog lučkog radnika“. U zakonodavstvu nekih država, lučki radnici „čine (pored drugih) pomorsko osoblje.“[10]

Djelatnost luke su lučke operacije ukrcaja, iskrcaja, prenošenja, skladištenja i općenito „premještanje tereta“ i „druge njima supsidijarne i komplementarne operacije.“ Lučki radnici su kvalificirani i specijalizirani slagači, vinčmani. Iskrcivači, mjeritelji, brojači, dizaličari, mehaničari, vozači traktora i drugi. Lučki slagači mogu biti i lučki radnici.[11]

Poslovi LTR označeni su i obavljaju se u morskoj luci sa tehnologijom kao „skupom znanja, sredstava i procesa…koji omogućuje more kao prometnica, na brodu, na dokovima, u i uz morske objekte i obalna postrojenja.

LTR je fizička osoba koja u radnom odnosu obavlja određene poslove za morsku luku – poslodavca, kako je i kada registrirana i u pravnom prometu.

U ovom radu poslodavac je morska luka kao pravna osoba, za koju radnik obavlja poslove (lučke operacije) na određenom radnom mjestu, mjestu rada i radnom okruženju na temelju ugovora o radu, po pravilima struke i uputama poslodavca, pod njegovim nadzorom, shodno naravi i vrsti rada. Morska luka, u svojstvu poslodavca, dužna je organizirati i dati radniku rad i nakon obavljenog, taj rad platiti kako je unaprijed utvrđeno.

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[8] Detaljnije u UČUR, Marinko, Nomotehnika u radnom pravu i pravu zaštite na radu, Veleučilište u Rijeci, Rijeka, 2007.

[9] TINTIĆ, Nikola, Radno i socijalno pravo (knjiga I, Radni odnosi), Narodne novine, Zagreb, 1969., str.49; 397-477.

[10] LALETA, Sandra, Specifičnosti radnih odnosa lučkih radnika u Italiji, Zbornik Pravnog fakultete, Rijeka, 1991., str.169.-186.

[11] RUKAVINA, Biserka, Ugovor o slagačkom poslu…Pravni fakultet, Split, 2010. „Slagački poslovi (slaganje tereta, ukrcaj i iskrcaj tereta čini jednu sadržajno povezanu cjelinu“.

Karakteristični poslovi, kako je već navedeno, su iskrcaj tereta s broda i drugih plovila na obalu, u vozila, prijevoz do skladišta, rad s kontejnerima, sortiranje, brojanje, mjerenje, vaganje, signiranje, uzorkovanje, prepakiranje i slično (djelatnosti terminala, skladišta, carinskih skladišta, robno transportnih i drugih centara), a operacije ukrcaja i iskrcaja predstavljaju početnu i završnu fazu pomorskog prijevoza.[12]

U morskoj luci „susreću se različite vrste aktivnosti koje obavljaju različiti subjekti“, kaže B. Kesić Kalina. Autonomnim općim normativnim aktom (u pravilu pravilnikom) utvrđuje se organizacija rada s popisom poslova na pojedinom radnom mjestu (naziv, narav i/ili vrsta rada). Radno mjesto je osnovna organizacijska jedinica, kao skup određenih poslova funkcionalno povezanih kao dio djelatnosti poslodavca – morske luke.

Poslovi se planiraju, organiziraju, koordiniraju i nadziru na terminalima i servisima, prema radnim normama i normativima rada. Svako radno mjesto ima i naziv, šifru, poslove i zadatke, organizacijsku hijerarhiju, uvjete koje radnik mora ispunjavati za rad i druge oznake karakteristične za to radno mjesto. Mjesta rada su lučki terminali na kojima se realizira lučka pretovarna djelatnost, a u servisima se obavlja servisiranje priveza, odvoza i drugo. Unutar terminala su poslovne jedinice, a unutar servisa su grupacije, radionice i druge grupe poslova. Pored LTR u tim jedinicama rade voditelji, specijalisti (sigurnosti, zaštite zdravlja, radnog okoliša, protupožarne zaštite), a na terminalima rukovoditelji terminala, operativni radnici, stručni suradnici, skladištari, nadzornici prekrcaja, vagari, markiranti, mehaničari, radnici na održavanju, na silosnim postrojenjima, dizaličari i drugi. [13]

3.2 Prava LTR i drugih radnika u morskoj luci – poslodavcu uređena autonomnim normativnim aktima

Ustavom i propisima (univerzalnim, regionalnim i nacionalnim) uređena su temeljna prava radnika, koja se još preciznije propisuju kolektivnim ugovorom, pravilnikom o radu i drugim autonomnim općim normativnim aktima, snagom prihvaćenih standarda, prava na kolektivno pregovaranje i sklapanje kolektivnih ugovora, dostojanstvo svakog radnika i prava na udruživanje i mirno rješavanje sporova, prava radnika u suodlučivanju s poslodavcem (radničko vijeće, u tijelima poslodavca, sporazum radničkog vijeća s poslodavcem, skupovi radnika, industrijske akcije), zaštita privatnosti radnika, a kako zakon određuje i pozivom na obaveznost, uz propisane uvjete, donošenja navedenih akata, stvaraju se primjereni odnosi poslodavaca i radnika.

3.2.1 Kolektivni ugovor

U dostupnim i analiziranim kolektivnim ugovorima sklopljenim u morskim lukama, a koji su na snazi, poštivane su objektivne nomotehničke oznake (pravna osnova, sadržaj, postupak, prostorno i vremensko važenje), a i odgovarajući „fond“ subjektivnih pretpostavki (znanje, gradivo, autonomnost) o : sklapanju ugovora o radu (u pravilu na neodređeno vrijeme), postupak raspoređivanja radnika u radnom odnosu, oglašavanje potreba za novim zadaćama, a za sadržaj ugovora o radu, upućuje se na pravilnik o sistematizaciji, pravilnik o plaći, pravilnik o zaštiti na radu…

Posebno pitanje je obrazovanje za rad u morskoj luci. Programi u strukovnim školama su heterogeni (najčešće nisu „ciljani“ za kompetencije u obavljanju lučkih operacija), a

[12] ZELENIKA, Ratko, Logistički sustavi, Ekonomski fakultet, Rijeka, 2005., str. 104.-110. i dr.; RUKAVINA, B., Ugovor o slagačkom poslu, cit. str. 53 i dr.; Zakon o radu, cit., čl. 4. i dr; Lučka infrastruktura – skup stabilnih objekata i uređaja koji služe za organiziranje i obavljanje lučke djelatnosti. Lučka suprastruktura – lučka skladišta, zgrade raznih namjena i fiksna pretovarna mehanizacija, tj. objekti koji omogućuju da luka služi kao amortizer u transportnom lancu, vidi KESIĆ, KALINA, B. Teorijski i praktični logistički pristup organizaciji luka Jugoslavije, Univerza u Mariboru, 1987. „U luci se razmjenjuje pomorstvo, željeznički, cestovni promet, avionski i cjevovodni promet te teret u uvozu, izvozu, tranzitu ili razvoju…“

[13] KIRINČIĆ, J., Luke i terminali, Školska knjiga, Zagreb, 1991., DUNDOVIĆ, Č., Optimalizacija primjene obalnih i morskih lučkih dizalica, Fakultet za pomorstvo, Rijeka, 1991., UČUR, M., MOSLAVAC, B., Rječnik radnog prava, Libertin, Rijeka, 2020.

autonomno se uređuju pitanje i odnosi obrazovanja u slučaju uvođenja novih tehnologija i/ili poslova.

Proces rada i radno vrijeme u morskim lukama organizirano je u smjenama; radni tjedan može trajati do 55 sati tjedno i sa preciznom preraspodjelom i mogućim odstupanjima. Tjedni odmor može se koristiti u skladu s detaljnim rasporedom rada, s time da „radnici imaju obavezu raditi tri vikenda u mjesecu“, uvažavajući ravnotežu između privatnog o poslovnog života. „Napuštanje“ radnog mjesta može se izvršiti „tek kada se osigura zamjena, i bez prekidanja operativnog procesa…“. Preciziraju se pitanja noćnog rada, rada u turnusima (poslodavac dogovara sa sindikatom), u preraspodjeli, prekovremenog rada, specifičnosti odmora i dopusta (stanka, dnevni odmor, tjedni odmor, plaćeni i neplaćeni dopust, godišnji odmor).

Kolektivni ugovor je po hijerarhiji najviši su autonomni normativni propis i samo u osnovnim određenjima regulira pitanja plaća i naknada i to „delegira“ da se uredi pravilnikom o plaćama (osnovica, dodaci, naknade=. To se odnosi i na pitanje zaštite radnika s umanjenom radnom sposobnošću, zaštite na radu i otkaza ugovora o radu.

„Ugovorni“ dio kolektivnog ugovora uređuje pitanja sindikata, mirnog rješavanja sporova i druga pitanja u skladu sa Zakonom o radu.[14]

3.2.2 Pravilnik o radu

Luka je veliki sustav brojnih subjekata i odnosa, pa je logično da u skladu s odredbama članka 26. (i drugih) Zakona o radu, uređuje organizaciju, rad i radne odnose pravilnicima o radu prilagođenima (svojoj) organizaciji rada, te da, koristeći načelo *in favorem laboratores* (povoljnije pravo u korist radnika) brojna prava tako i uredi. U tome posebnu ulogu imaju sindikati koji su organizirani i djeluju u luci, kao i radnička vijeća. U praksi je najčešće donesen i u primjeni pravilnik o organizaciji rada i sistematizaciji radnih mjesta, pravilnik o radu (radnim odnosima), pravilnik o obrazovanju i stručnom usavršavanju, pravilnik o plaćama, pravilnik o zaštiti na radu i drugi (zaštita privatnosti i dostojanstva radnika, zaštita od požara, o lučkom redu…).

Karakteristična pitanja u pravilnicima o radu u morskim lukama su o : smjenskom radu, noćnom radu (računanje i plaćanje, trajanje i ograničenje), rad u turnusu, prekovremeni rad (trajanje u tjednu i godini, zabrane, plaćanje i drugo), odmori i dopusti, plaća i naknada (redovito uvećanje, opasni teret, smjenski rad, rad po kiši i visokoj temperaturi), pravo na jubilarne nagrade, odgovornosti (stegovna, za štetu…).

Pravilnik o radu mora biti originalan, precizan, primjenjiv i ažuran autonomni propis, dostupan, ali bez protuzakonitih odredbi, jer su u tom slučaju te odredbe ništetne. Iskustvo subjekata u morskoj luci (kako predstavnika rada, tako i predstavnika kapitala) omogućavaju da se pravilnikom o radu uredi rad i radni odnosi u cilju vladavine prava i pravne sigurnosti.[15]

3.2.3 Sigurnost i zaštita zdravlja radnika na radu

U brojnim aktivnostima subjekata u realiziranju djelatnosti u morskim lukama, obavezna je, nezaobilazna, složena, zahtjevna i skupa organizacija, realizacija i nadzor, sigurnost i zaštita na radu LTR (i drugih osoba) koji rade, odnosno obavljaju bilo koju lučku operaciju, u bilo koje vrijeme. Naglašeno je preventivno djelovanje i odgovornost poslodavca – morske luke. Tu ne smije biti prakticizma, površnosti i improvizacije, jer je u pitanju djelovanje koje u punom smislu, zahtijeva maksimalno znanje, odnosno prema radu (prema sebi, drugim radnicima, sredstvima) i svim drugim čimbenicima koji mogu ugroziti sigurnost i zdravlje radnika, drugih osoba i radnog okoliša.

[14] UČUR, M., Radnopravni status lučkih radnika, cit. str. 77-100., Zakon o radu, cit. članak 192.-204.
[15] UČUR, M., cit., str.100.-123., Zakon o radu, cit. članak 26. i 27., 69.-72. i drugi; UČUR, M., Nomotehnika u radnom pravu i pravu zaštite na radu, cit.

Prema dostupnim autonomnim općim (i drugim) aktima u morskim lukama (u svojstvu poslodavca), regulirana su ova pitanja i odnosi: poslovi i zadaci svakog radnog mjesta LTR (radne operacije u procesu rada, alati, strojevi, uređaji, prostori i prostorije, način obavljanja rada, buka, vibracije, prašina, zrak, higijenski uvjeti (mirisi, dim, vlaga…); osobna zaštitna oprema (radna odijela, radna obuća i dr.); radno vrijeme kao uvjet rada (i drugi uvjeti rada); radna, zdravstvena i druga sposobnost radnika; rizici od ozljeda, profesionalnih bolesti i drugih bolesti u vezi s radom; pregledi i ispitivanja sredstava rada; ispitivanje radnog okoliša; napori i štetnosti; informiranje, obavješćivanje, osposobljavanje i drugo; posebna ovlaštenja poslodavca, povjerenici radnika i stručnjaci u zaštiti.

U svim analiziranim općim autonomnim aktima u morskim lukama – poslodavcima posebno su uređena prava, obveze i odgovornosti radnika i poslodavca, kao osnovnih subjekata sigurnosti i zaštite zdravlja na radu, naglašavajući brojne opasnosti i štetnosti. To se posebno odnosi na akt procjena rizika.[16]

Autonomni opći normativni akti o sigurnosti i zaštiti zdravlja radnika na radu jesu: pravilnik o zaštiti na radu, pravilnik o osobnoj zaštitnoj opremi, pravilnik o radu s teretom, s transporterima, s viličarima, s dizalicama, s kontejnerima, s vozilima i utovarivačima, pravilnik o zaštiti od požara, evakuaciji i spašavanju, pravilnik o pružanju prve pomoći, pravilnik o osposobljavanju za siguran rad i drugi, [17] što govori o kompleksnosti metoda i postupaka u ovoj oblasti odnosa u morskim lukama. Odnos prema sigurnosti i zaštiti zdravlja na radu zahtijeva sve profesionalniji odnos i mora biti preventivan proces, ali i dio „proizvodnje“, odnosno realiziranja zakonito registrirane djelatnosti u morskim lukama, uvažavajući znanstvena, stručna i zakonodavna rješenja, ali i ogromno iskustvo lučkog rada koje je omogućilo opstanak luka.

4. ZAKLJUČAK

Rad i radni odnosi LTR (i drugih radnika) u morskim lukama u svojstvu poslodavca u Republici Hrvatskoj su složeni, zahtjevni, puni rizika i specifičnih uvjeta rada, zbog brojnih posebnosti (karakterističnosti) u općim oznakama radnog odnosa kao pravnog odnosa među individualnim subjektima (morska luka – poslodavac i radnik – LTR ili drugi radnici u morskoj luci), odnosno kolektivnim subjektima (udruga poslodavaca odnosno udruga radnika).

Radni odnosi LTR u morskim lukama determinirani su brojnim objektivnim čimbenicima (djelatnost, kretanja u svjetskim, regionalnim i nacionalnim (i svim odnosima)), razmjerima i razinama. To je vidljivo i iz propisa (univerzalnog, regionalnog, nacionalnog karaktera) različitog naziva, adresanata, postupaka donošenja, prostornog i vremenskog važenja (heteronomni propisi), što upotpunjuju opći autonomni normativni akti (kolektivni ugovori, pravilnici o radu i drugi).

Jedna od oznaka posebnosti (specifičnosti) radnih odnosa u morskim lukama su proizašli iz djelatnosti morskih luka (lučkih operacija) i uvjeta rada (fizičke, organizacijske, socijalne i pravne naravi) i da su u realiziranju (ostvarivanju, nadzoru i zaštiti) u najneposrednijoj vezi s radnicima (radom i radnim odnosima) u svim vrstama transporta i prometa (prijevoza i transporta, ali i operacija u vezi s prijevozom roba, ljudi i komunikacije).

Sve te djelatnosti povezuje rad radnika. Radnici omogućavaju logistiku i promet u „lancu“ svih navedenih djelatnosti, koje su međusobno povezane (rad pomoraca na brodovima koji plove od luke do luke, rad lučkih radnika, rad radnika u cestovnom, željezničkom i drugom prijevozu) brojnim obilježjima (ekonomskim, prometnim, organizacijskim, tehničkim,

[16] Zakon o zaštiti na radu, N.N. 71/14 do 96/18

[17] UČUR, M., Radnopravni status lučkih radnika, cit.; Konvencija MORa (ILO,OIT) o zaštiti u knjizi UČUR, M., LALETA, S., Konvencije MORa s komentarima, Pravni fakultet, Rijeka, TIM press, Zagreb, 2007.; Direktive EU u knjizi UČUR. M., Vrela međunarodnog prava sigurnosti i zaštite zdravlja na radu, Libertin naklada, Rijeka; Pravilnik o ispitivanju radnog okoliša, N.N. 16/16, 120/22; Pravilnik o poslovima s posebnim uvjetima rada, N.N. 5/84.; U odredbama članka 101-106. Zakona o zaštiti na radu, N.N. 71/14, 118/14, 94/18, 96/18 propisi koji ostaju na snazi do donošenja novih propisa, trebaju biti uvršteni u vrela koja su korištena za pisanje ovoga rada, UČUR, M., KOVAČ, C., ŠIŠAKOVIĆ, D., KRIŠTO, J., Osnove prava i zakonodavstvo sigurnosti, ZIRS, Zagreb, 2023.

tehnološkim, društvenim, kulturnim…). Promjene su nužne, prisutne i vidljive u proizvodnji (u najširem smislu), na zahtjevnom tržištu, prostornoj i vremenskoj svekolikoj transformaciji i potrebama brojnih subjekata. Sve je prisutnija internacionalizacija poslovanja u unaprjeđivanju tehnologije neshvaćenih razmjera. To ne smije zanemariti činjenicu da to pripada čovjeku (za njega, uz njega, njegov život, rad i opstanak). Slijedom toga, bez obzira na fleksibilizaciju oblika i načina rada, radni odnos, kao poseban pravni odnos ima svoj statički proračun, koji mora opstati i biti otporan na navalu raznih vrsta rizika.

Sadržaj prava, obveza i odgovornosti u radnom odnosu LTR i drugih radnika u morskim lukama zahtijeva više multidisciplinarnog izučavanja tih odnosa, novim stručnim i znanstvenim metodama, ne samo zbog naglašavanja ljudskih potencijala (kadrova), već i zbog novih spoznaja, neraskidivih veza (svojevrsnih koncentričnih odnosa) radnika u pomorstvu, morskim lukama, onih koji realiziraju logističke veze i drugih, u bilo kojoj grani prometa. Zahtjevi su veliki i sve „noviji“. To je empirijska stvarnost „spojenih posuda“ ovih odnosa.

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Review

LABOUR AND LABOUR RELATIONS OF PORT TRANSPORT WORKERS IN SEAPORTS OF THE REPUBLIC OF CROATIA

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ABSTRACT

Work and labour relations in seaports have numerous specific features (particularities, characteristics) that need to be studied, analysed, applied, and protected in accordance with the legal norms of heteronomous and autonomous regulations (collective agreements, rulebooks, agreements, etc.). This requires not only legal methods, but also the application of methods from other scientific disciplines (economic, transport, technical, technological, ergonomic, sociological, medical, and others). This is one of the reasons for applying multidisciplinarity and interdisciplinarity. This paper discusses the specific features of labour relations of port transport workers (PTW) in the seaports of the Republic of Croatia, particularly in relation to the organisation of workplaces, places of work, the working environment, occupational safety and health protection, trade union organisation, and working conditions, with an impact on seafarers and other workers in economic activities, as well as those who form "interconnected systems" within the overall transport and traffic sector (without taking into account other activities that constitute links in the national economic chain, whose research should be continued as thoroughly as possible).

Keywords: *seaport, work and labour relations of port transport workers, working conditions, technical, technological, economic and other links with workers in traffic, transport, and other activities.*

Prethodno priopćenje

EKONOMSKA ANALIZA SUSTAVA JAVNOG PRIJEVOZA U GRADU VUKOVARU

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SAŽETAK

Ovaj rad analizira održivost i ekonomsku opravdanost sustava javnog prijevoza u gradu Vukovaru, s posebnim naglaskom na učinke povećanja cijena karata i zadovoljstvo korisnika uslugom. Cilj istraživanja jest utvrditi stanje sustava javnog prijevoza, identificirati ključne izazove te ispitati percepciju i stupanj zadovoljstva korisnika. U teorijskom dijelu rada razmatraju se koncepti održive mobilnosti, ekonomski modeli javnog prijevoza, zakonski okvir te uloga lokalne samouprave u organizaciji i financiranju usluge. Empirijski dio temelji se na anketnom istraživanju provedenom među korisnicima javnog prijevoza, kojim se prikupljaju podaci o učestalosti korištenja, zadovoljstvu uslugom, percepciji cijena i spremnosti korisnika na promjene u učestalosti korištenja javnog prijevoza u odnosu na cijenu i kvalitetu usluge. Uz primarne podatke analiziraju se i proračunska izdvajanja Grada Vukovara za javni prijevoz. Analiza omogućuje uvid u odnos između cijene, kvalitete usluge i korištenja javnog prijevoza te ukazuje na izazove u osiguravanju njegove financijske i socijalne održivosti. Zaključuje se da rezultati istraživanja mogu poslužiti kao podloga za unaprjeđenje planiranja i financiranja javnog prijevoza na lokalnoj razini.

***Ključne riječi**: javni prijevoz, održivost, subvencioniranje, zadovoljstvo korisnika, Grad Vukovar*

1. UVOD

Razvijen i pouzdan sustav javnog prijevoza temelj je modernog društva i preduvjet kvalitete života stanovnika. Posebno u manjim i srednje velikim gradovima javni prijevoz suočava se s izazovom zbog niže gustoće naseljenosti, manjeg broja korisnika i ograničenih lokalnih proračuna. To rezultira višim troškovima prijevoza po putniku i povećanom potrebom za subvencioniranjem. Stoga organizacija i financiranje javnog prijevoza postaju složen proces koji zahtijeva pažljivo planiranje i upravljanje.

Vukovar je primjer grada koji se suočava s otežanim postizanjem ekonomski održivog modela javnog prijevoza. Proračunska izdvajanja za ovu uslugu rastu, a sve je izraženija potreba za modernizacijom sustava, učinkovitošću i jačom kontrolom kvalitete usluge. Dodatno, značajno povećanje cijena karata, koje je stupilo na snagu u listopadu 2025. godine, izazvalo je veliko nezadovoljstvo građana, osobito umirovljenika i kućanstava s nižim primanjima. Ovaj problem otvorio je pitanje ekonomske opravdanosti postojećeg modela prijevoza, kao i usklađenosti cijene i kvalitete usluge.

Predmet ovoga rada je ekonomska analiza modela javnog prijevoza u gradu Vukovaru, s naglaskom na percepciju i zadovoljstvo korisnika uslugom te procjeni ekonomske opravdanosti i održivosti postojećeg modela prijevoza. U skladu s navedenim, postavljaju se sljedeće hipoteze:

H1: Zadovoljstvo građana javnim prijevozom u Vukovaru smanjilo se nakon povećanja cijena karata.

H2: Održivost javnog prijevoza u gradu Vukovaru nije moguće postići bez značajne subvencije lokalne samouprave.

H3**:** Korištenje javnog prijevoza u Vukovaru osjetljivo je na promjene cijene i kvalitete usluge.

Postavljene hipoteze u radu analizirane su kroz empirijsko istraživanje, a njihova se potvrda razmatra u zaključnom poglavlju. Rad je strukturiran u više poglavlja: nakon uvoda slijedi teorijski okvir i opis konteksta javnog prijevoza u gradu Vukovaru, potom metodologija istraživanja, rezultati i rasprava te zaključak.

2. EKONOMSKE ZNAČAJKE I ODRŽIVOST JAVNOG PRIJEVOZA

2.1 Teorijski okvir i europske smjernice

Koncept održive mobilnosti polazi od postavki da javni prijevoz ima važnu ulogu ne samo kao tržišna usluga, nego i infrastrukturna i socijalna funkcija grada. Stoga javni sektor ima ključnu ulogu u planiranju, koordinaciji i financiranju sustava. Ekonomska teorija javnog prijevoza polazi od činjenice da se radi o javnoj usluzi koja, zbog visokih fiksnih troškova i društvene funkcije, ne može dugoročno funkcionirati isključivo na tržišnim osnovama, zbog čega subvencioniranje predstavlja standardni instrument javne politike, a ne iznimku (Hörcher, Tirachini, 2021).

Kako ističu Mrvica Mađarac, Majstorović i Gubić Kučan (2022), javna uprava kroz strateške dokumente i razvojne politike stvara preduvjete za razvoj mobilnosti, što je posebno važno u gradovima srednje veličine gdje treba uravnotežiti potrebe korisnika i fiskalne mogućnosti lokalne samouprave. U europskim gradovima javni prijevoz razvija se s ciljem smanjenja automobilskog prometa, povećanja dostupnosti prijevozne usluge te izgradnje ekološki prihvatljivog i održivog prometnog sustava (Docherty et al., 2008; prema Šišak i Gašparović, 2025). U literaturi je uobičajeno da se javni prijevoz najčešće povezuje s većim urbanim sredinama i gušćom mrežom linija, no javni prijevoz postoji i u manjim i srednje velikim gradovima, gdje se organizacija prilagođava lokalnim uvjetima, nižoj gustoći potražnje i većoj ovisnosti o subvencijama (White, 2017; prema Šišak i Gašparović, 2025). U takvim sredinama on ima snažnu socijalnu funkciju jer osigurava mobilnost učenika, studenata, starijih osoba i drugih skupina koje ovise o organiziranom prijevozu (Alhassan i Anciaes, 2025).

Empirijska istraživanja pokazuju da je potražnja za javnim prijevozom osjetljiva na promjene cijena, pri čemu povećanje cijena rezultira smanjenjem broja putovanja, osobito među redovitim korisnicima i ranjivim skupinama stanovništva (Kholodov et al., 2021). Da je potražnja za javnim prijevozom osjetljiva na promjene cijena te da povećanje cijena dugoročno dovodi do smanjenja korištenja javnog prijevoza potvrđuje i Wardman (2022). Upravo zbog izražene cjenovne osjetljivosti, uloga subvencija postaje ključna u ublažavanju negativnih učinaka poskupljenja. Prema Guzman i Cantillo-Garcia (2024) subvencioniranje javnog prijevoza ima pozitivan učinak na korištenje usluge i zadovoljstvo korisnika, osobito među ranjivim skupinama stanovništva. Subvencije ne djeluju samo kroz smanjenje cijene, već i kroz jačanje percepcije socijalne pravednosti i povjerenja u sustav javnog prijevoza.

OECD (2020) upozorava da održiv sustav javnog prijevoza zahtijeva planiranje temeljeno na stvarnim potrebama korisnika, budući da neuravnotežena cijena ili nedovoljna pokrivenost linijama mogu povećati socijalnu isključenost. Ističe se i važnost modernizacije voznog parka te ulaganja u energetski učinkovita vozila kao način smanjenja operativnih troškova i povećanja pouzdanosti sustava.

Novija istraživanja dodatno naglašavaju da ulaganja u javni prijevoz imaju šire društvene i ekonomske učinke te da poboljšanje kvalitete, dostupnost i pouzdanost usluge pozitivno utječu na korištenje javnog prijevoza i socijalnu uključenost korisnika (Alhassan i Anciaes, 2025). Prema Dubé et al. (2024) javni prijevoz, osobito u gradovima srednje veličine, ne može se dugoročno vrednovati isključivo prema tržišnim kriterijima, već prema njegovim društvenim, ekonomskim i prostornim učincima. Analitički pristupi naglašavaju potrebu uravnoteženja operativnih troškova, kvalitete usluge i društvenih ciljeva, pri čemu odluke o cijenama i subvencijama imaju izravan utjecaj na učinkovitost i prihvatljivost sustava. Potrebno je da se odluke o cijenama, subvencijama i mreži linija donose na temelju analize, a ne samo na osnovu fiskalnih ograničenja.

Slične smjernice donosi Europska komisija (2021), prema kojoj učinkovito planiranje mora biti usklađeno s prostornim rasporedom obrazovnih, zdravstvenih i gospodarskih funkcija grada. Komisija naglašava da javni prijevoz mora ostati cjenovno pristupačan kako bi se izbjeglo produbljivanje socijalnih nejednakosti, pri čemu su ranjive skupine posebno osjetljive na promjene cijena. Kvaliteta usluge, uključujući učestalost polazaka, pouzdanost, pristupačnost i udobnost, izravno utječe na spremnost građana da koriste javni prijevoz i ključna je za povećanje potražnje. Preporuke UITP-a (2022) dodatno naglašavaju potrebu optimizacije mreže linija i kapaciteta kroz upravljanje potražnjom, osobito u sredinama s manjim brojem korisnika. Prema UITP-u, potražnja je izrazito osjetljiva na kvalitetu usluge, a smanjena učestalost ili pouzdanost dovode do pada broja putnika čak i kada su cijene stabilne. Ističe se i snažna socijalna dimenzija javnog prijevoza, zbog koje sustav mora osigurati minimalnu dostupnost usluge bez obzira na tržišne uvjete.

Javni linijski prijevoz putnika u Republici Hrvatskoj uređen je Zakonom o prijevozu u cestovnom prometu (NN 41/18, 98/19, 30/21, 89/21, 114/22 i 136/24), koji definira uvjete obavljanja prijevoza, nadležnosti javnih tijela te obveze prijevoznika i jedinica lokalne samouprave. Prema Zakonu, javni linijski prijevoz obavlja se na unaprijed utvrđenim linijama, prema voznom redu, cjeniku i Općim uvjetima prijevoza. Smatra se oblikom javnog dobra koje mora biti dostupno svim građanima pod jednakim uvjetima. Uloga jedinica lokalne samouprave (grad ili općina) uključuje osiguranje dostupnosti javnog prijevoza, ugovaranje javne usluge, financiranje i subvencioniranje prijevoza, planiranje mreže linija te nadzor nad kvalitetom usluge. Uredba (EZ) br. 1370/2007 Europskog parlamenta i Vijeća definira način na koji javna tijela mogu organizirati i financirati usluge javnog putničkog prijevoza putem ugovora o javnim uslugama. Njome se propisuje da jedinice lokalne samouprave mogu subvencionirati prijevoznike ako ugovorom jasno definiraju opseg, kvalitetu i trajanje javne usluge te osiguraju transparentnost dodijeljenih sredstava (EU, 2007). Vidljivo je da održivost javnog prijevoza ovisi o usklađenosti zakonskog okvira, ekonomskoj opravdanosti usluge i potrebama lokalnog stanovništva.

Unatoč nastojanjima da se kroz modele optimalnog subvencioniranja postigne učinkovit i pravedan sustav javnog prijevoza, stvarne financijske politike često odstupaju od tih preporuka. Prema Cantneru et al. (2022), kako navode Strommer et al. (2023) nedovoljno financiranje tipična je pojava u društvima ovisnima o automobilima, uključujući Sjedinjene Američke Države, dok nedavni trendovi pokazuju da se neopravdane političke odluke mogu dogoditi i u suprotnoj krajnosti: nakon pandemije Covid-19, nekoliko europskih zemalja uvelo je praktički besplatan pristup javnom prijevozu. Analize učinaka takvih mjera pokazuju da potpuno ili djelomično besplatan (snažno subvencioniran) javni prijevoz ima pozitivan učinak

na korištenje usluge, ali ne dovodi nužno do smanjenja automobilskog prometa i dugoročne fiskalne održivosti (Lu et al., 2024).

U nastavku se teorijski okviri primjenjuju na primjeru grada Vukovara koji, zbog svojih demografskih obilježja, mreže naselja i fiskalnih ograničenja pruža dobar uvid u izazove i mogućnosti organizacije javnog prijevoza u srednje velikim gradovima. Prikazat će se konkretni izazovi financiranja, priuštivosti i modernizacije sustava javnog prijevoza.

2.2. Javni prijevoz u gradu Vukovaru

Javni prijevoz u gradu Vukovaru oslanja se na lokalne autobusne linije koje povezuju središte grada s prigradskim naseljima, obrazovnim ustanovama, zdravstvenim i sportskim objektima te gospodarskim zonama. Sustav je organiziran tako da zadovolji osnovne potrebe mobilnosti građana no njegova fleksibilnost ograničena je fiskalnim mogućnostima Grada i operativnim uvjetima pružatelja usluge. Broj linija i njihova učestalost prilagođeni su dnevnim opterećenjima, prvenstveno školskom i radnom prometu. Izvan ovih blokova rasporeda polasci su rjeđi što korisnicima predstavlja ključan nedostatak sustava.

Javni prijevoz u Vukovaru u velikoj mjeri ovisi o subvencijama Grada, što je karakteristično za gradove manje i srednje veličine u kojima prihodi od prodaje karata ne pokrivaju operativne troškove prijevoznika. Ovisnost o subvencijama stvara pritisak na gradski proračun te također smanjuje prostor za ulaganje u modernizaciju i unaprjeđenje usluge. Mali broj korisnika, ograničen broj polazaka i niska popunjenost kapaciteta nisu dostatni za pokriće visokih operativnih troškova po putniku. Zbog toga javni prijevoz gotovo neizbježno posluje s negativnim saldom, koji se ne može nadoknaditi povećanjem cijena karata bez negativnih posljedica za korisnike. Svako povećanje cijena dodatno opterećuje putnike i može dovesti do pada broja korisnika, dok snižavanje cijena predstavlja dodatni financijski teret za grad. Stoga je važno pronaći ravnotežu između fiskalnih mogućnosti lokalne samouprave i potreba krajnjih korisnika kako bi se održala dostupnost i funkcionalnost javnog prijevoza.

Prema Hörcheru i Tirachiniju (2021), potražnja za javnim prijevozom osjetljiva je na promjene cijena, pri čemu povećanje cijena često rezultira padom broja korisnika, osobito u sredinama s manjom potražnjom i ograničenim alternativama prijevoza. Dakle, povećanje cijena karata može kratkoročno poboljšati prihod prijevoznika, ali istodobno povećano financijsko opterećenje korisnika može dovesti do pada potražnje. Suprotno tome, snižavanje cijena bez kompenzacijskih mjera pojačava pritisak na gradski proračun. Zbog toga je potrebno tražiti ravnotežu između priuštivosti za korisnike i financijske održivosti sustava. Značajno povećanje cijena karata u gradu Vukovaru, više od 200%, u listopadu 2025. godine izazvalo je snažnu reakciju korisnika javnog prijevoza i otvorilo pitanje usklađenosti cijene i kvalitete usluge. Povećanjem cijena karata posebno su pogođeni umirovljenici kao jedna od najranjivijih skupina korisnika. Grad je i prije poskupljenja provodio socijalnu politiku u području javnog prijevoza. Odlukom o financiranju cijene mjesečne karte, od 1. siječnja 2025. godine Grad je osobama starijima od 65 godina s prebivalištem na području grada osigurao potpuno besplatan prijevoz, u cijelosti financiran iz gradskog proračuna. Ova mjera bila je važan oblik podrške starijoj populaciji koja u velikoj mjeri ovisi o javnom prijevozu. Nakon isteka dotadašnje koncesije i stupanjem na snagu nove, došlo je do značajnog povećanja cijena svih vrsta karata. Najveći porast zabilježen je kod mjesečnih karata za umirovljenike: cijena je porasla sa 6,50 eura na 20 eura čime je u praksi ukinut dotadašnji model besplatnog prijevoza financiranog od strane Grada. Kako bi ublažio posljedice poskupljenja karata, Grad Vukovar organizirao je javne tribine s umirovljenicima. Predstavljene su im dvije opcije potpore: sufinanciranje mjesečne karte u iznosu od 7 eura ili jednokratna pomoć od 84 eura za umirovljenike s mirovinom do 650 eura. Većina sudionika odlučila se za model sufinanciranja mjesečne karte (Grad Vukovar, 2025c). Ovaj slučaj pokazuje da se cijene javnog prijevoza ne mogu promatrati isključivo iz perspektive

ekonomske opravdanosti prijevoznika, već ih je potrebno razmatrati i kroz prizmu socijalne pravednosti, priuštivosti i javnog interesa.

Kako bi se prikazala dinamika financiranja javnog prijevoza u gradu Vukovaru, u Tablici 1 prikazana su proračunska izdvajanja za ovu namjenu u razdoblju od 2023. do 2025. godine.

Tablica 1. Proračunska izdvajanja za javni prijevoz Grada Vukovara

Godina	Ukupna izdvajanja za javni prijevoz (EUR)	Promjena u odnosu na prethodnu godinu (%)	Udio u ukupnim rashodima proračuna (%)
2023.	279.802,07	–	1,26
2024.	267.300,62	– 4,47	0,93
2025.*	415.000,00	+ 55,23	1,11

**Planirani / proračunski iznos. Konačni iznos bit će poznat nakon završetka proračunske godine 2026.*

Izvor: Grad Vukovar (2025b)

Na temelju prikazanih podataka Grada Vukovara vidljivo je da se javni prijevoz u Vukovaru u velikoj mjeri financira iz gradskog proračuna. U 2023. godini izdvajanja su iznosila 279.802,07 eura, što je činilo 1,26 % ukupnih rashoda proračuna. U 2024. godini zabilježen je blagi pad izdvajanja na 267.300,62 eura (– 4,47 %), uz smanjenje udjela u proračunu na 0,93 %. Za 2025. godinu planirano je znatno povećanje sredstava na ukupno 415.000,00 eura, što predstavlja porast od 55,23 % u odnosu na prethodnu godinu te udio od 1,11 % u ukupnim rashodima proračuna. Navedeni podaci potvrđuju snažnu fiskalnu ovisnost sustava javnog prijevoza o subvencijama lokalne samouprave, osobito u kontekstu socijalno osjetljivih skupina poput učenika, studenata i starijih osoba.

Ovakav trend potvrđuje da trenutni model financiranja javnog prijevoza ima ograničenu ekonomsku održivost te stvara kontinuirani pritisak na lokalni proračun, osobito u uvjetima rasta operativnih troškova i smanjene potražnje uzrokovane povećanjem cijena karata. U skladu je s nalazima OECD-a (2020), koji ističe da u gradovima srednje veličine javni prijevoz rijetko može funkcionirati bez kontinuiranih subvencija, osobito kada ima izraženu socijalnu funkciju.

Tablica 2. Struktura proračunskih izdvajanja za sufinanciranje javnog prijevoza po skupinama korisnika (2023.–2025.)

Skupina korisnika	2023. (EUR)	2024. (EUR)	2025.* (EUR)
Učenici (gradski i međugradski)	111.770,47	108.515,57	116.594,68
Studenti	38.580,98	33.208,00	34.858,84
Starije osobe	126.038,75	122.588,55	137.181,00
Osobe s posebnim potrebama	3.411,87	2.970,50	3.055,00
Ukupno	279.802,07	267.282,62	291.689,52

** Planirani / proračunski iznos. Konačni iznos bit će poznat nakon završetka proračunske godine 2026.*

Izvor: Grad Vukovar (2025b)

Podaci iz Tablice 2 pokazuju da se najveći dio proračunskih sredstava za sufinanciranje javnog prijevoza u gradu Vukovaru kontinuirano izdvaja za starije osobe i za prijevoz učenika (gradski i međugradski javni prijevoz učenika srednjih škola s prebivalištem na području grada Vukovara). Ovakav model sufinanciranja smanjuje financijsko opterećenje kućanstava i potiče redovito korištenje javnog prijevoza među mlađom populacijom, dok istodobno subvencije za starije osobe osiguravaju osnovnu razinu mobilnosti i socijalne uključenost Takva struktura izdvajanja upućuje na to da se javni prijevoz ne promatra isključivo kao prometna usluga, već i kao instrument socijalne politike lokalne samouprave.

Iako proračunska izdvajanja potvrđuju da je sustav javnog prijevoza u gradu Vukovaru ovisan o subvencijama, Grad je razmatrao i dugoročnije rješenje koje bi omogućilo veću kontrolu nad kvalitetom i troškovima usluge. U tom kontekstu analizirana je mogućnost uspostave vlastitog gradskog prijevoza kroz nabavu autobusa. Prema dostupnim podacima, sukladno planiranom voznom redu i broju linija, potrebno je u prosjeku 7 autobusa, 5 za redovne linije i 2 za rezervne kapacitete. Sukladno mogućnostima sufinanciranja iz fondova Europske unije, Grad je planirao nabavu 8 električnih autobusa (procjena nabave uključivala je dodatni operativni kapacitet i rezervu), čija je procijenjena vrijednosti nabave iznosila približno 4,8 milijuna eura. Međutim, nakon provedene analize tržišta, Grad Vukovar odustao je od realizacije navedenog ulaganja. Kao problem izdvojeni su visoki troškovi nabave električnih autobusa te nepostojanje servisne i tehničke infrastrukture potrebne za redovno održavanje i popravke vozila na lokalnom području. Umjesto toga Grad je sklopio koncesijski ugovor za obavljanje komunalne djelatnosti prijevoza putnika za razdoblje od tri godine uz mogućnosti da se u međuvremenu osiguraju sredstva za nabavu vlastitih autobusa i ustrojstvo gradske prijevozničke tvrtke. Ova namjera ulaganja dio je šire strategije usmjerene na povećanje energetske učinkovitosti, smanjenje ovisnosti o privatnim prijevoznicima te podizanje kvalitete usluge (Grad Vukovar, 2025a).

Učinkovitost sustava može se unaprijediti primjenom digitalnih tehnologija koje su posljednjih godina u središtu interesa istraživača zbog svojeg potencijala u razvoju sustava pametnog prijevoza. Koncept pametnog prijevoza uključuje integrirano upravljanje prometom, poboljšanje logistike, učinkovite sustave parkiranja i poboljšanje sigurnosnih mjera kroz primjenu digitalnih tehnologija u prometnim sustavima (Oladimeji et. al., 2023).

Modernizacija javnog prijevoza ne ovisi samo o raspoloživim sredstvima nego i o sposobnosti lokalnih dionika da zajednički planiraju, pripreme i provedu razvojne projekte. Jedan od koncepata koji se može primijeniti pri razmatranju razvojnih iskoraka jest Triple Helix model, koji naglašava suradnju akademske zajednice, poslovnog sektora i javne uprave. U gradovima srednje veličine suradnja je često brža i izravnija, što može ubrzati donošenje kvalitetnih odluka i provedbu inovacija. Kako navode Majstorović et al. (2022), suradnja dionika na lokalnoj razini omogućuje stvaranje „prostora znanja“, „prostora konsenzusa“ i „prostora inovacija“, što može biti poticaj razvoju lokalne zajednice. U gradu Vukovaru takav potencijal dodatno jača činjenica da grad ima vlastitu visokoobrazovnu instituciju, Veleučilište „Lavoslav Ružička“, koja se može pozicionirati kao akademski partner u Triple Helix sustavu. Kao lokalna institucija znanja, Veleučilište može pružiti analitičku i istraživačku podršku, razvoj inovativnih rješenja i uključivanje u projekte od važnosti za Grad, uključujući i projekte modernizacije javnog prijevoza.

3. EMPIRIJSKO ISTRAŽIVANJE

3.1 Metodologija istraživanja

U svrhu ovoga rada provedeno je kvantitativno deskriptivno istraživanje temeljeno na anketnom upitniku. Cilj istraživanja bio je ispitati zadovoljstvo korisnika javnog prijevoza te percepciju ekonomske opravdanosti javnog prijevoza kao i steći uvid u čimbenike povezane s ekonomskom održivošću sustava.

Kao instrument korišten je anketni upitnik koji je podijeljen u četiri cjeline: socio-demografska obilježja ispitanika, učestalost i svrha korištenja javnog prijevoza, zadovoljstvo pojedinim aspektima usluge te stavovi o cijenama karata i mogućim poboljšanjima. U istraživanje su uključeni korisnici javnog prijevoza na području grada Vukovara, različitih dobnih skupina, zanimanja i učestalosti korištenja javnog prijevoza. Ukupan broj ispitanika iznosio je 120. Uzorak je uključio i bivše korisnike radi procjene učinka poskupljenja. Za potrebe istraživanja razvijen je anketni upitnik koji se sastojao od 12 pitanja, od kojih je jedno pitanje obuhvaćalo pet tvrdnji za procjenu zadovoljstva korištenja, mjerenih Likertovom skalom od pet stupnjeva (1 - uopće nisam zadovoljan/na, 5 - u potpunosti sam zadovoljan/na). Upitnik je sadržavao pitanja zatvorenog tipa te jedno pitanje otvorenog tipa. Način ispunjavanja upitnika (samostalno ili uz pomoć studenta) evidentiran je zasebnim kontrolnim pitanjem radi kontrole načina prikupljanja podataka.

Podaci su prikupljani kombinacijom online ispunjavanja upitnika putem alata Google Forms (poveznica/QR kod) te asistiranog ispunjavanja za ispitanike koji nisu mogli samostalno ispuniti online upitnik, pri čemu su studenti čitali pitanja i unosili odgovore koje su ispitanici davali. Online upitnik bio je identičan u svim slučajevima, neovisno o načinu ispunjavanja. Starijim ispitanicima ili ispitanicima s poteškoćama u korištenju mobilnih uređaja pružena je pomoć isključivo u tehničkom smislu, bez utjecaja na sadržaj odgovora. Način ispunjavanja upitnika evidentiran je kao kontrolna varijabla.

Ispitanici su u istraživanju sudjelovali dobrovoljno, osigurana im je anonimnost i prethodno su upoznati s ciljem istraživanja. Istraživanje je provedeno tijekom siječnja 2026. godine. Statistička obrada podataka provedena je uz pomoć programa JASP (verzija 0.95.4). U analizi su korištene deskriptivne statističke metode te hi-kvadrat test za ispitivanje razlika u raspodjeli odgovora. S obzirom na veličinu i strukturu uzorka, primjena složenijih statističkih modela nije bila primjerena.

Istraživanje se temelji na prigodnom uzorku u kojem dominiraju učenici i studenti, zbog čega rezultati prvenstveno odražavaju percepciju mlađe populacije korisnika javnog prijevoza.

3.2 Sekundarni podaci i fiskalni pokazatelji

Uz primarne podatke prikupljene anketnim istraživanjem, u radu su korišteni i sekundarni podaci o financiranju i sufinanciranju javnog prijevoza, dobiveni iz interne evidencije Grada Vukovara za razdoblje 2023. do 2025. godine. Ovi podaci korišteni su za analizu proračunskih izdvajanja te za procjenu fiskalne održivosti sustava javnog prijevoza na lokalnoj razini.

4. REZULTATI I RASPRAVA

U istraživanju je sudjelovalo ukupno 120 ispitanika. Većinu ispitanika činile su žene (57,5 %), dok je muškaraca bilo 42,5 %. Najzastupljenija dobna skupina bila je dobna skupina do 20 godina (n = 83), dok je najmanji udio ispitanika bio u dobnoj skupini od 51 do 65 godina (n = 4). Prema statusu, najveći udio ispitanika čine učenici (n = 77), dok su ostale skupine znatno manje zastupljene: zaposleni (n = 13), studenti (n = 12), nezaposleni (n = 9) te umirovljenici (n = 9). Ovakva struktura uzorka u skladu je s obrascem korištenja javnog prijevoza u Vukovaru, gdje učenici i studenti čine najčešće korisnike gradskog prijevoza. Iako je udio umirovljenika u uzorku manji, njihova važnost za sustav javnog prijevoza vidljiva je kroz značajna proračunska izdvajanja Grada Vukovara za sufinanciranje prijevoza starijih osoba, što potvrđuje izraženu socijalnu dimenziju sustava.

Analiza učestalosti korištenja javnog prijevoza pokazuje da najveći broj ispitanika koristi javni prijevoz svakodnevno (n = 40). Slijede ispitanici koji javni prijevoz koriste povremeno (n = 28)

te nekoliko puta tjedno (n = 25). Njih 24 navodi da javni prijevoz trenutno ne koristi, dok ga najmanji broj ispitanika koristi jednom tjedno (n = 3).

Najveći broj ispitanika koristi javni prijevoz u svrhu škole ili studija (n = 51). Slijedi korištenje javnog prijevoza radi rekreacije i slobodnog vremena (n = 15), dok ispitanici javni prijevoz koriste i za odlazak na posao (n = 9) te posjete zdravstvenim ustanovama (n = 9). Manji broj ispitanika navodi kupovinu i obavljanje svakodnevnih poslova (n = 7) kao glavnu svrhu korištenja, dok su ostali razlozi zastupljeni u manjem opsegu.

Analiza percepcije povezanosti linija pokazuje da ispitanici nemaju izraženo negativnu, ali ni izrazito pozitivnu percepciju umreženosti gradskog prijevoza. Najveći broj ispitanika ocijenio je povezanost linija srednjom ocjenom, dok su ostale ocjene raspoređene relativno ravnomjerno. Ovakvi rezultati upućuju na to da povezanost linija nije primarni izvor nezadovoljstva, ali predstavlja područje u kojem postoji prostor za funkcionalna poboljšanja.

Analiza percepcije učestalosti polazaka pokazuje da korisnici javnog prijevoza učestalost polazaka ocjenjuju uglavnom srednjim ocjenama, pri čemu dominira ocjena 2. Rezultati upućuju na to da se učestalost polazaka percipira kao umjerena, što sugerira da organizacijski elementi sustava predstavljaju područje za postupna poboljšanja, ali ne i primarni izvor nezadovoljstva korisnika. Slično tome, percepcija pouzdanosti javnog prijevoza u smislu poštivanja voznog reda ukazuje na pretežno umjereno pozitivnu ocjenu, bez izraženih negativnih ili izrazito pozitivnih odstupanja. Dodatna analiza pokazuje da učenici i studenti češće koriste javni prijevoz na dnevnoj razini u odnosu na ostale skupine ispitanika. Ovakav rezultat potvrđuje važnost osiguravanja mobilnosti mlađe populacije koja često nema pristup privatnom prijevozu.

Percepcija kvalitete autobusa, uključujući čistoću, udobnost i pristupačnost, pokazuje umjerenu razinu zadovoljstva korisnika. Većina ispitanika dala je srednje ocjene, dok je manji broj korisnika izrazio visoko zadovoljstvo kvalitetom vozila. Iako razlike u odgovorima nisu statistički značajne, rezultati ukazuju na potrebu modernizacije voznog parka, što je u skladu s planovima Grada Vukovara o ulaganjima u nova, energetski učinkovitija vozila.

Tablica 3. Percepcija cijene i kvalitete usluge

Zadovoljstvo odnosom cijene i kvalitete usluge	Observed	Expected: Multinomial
1	44	19.20
2	19	19.20
3	15	19.20
4	10	19.20
5	8	19.20

Izvor: Izrada autora

Analiza odnosa cijene i kvalitete usluge javnog prijevoza pokazala je statistički značajnu razliku u raspodjeli odgovora ispitanika. Većina ispitanika smatra da cijena javnog prijevoza nije u skladu s kvalitetom pružene usluge. Hi-kvadrat test potvrđuje postojanje statistički značajne povezanosti između percepcije cijene i ocjene kvalitete usluge ($\chi^2 = 43{,}90$; $p < 0{,}001$). Ovaj rezultat upućuje na izraženo nezadovoljstvo korisnika, osobito u kontekstu značajnog povećanja cijena karata u 2025. godini, te predstavlja empirijsku potvrdu visoke cjenovne osjetljivosti korisnika javnog prijevoza. Dobiveni nalazi u skladu su s prethodnim istraživanjima koja naglašavaju važnost usklađivanja cijene i kvalitete usluge te opravdanost intervencija lokalne samouprave kroz modele subvencioniranja.

Tablica 4. Utjecaj povećanja cijena na ponašanje korisnika

Kako je povećanje cijena karata iz listopada 2025. (poskupljenje) utjecalo na Vaše korištenje javnog prijevoza?	Observed	Expected: Multinomial
Koristim ga jednako kao i prije	49	30.00
Koristim ga rjeđe	24	30.00
Koristim ga znatno rjeđe	25	30.00
Potpuno sam prestao/la koristiti javni prijevoz	22	30.00

Izvor: izrada autora

Rezultati pokazuju da je povećanje cijena imalo statistički značajan utjecaj na korištenje javnog prijevoza ($\chi^2 = 16{,}20$; $p = 0{,}001$). Iako dio ispitanika navodi da javni prijevoz koristi jednako kao i prije, značajan udio ispitanika koristi ga rjeđe ili znatno rjeđe, dok je dio ispitanika u potpunosti prestao koristiti javni prijevoz. Ovakvi nalazi potvrđuju da povećanje cijena, bez paralelnog unaprjeđenja kvalitete usluge, može imati kontraproduktivne učinke te dugoročno ugroziti financijsku održivost sustava.

Tablica 5. Spremnost na češće korištenje javnog prijevoza

Biste li javni prijevoz koristili češće kada bi cijene karata bile niže?	Observed	Expected: Multinomial
Da	80	40.00
Ne	26	40.00
Već ga koristim maksimalno često	14	40.00

Izvor: izrada autora

Ispitanici u velikoj mjeri iskazuju spremnost na češće korištenje javnog prijevoza u slučaju nižih cijena karata ili poboljšanja mreže linija i učestalosti polazaka. Ovaj nalaz potvrđuje da potražnja za javnim prijevozom nije isključivo ograničena navikama korisnika, već snažno ovisi o kombinaciji cijene, dostupnosti i kvalitete usluge.

Nadalje, rezultati istraživanja pokazuju izrazito visoku razinu podrške subvencioniranju javnog prijevoza za određene skupine korisnika. Velika većina ispitanika podržava model u kojem Grad subvencionira prijevoz učenika, studenata, umirovljenika i socijalno osjetljivih skupina. Ovakav nalaz potvrđuje da javnost javni prijevoz percipira prvenstveno kao socijalnu i javnu uslugu, a ne isključivo kao tržišni proizvod.

Na otvoreno pitanje o mogućim poboljšanjima javnog prijevoza ispitanici su najčešće isticali potrebu za smanjenjem cijene karata, osobito za učenike, studente i umirovljenike. Uz cijenu, naglašena je potreba za unaprjeđenjem kvalitete usluge, uključujući modernije i čišće autobuse, veću udobnost, bolju klimatizaciju i pristupačnost osobama s invaliditetom. Dio odgovora odnosio se i na ponašanje vozača te kvalitetu komunikacije s korisnicima, kao i na bolju povezanost pojedinih dijelova grada. Otvoreni odgovori potvrđuju rezultate kvantitativnog dijela istraživanja te ukazuju da su cijena prijevoza, organizacija linija i kvaliteta usluge ključni čimbenici za unaprjeđenje javnog prijevoza u gradu Vukovaru.

Budući da je istraživanje provedeno na prigodnom uzorku, u kojem dominiraju učenici i studenti, dobivene rezultate potrebno je interpretirati uz određeni oprez jer uzorak ne odražava u potpunosti strukturu svih korisnika javnog prijevoza. Ipak, s obzirom na to da upravo mlađa populacija čini značajan dio korisnika javnog prijevoza, dobiveni rezultati pružaju relevantan uvid u percepciju jedne od ključnih skupina korisnika. U gradovima s manjim brojem korisnika, poput Vukovara, povećanje cijena karata dodatno povećava rizik gubitka putnika, dok održavanje pristupačne cijene bez subvencija stvara pritisak na lokalni proračun, što potvrđuje nalaze ekonomske literature o javnom prijevozu prema kojima sustav zbog svoje društvene funkcije ne može dugoročno funkcionirati isključivo na tržišnim osnovama (Hörcher i Tirachini, 2021). Snažna reakcija korisnika na povećanje cijena u

Vukovaru u skladu je s nalazima Wardmana (2022), koji pokazuje da cjenovne promjene u javnom prijevozu imaju značajan i dugotrajan učinak na ponašanje korisnika. Dobiveni rezultati upućuju na to da povećanje cijena bez paralelnog unaprjeđenja kvalitete usluge može imati kontraproduktivne učinke i dodatno oslabiti korištenje javnog prijevoza. Odluka Grada Vukovara o sufinanciranju mjesečnih karata za umirovljenike u skladu je s nalazima Guzmana i Cantillo-Garcia (2024), koji ističu da subvencije mogu ublažiti negativne učinke poskupljenja na zadovoljstvo korisnika i zadržati razinu korištenja javnog prijevoza.

Analiza proračunskih izdvajanja Grada dodatno potvrđuje ekonomsku dimenziju održivosti javnog prijevoza u gradu Vukovaru. U promatranom razdoblju, za financiranje i sufinanciranje javnog prijevoza izdvajano je između približno 267.000 i 415.000 eura godišnje. Proračunska izdvajanja za javni prijevoz čine između približno 0,9 % i 1,3 % ukupnih rashoda gradskog proračuna. Uzimajući u obzir relativno mali broj korisnika, ovakva izdvajanja ukazuju na značajnu fiskalnu ulogu lokalne samouprave u održavanju sustava javnog prijevoza. time se potvrđuje da javni prijevoz zahtijeva kontinuiranu potporu kako bi se osigurala dostupnost usluge različitim skupinama stanovništva.

Empirijski nalazi u skladu su s rezultatima prethodnih istraživanja koja ukazuju na visoku cjenovnu osjetljivost potražnje za javnim prijevozom (Wardman, 2022; Hörcher, 2021). Potvrđuju se teorijske pretpostavke da se javni prijevoz u gradovima poput Vukovara ne može promatrati isključivo kroz tržišnu logiku, već kao javna usluga s izraženom socijalnom funkcijom.

5. ZAKLJUČAK

Ovim radom provedena je ekonomska analiza sustava javnog prijevoza u gradu Vukovaru s ciljem sagledavanja njegove održivosti, ekonomske opravdanosti i percepcije korisnika o njegovim uslugama. Polazeći od teorijskih postavki javnog prijevoza kao javne i socijalne usluge, a ne isključivo kao tržišnog proizvoda, istraživanje je nastojalo empirijski ispitati čimbenike koji utječu na oblikovanje korisničkog iskustva.

Dobiveni empirijski nalazi potvrđuju početnu pretpostavku rada da u gradovima poput Vukovara javni prijevoz ne može funkcionirati isključivo prema tržišnim načelima. Korištenje javnog prijevoza pokazalo se osjetljivim na promjene cijene i kvalitetu usluge, pri čemu se povećanje cijena karata negativno odrazilo na zadovoljstvo korisnika i njihovu spremnost na korištenje javnog prijevoza. Istodobno, rezultati upućuju na to da bi niže cijene karata, kao i češće i bolje prilagođene linije, mogle imati značajan pozitivan učinak na učestalost korištenja javnog prijevoza. Kvalitativna analiza otvorenih odgovora dodatno potvrđuje važnost ekonomske dostupnosti, učestalosti linija i kvalitete usluge kao dominantnih elemenata u percepciji javnog prijevoza.

Analiza proračunskih izdvajanja pokazuje da je sustav javnog prijevoza u gradu Vukovaru snažno ovisan o subvencijama lokalne samouprave, što potvrđuje tezu da dugoročna održivost javnog prijevoza u srednje velikim gradovima nije ostvariva bez kontinuirane financijske potpore. Takva ovisnost dodatno naglašava socijalnu dimenziju javnog prijevoza i njegovu ulogu u osiguravanju mobilnosti učenika, studenata, starijih osoba i drugih osjetljivih skupina stanovništva.

Iako su u uzorku dominantno zastupljeni učenici srednjih škola koji ostvaruju pravo na besplatan gradski prijevoz, njihova percepcija cijene i vrijednosti usluge ostaje relevantna jer se odnosi na opću ekonomsku opravdanost sustava te na potencijalno buduće korisničko ponašanje izvan statusa učenika. Time se dodatno potvrđuje da se učinkovitost sustava javnog prijevoza ne može vrednovati isključivo kroz trenutačne financijske aranžmane, već kroz širi društveni i ekonomski kontekst.

Za buduća istraživanja preporučuje se detaljnija analiza učinaka cjenovnih i organizacijskih promjena na ponašanje korisnika, kao i usporedba s drugim gradovima slične veličine, kako bi se dobiveni nalazi dodatno istražili i razumjeli.

Zaključno, rezultati istraživanja potvrđuju da je sustav javnog prijevoza u gradu Vukovaru obilježen snažnom međuovisnošću ekonomskih, organizacijskih i socijalnih čimbenika što je u skladu s teorijskim modelima javnog prijevoza i europskim smjernicama za razvoj održive mobilnosti u gradovima srednje veličine.

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Preliminary Communication

ECONOMIC ANALYSIS OF THE PUBLIC TRANSPORT SYSTEM IN THE CITY OF VUKOVAR

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ABSTRACT

This paper analyses the sustainability and economic viability of the public transport system in the City of Vukovar, with a particular focus on the effects of fare increases and users' satisfaction with the service. The aim of the research is to assess the current state of the public transport system, identify key challenges, and examine users' perceptions and levels of satisfaction. The theoretical part discusses the concepts of sustainable mobility, economic models of public transport, the legal framework, and the role of local government in organising and financing the service. The empirical part is based on a survey conducted among public transport users, collecting data on frequency of use, satisfaction with the service, fare perceptions, and users' willingness to change how often they use public transport in relation to fare levels and service quality. In addition to primary data, the analysis includes the City of Vukovar's budgetary allocations for public transport. The analysis provides insight into the relationship between fares, service quality, and public transport use, and highlights the challenges of ensuring both financial and social sustainability. It is concluded that the research findings can serve as a basis for improving the planning and financing of public transport at the local level.

Keywords: *public transport, sustainability, subsidisation, user satisfaction, City of Vukovar*

Prethodno priopćenje

TROŠKOVI RADA I PROFITABILNOST U TAKSI DJELATNOSTI U UVJETIMA AUTONOMNOG PRIJEVOZA

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SAŽETAK

Rad analizira učinke uvođenja robotaksija na tržište taksi djelatnosti, s naglaskom na troškove rada i profitabilnost sektora. Taksi djelatnost u Hrvatskoj, osobito u urbanim sredinama poput Zagreba, obilježena je visokim i rastućim troškovima rada, koji čine značajan udio ukupnih troškova poslovanja. Sektor karakterizira i visok udio mikro i malih poduzetnika, pri čemu mikropoduzetnici imaju najveći relativni udio troškova osoblja i najnižu otpornost na rast troškova i tržišne šokove. Financijski pokazatelji upućuju na strukturnu slabost djelatnosti, s vrlo niskim EBITDA i neto profitnim maržama te slabim povratom na kapital, što dovodi u pitanje njezinu dugoročnu održivost. U tom kontekstu, robotaksiji predstavljaju značajnu tehnološku promjenu jer automatizacija prijevoza omogućuje znatno smanjenje ili eliminaciju troškova rada vozača, čime se potencijalno povećava troškovna učinkovitost i profitabilnost novih poslovnih modela. Istodobno, takav razvoj može dodatno pogoršati tržišni položaj tradicionalnih taksi prijevoznika, osobito mikro i malih poduzeća koja nemaju kapacitet za ulaganja u novu tehnologiju. Rad se dodatno konceptualno osvrće na moguće učinke robotaksija na funkcioniranje usluge u urbanim sredinama. Kao potencijalne prednosti navode se veća dostupnost usluge, niže cijene, standardiziranija kvaliteta, bolja iskorištenost voznog parka, veća sigurnost i ograničavanje sive ekonomije, dok se kao rizici ističu tehnološka pouzdanost, regulatorni izazovi, prihvaćanje od strane korisnika te negativni socioekonomski učinci poput gubitka radnih mjesta i koncentracije tržišta. Zaključno, uvođenje robotaksija može temeljito promijeniti strukturu troškova i profitabilnost taksi djelatnosti, pri čemu će stvarni učinci ovisiti o načinu implementacije, regulatornom okviru i prilagodbi postojećih sudionika na tržištu.

Ključne riječi: *autonomni prijevoz, profitabilnost, robotaksi, taksi djelatnost, troškovi rada*

1. UVOD

U posljednjem desetljeću tržište taksi djelatnosti suočeno je s dubokim tehnološkim i organizacijskim promjenama, ponajprije uslijed razvoja autonomnih vozila i pojave robotaksija. Polazišna točka ovog rada jest činjenica da je taksi djelatnost u Hrvatskoj, osobito u urbanim sredinama poput Grada Zagreba, obilježena visokim i rastućim troškovima rada, pri čemu troškovi osoblja čine značajan udio ukupnih troškova poslovanja te dodatno opterećuju već ionako nisku profitabilnost sektora.

Strukturnu ranjivost dodatno pojačava izrazito visok udio mikro i malih poduzetnika, koji istodobno imaju najveći relativni udio troškova osoblja i najmanju otpornost na rast troškova i tržišne šokove. Financijski pokazatelji, poput vrlo niskih ili negativnih EBITDA i neto profitnih marži te slabog ili negativnog povrata na aktivu, upućuju na to da postojeći poslovni modeli taksi djelatnosti teško osiguravaju zadovoljavajuću razinu profitabilnosti i dugoročnu

održivost. U tom kontekstu, uvođenje robotaksija otvara pitanje u kojoj mjeri automatizacija prijevoza - kroz eliminaciju ili snažno smanjenje troškova rada vozača - može promijeniti strukturu troškova i profitabilnost sektora, ali i produbiti jaz između novih poslovnih modela i tradicionalnih taksi prijevoznika.

Cilj rada je istražiti profitabilnost segmenta taksi djelatnosti na primjeru Grada Zagreba te sagledati kako bi uvođenje autonomnog prijevoza moglo utjecati na profitabilnost tog segmenta i održivost postojećeg poslovnog modela.

Polazeći od navedenog, u radu se provjerava sljedeća istraživačka hipoteza:

H1: Visoki udio troškova rada vozača važan je uzrok niske profitabilnosti taksi djelatnosti u Gradu Zagrebu, a njihova eliminacija ili značajno smanjenje znatno bi povećala profitabilnost sektora. Uz provjeru ove hipoteze, rad se u kvalitativnom dijelu osvrće na šire implikacije uvođenja autonomnog prijevoza na tržište rada, organizacijski model usluge i razinu tržišne koncentracije u taksi sektoru.

2. METODOLOGIJA

Istraživanje se temelji na sekundarnim izvorima podataka, prije svega agregiranim godišnjim financijskim izvještajima poduzetnika koje priprema Financijska agencija (FINA). Korišteni su podaci za poslovne godine od 2020. do 2024. Također su korišteni demografski i ekonomski pokazatelji iz Statističkog ljetopisa Grada Zagreba. Provedena je deskriptivna i komparativna analiza osnovnih pokazatelja profitabilnosti (EBITDA marža, neto profitna marža, ROA, ROE) za taksi djelatnost u Gradu Zagrebu, uz usporedbu s ukupnim gospodarstvom i djelatnošću prijevoza i skladištenja na razini Zagreba i Hrvatske.

Agregirani godišnji financijski izvještaji obuhvaćaju podatke trgovačkih društava registriranih u Republici Hrvatskoj te obrta i drugih poslovnih subjekata koji posluju u sustavu poreza na dobit. Dakle, u analizu nisu uključeni podaci za obrte i druge poslovne subjekte koji posluju u sustavu poreza na dohodak, uključujući one koji porez plaćaju paušalno. Budući da se veći dio prometa u taksi djelatnosti u urbanim sredinama odvija upravo kroz subjekte u sustavu poreza na dobit, dobiveni se rezultati mogu smatrati reprezentativnima za formalni segment tržišta, ali ne i za cjelokupnu (uključujući sivu) ekonomsku aktivnost u sektoru.

Dodatno je izrađena scenarijska analiza u kojoj se simulira hipotetski slučaj eliminacije troškova zaposlenika, radi procjene koliko bi smanjenje troškova rada utjecalo na profitabilnost taksi sektora uz usporedbu prema cjelokupnom gospodarstvu i sektoru prijevoza i skladištenja. Na temelju dobivenih rezultata razmatraju se očekivani učinci uvođenja autonomnog prijevoza (robotaksija) na troškove rada, profitabilnost i strukturne promjene u taksi djelatnosti.

3. RAZVOJ I OBILJEŽJA TAKSI TRŽIŠTA U GRADU ZAGREBU

Grad Zagreb ima oko 774 tisuće stanovnika, a metropolitansko područje nešto više od milijun stanovnika, što ga svrstava među srednje velike europske prijestolnice. Po broju stanovnika usporediv je s gradovima poput Stockholma i Amsterdama, a po površini (641 km²) među većima je u Europi, na razini Madrida, a veći primjerice od Budimpešte i Beča. Posljedica velike površine i relativno manjeg broja stanovnika je niža prosječna gustoća naseljenosti u odnosu na većinu europskih glavnih gradova, pri čemu je najviša gustoća u središnjim i višestambenim četvrtima poput Donjeg grada, Trešnjevke, Trnja i Novog Zagreba.

Razvedena struktura naselja izravno utječe na organizaciju javnog prijevoza koji se temelji na tramvaju kao glavnoj okosnici, autobusnim linijama koje povezuju rubne i slabije urbanizirane dijelove grada te trenutno nedovoljno iskorištenom sustavu prigradske željeznice. Za putovanja izvan glavnih koridora javnog prijevoza i u rubnim dijelovima s rjeđom i neredovitom uslugom, taksi prijevoz djeluje kao fleksibilna dopuna javnom prijevozu.

Iz Tablice 1 vidljivo je da je broj taksi vozila u Zagrebu porastao s 1.037 u 2010. na 4.370 u 2024. godini, odnosno više od tri puta. Pritom se osnovni demografski, turistički i ekonomski

pokazatelji nisu mijenjali usporedivom dinamikom, što upućuje da rast broja taksi vozila ne proizlazi primarno iz rasta stanovništva, turizma ili dohodaka. Ključan poticaj predstavljao je novi Zakon o prijevozu u cestovnom prometu (NN 41/2018) kojim je ukinuto ograničenje broja taksi vozila po jedinici lokalne samouprave, omogućeno naručivanje i plaćanje putem elektroničkih aplikacija te pojednostavljeni uvjeti za dobivanje dozvola. Posljedično je u razdoblju nakon 2018. Zagreb u kratkom vremenu prešao iz relativno ograničenog u izrazito liberalizirano i konkurentno taksi tržište, što se posebno očituje u skoku broja vozila između 2017. i 2019. godine.

Tablica 1. Kretanje broja taksi vozila te odabrani demografski, turistički i ekonomski pokazatelji grada Zagreba u razdoblju 2010. - 2024.

Godina	Broj taksi vozila	Broj stanovnika	Broj turista (dolazaka)	Broj noćenja	Neto plaća / zaposleni	BDP po stanovniku
2024.	4.370	774.225	1.419.929	2.646.443	1.510	n/a
2023.	3.935	771.062	1.300.694	2.507.454	1.320	34.518
2022.	3.172	767.745	1.078.669	2.206.044	1.178	28.988
2021.	3.172	768.054	634.795	1.375.248	1.105	25.805
2020.	2.870	809.268	342.472	780.077	1.036	22.810
2019.	3.597	807.254	1.454.019	2.638.962	1.009	24.639
2018.	2.110	804.507	1.400.201	2.511.817	976	23.159
2017.	1.410	802.762	1.286.087	2.263.758	927	21.634
2016.	1.410	802.338	1.152.598	2.016.107	870	20.327
2015.	1.290	798.500	1.077.778	1.804.290	878	19.477
2014.	1.316	798.500	967.902	1.602.420	844	18.727
2013.	1.343	795.900	876.604	1.451.891	843	18.829
2012.	1.435	790.017	767.366	1.245.669	846	19.228
2011.	1.037	790.017	730.945	1.183.125	849	19.008
2010.	1.037	792.875	666.106	1.085.597	852	19.320

Izvor: obrada autora prema Grad Zagreb (2011-2025)

4. PROFITABILNOST TAKSI DJELATNOSTI U ZAGREBU

Taksi djelatnost u Gradu Zagrebu čini 0,009% ukupne aktive i 0,021% poslovnih prihoda svih poduzetnika u sustavu poreza na dobit, odnosno 0,157% aktive i 0,677% prihoda unutar djelatnosti prijevoza i skladištenja. Na temelju toga može se zaključiti da taksi djelatnost predstavlja vrlo mali segment gradskog gospodarstva.

Tablica 2. Pokazatelji profitabilnosti taksi djelatnosti u Gradu Zagrebu u razdoblju 2020. - 2024.

Pokazatelj	2020.	2021.	2022.	2023.	2024.
Aktiva	8.274.779	8.186.227	10.732.138	10.176.468	10.225.662
Kapital	-761.500	-1.762.560	-1.750.566	-838.415	-2.272.798
Poslovni prihodi	14.159.205	12.280.207	17.420.697	18.872.771	17.490.340
Neto dobit (gubitak)	-257.174	-839.045	-462.206	89.292	-583.968
EBITDA	-396.909	-1.231.070	-61.352	857.505	10.245
ROA	-3,1%	-10,2%	-4,3%	0,9%	-5,7%
ROE	33,8%	47,6%	26,4%	-10,7%	25,7%
Neto profitna marža	-1,8%	-6,8%	-2,7%	0,5%	-3,3%
EBITDA marža	-2,8%	-10,0%	-0,4%	4,5%	0,1%

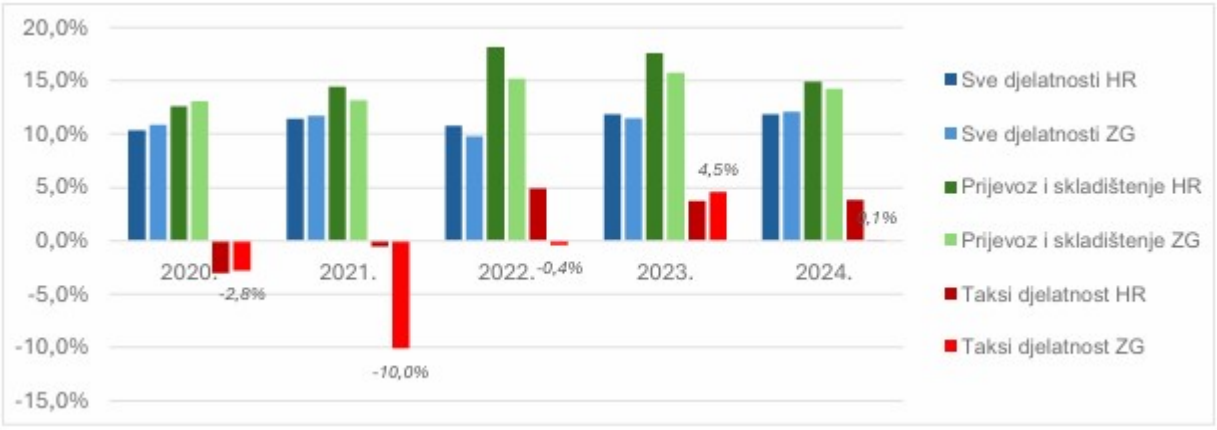
Izvor: obrada autora prema Financijska agencija (2020-2024)

Analiza pokazatelja profitabilnosti u razdoblju 2020.-2024. upućuje na nisku i izrazito volatilnu profitabilnost, s učestalim neto gubicima i skromnim maržama. Negativni rezultati u 2020. i 2021. godini ponajprije su povezani s padom mobilnosti stanovništva i turističkih dolazaka uslijed pandemije bolesti Covid-19, dok privremeno poboljšanje u 2023. odražava oporavak prometa i potražnje za prijevozom. Ponovno pogoršanje profitabilnosti u 2024. godini sugerira da pandemija nije ključni strukturni problem djelatnosti. Sektor se suočava s visokim ulaznim troškovima (gorivo, rad, održavanje voznog parka) i snažnom konkurencijom platformskih usluga prijevoza, za koje recentna istraživanja pokazuju negativan utjecaj na tržišni udio i profitne marže tradicionalnih taksi prijevoznika (npr. Diao, Jiang i Tian, 2023).

Valja istaknuti da je interpretacija pokazatelja ROE u ovom slučaju ograničena, budući da je kapital promatranog sektora tijekom cijelog razdoblja negativan. Posljedično, visoke vrijednosti ROE ne odražavaju stvarnu profitabilnost, nego su rezultat kombinacije negativnog kapitala i gubitaka, zbog čega je prikladnije osloniti se na ROA i marže kao relevantnije pokazatelje. Dugotrajno iskazivanje negativnog kapitala ukazuje na strukturnu prezaduženost i akumulirane gubitke, što upućuje na povišenu razinu financijskog rizika. U takvim okolnostima ključni izazov nije samo niska profitabilnost, već i održavanje likvidnosti te sposobnost urednog podmirivanja obveza, a valja naglasiti da je prema Stečajnom zakonu ovo jedan od stečajnih razloga (Narodne novine 71/2015).

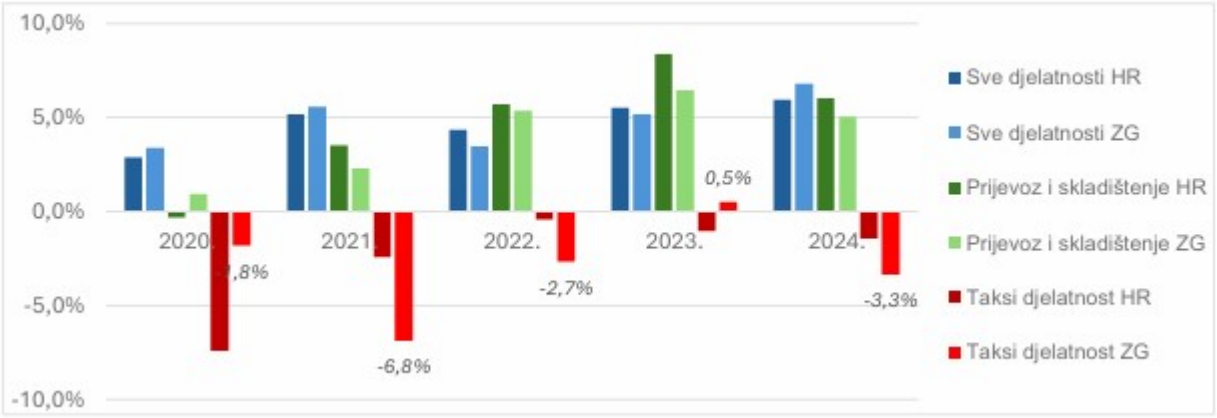
Detaljniji uvid u relativnu profitabilnost taksi djelatnosti u odnosu na usporedne skupine dan je na sljedećim grafičkim prikazima (Grafikoni 1-3).

Grafikon 1. EBITDA marža taksi djelatnosti u Gradu Zagrebu i usporedne skupine



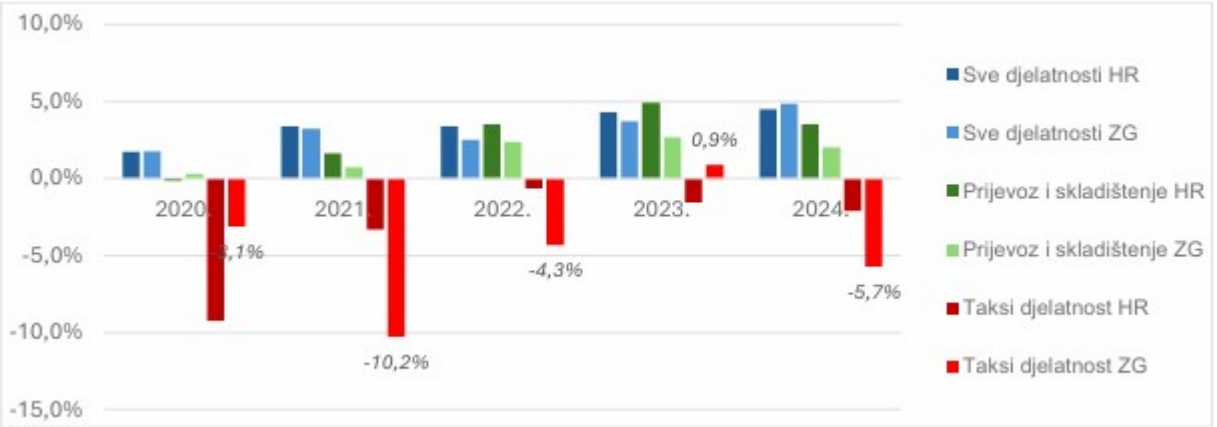
Izvor: obrada autora prema Financijska agencija (2020-2024)

Grafikon 2. Neto profitna marža taksi djelatnosti u Gradu Zagrebu i usporedne skupine



Izvor: obrada autora prema Financijska agencija (2020-2024)

Grafikon 3. ROA taksi djelatnosti u Gradu Zagrebu i usporedne skupine



Izvor: obrada autora prema Financijska agencija (2020-2024)

Grafički prikazi EBITDA marže, neto profitne marže i povrata na aktivu (Grafikoni 1-3) pokazuju da je profitabilnost taksi djelatnosti u Gradu Zagrebu tijekom gotovo cijelog promatranog razdoblja niža od prosjeka ukupnog gospodarstva i sektora prijevoza i skladištenja, uz česte negativne vrijednosti. Tek 2023. godine bilježi se kratkotrajno poboljšanje, no već 2024. pokazatelji se ponovno pogoršavaju, čime se potvrđuje da je riječ o dugotrajno niskoprofitabilnoj djelatnosti s povišenim rizikom poslovanja.

5. AUTONOMNI PRIJEVOZ I ROBOTAKSIJI

5.1. Razvoj autonomnih vozila i robotaksija

Razvoj autonomnih vozila i usluga robotaksija jedna je od najznačajnijih tehnoloških promjena u cestovnom prijevozu putnika. Autonomna vozila u užem smislu jesu vozila opremljena sustavima koji omogućuju preuzimanje većeg dijela ili cjelokupne funkcije upravljanja bez izravne intervencije vozača, pri čemu se razine automatizacije kreću od potpunog oslanjanja na vozača do potpuno autonomne vožnje. SAE International (2021) u međunarodnom standardu J3016 razlikuje šest razina automatizacije (0-5), od razine bez automatizacije do razine potpune autonomne vožnje bez vozača, što je danas dominantno prihvaćen referentni okvir. U tom se okviru robotaksiji definiraju kao poslovni model u kojem operator putem flote visoko ili potpuno autonomnih vozila pruža uslugu prijevoza na zahtjev, uz znatno drukčiju strukturu troškova i organizacije usluge u odnosu na tradicionalne taksi prijevoznike.

Globalna iskustva pokazuju da su SAD i Kina trenutačno najnaprednija tržišta u razvoju i komercijalnoj primjeni robotaksija, dok Europa zaostaje ponajprije zbog regulatorne nesigurnosti i sporijeg donošenja strateških odluka. U SAD-u je najistaknutiji primjer kompanija Waymo, čiji su robotaksiji do kraja 2025. obavili više od 14 milijuna potpuno autonomnih vožnji, uz više od milijun vožnji mjesečno i postupno širenje na veći broj gradova. Prema analizi Boston Consulting Groupa (2026), do 2035. godine u velikim gradovima diljem svijeta moglo bi prometovati najmanje 700 tisuća, a u optimističnom scenariju i do 3 milijuna potpuno autonomnih robotaksija, pri čemu se očekuje da će se najbrže širenje odvijati upravo u SAD-u i Kini, dok će Europa kasniti zbog sporijeg prilagođavanja propisa.

5.2. Razvoj projekata robotaksija u Hrvatskoj i Gradu Zagrebu

Ključni nositelj razvoja robotaksi projekata u Hrvatskoj je grupa Rimac kroz tvrtku Project 3 Mobility, danas brend Verne, koja razvija integrirani ekosustav urbane autonomne mobilnosti. Verne obuhvaća autonomno električno vozilo razine 4 prema SAE standardu, digitalnu platformu za naručivanje vožnji te prateću infrastrukturu za upravljanje flotom, pri čemu je vozilo od početka koncipirano bez klasičnog upravljača i pedala, kao kompaktni dvosjed optimiran za autonomnu vožnju. Za percepciju okoline i planiranje vožnje koristi kombinaciju kamera, radara i lidara te napredne softverske sustave, dok je unutrašnjost dizajnirana tako da naglasak stavlja na iskustvo putnika: relativno prostran putnički prostor i mogućnost prilagodbe ambijenta (temperatura, rasvjeta, glazba) putem aplikacije (Verne, 2024).

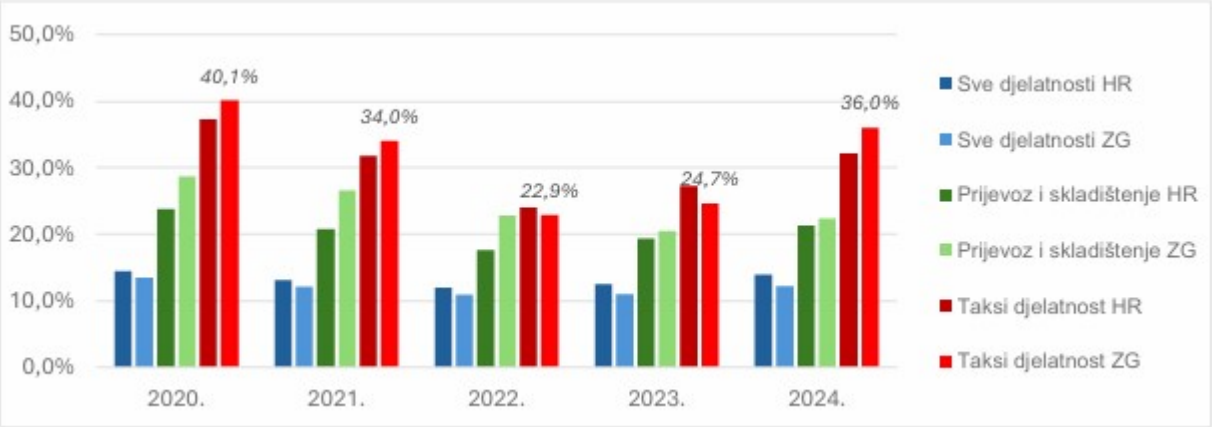
U svakom gradu u kojem će usluga biti dostupna predviđen je središnji Mothership centar za punjenje, čišćenje, pregled i servis vozila te operativni nadzor flote, dok se sama usluga organizira kao prijevoz na zahtjev putem mobilne aplikacije. Zagreb je odabran kao prvi grad u kojem bi Verne trebao započeti komercijalni rad, uz paralelnu izgradnju proizvodnog pogona i logističke infrastrukture, što ga čini relevantnim studijskim primjerom za analizu utjecaja autonomnog prijevoza na lokalno taksi tržište. U poslovnoj zoni Lučko gradi se namjenski proizvodni pogon za serijsku proizvodnju autonomnih električnih vozila, s planiranim početkom rada 2026. godine i početnim kapacitetom od nekoliko stotina vozila godišnje te mogućnošću postupnog povećanja. Sva vozila namijenjena domaćim i inozemnim gradovima trebala bi se proizvoditi u Hrvatskoj, što projektu daje dodatnu stratešku težinu za nacionalno gospodarstvo, a istodobno ubrzava suočavanje lokalnog taksi tržišta s posljedicama uvođenja autonomnog prijevoza (Verne, 2024).

5.3. Očekivani učinci autonomnog prijevoza na troškove rada i profitabilnost taksi sektora

U razdoblju 2020.-2024. udio troškova zaposlenika u poslovnim prihodima taksi djelatnosti u Gradu Zagrebu kreće se između približno 23 i 40%, pri čemu su osobito visoke vrijednosti zabilježene 2020. (40,1%) i 2024. godine (36,0%). Godine 2020. i 2021. obilježene su izvanrednim okolnostima pandemije bolesti Covid-19, uz snažan pad potražnje i

iskorištenosti kapaciteta, zbog čega njihove pokazatelje treba tumačiti s određenom rezervom. Unatoč tome, čak i u uobičajenim godinama nakon pandemije udjeli od 22,9% u 2022. i 24,7% u 2023. znatno su viši od prosjeka svih djelatnosti u Zagrebu i Hrvatskoj te iznad razina zabilježenih u široj djelatnosti prijevoza i skladištenja, što potvrđuje da je taksi djelatnost izrazito radno intenzivna. Usporedba s nacionalnim prosjekom taksi djelatnosti pokazuje da se Zagreb u pravilu kreće oko ili blago iznad nacionalnih vrijednosti, pa se dobiveni omjeri mogu smatrati reprezentativnima za sektor u cjelini.

Grafikon 4. Udio troškova zaposlenika u poslovnim prihodima - usporedba taksi djelatnosti, sektora prijevoza i skladištenja te svih djelatnosti u Hrvatskoj i Gradu Zagrebu, 2020.–2024.



Izvor: obrada autora prema Financijska agencija (2020-2024)

Kako bi se ilustrirala važnost troškova rada, izračunat je rezultat poslovanja uz pretpostavku da poduzetnici nemaju troškove zaposlenika. Važno je naglasiti da ovakav scenarij predstavlja pojednostavljenu analitičku simulaciju. Cilj simulacije nije procijeniti profitabilnost robotaksi modela, nego sagledati relativnu važnost troškova rada u postojećem poslovnom modelu taksi djelatnosti. U stvarnom scenariju prelaska na autonomni prijevoz troškovi rada ne bi u potpunosti nestali, nego bi se djelomično transformirali u druge oblike rada povezane s održavanjem vozila, upravljanjem flotom, nadzorom sustava i korisničkom podrškom. Istodobno bi došlo do povećanja kapitalne intenzivnosti poslovanja zbog visokih ulaganja u autonomna vozila, infrastrukturu, IT sustave i operativne centre. Stoga prikazani hipotetski rezultati ne predstavljaju procjenu profitabilnosti robotaksi modela, nego ilustrativnu procjenu utjecaja jedne ključne komponente troškova na postojeći poslovni model taksi djelatnosti.

Tablica 3. Pokazatelji profitabilnosti s uključenim i isključenim troškovima zaposlenika za taksi djelatnost, sektor prijevoza i skladištenja te sve djelatnosti u Gradu Zagrebu i Hrvatskoj

Pokazatelj uspješnosti	**Djelatnost**	**Zagreb**		**Hrvatska**	
		S troškovima osoblja	**Bez troškova osoblja**	**S troškovima osoblja**	**Bez troškova osoblja**
EBITDA marža	Sve djelatnosti	11,2%	22,5%	11,5%	24,3%
	Prijevoz i skladištenje	15,0%	36,9%	16,8%	36,3%
	Taksi djelatnost	1,5%	29,3%	4,1%	32,2%
Neto profitna marža	Sve djelatnosti	5,2%	16,6%	5,3%	18,1%
	Prijevoz i skladištenje	5,6%	27,5%	6,7%	26,2%

	Taksi djelatnost	-1,8%	26,0%	-1,0%	27,1%
ROA	Sve djelatnosti	3,7%	11,9%	4,1%	14,0%
	Prijevoz i skladištenje	2,3%	11,4%	4,0%	15,5%
	Taksi djelatnost	-3,1%	44,9%	-1,5%	41,6%

Izvor: obrada autora prema Financijska agencija (2022-2024)

Izračun 'bez troškova osoblja' prikazuje hipotetske vrijednosti EBITDA marže, neto profitne marže i ROA uz pretpostavku da poduzetnici nemaju troškove zaposlenika. Podaci se odnose na prosjek razdoblja 2022.-2024., a 2020. i 2021. su isključene zbog utjecaja Covid-19 pandemije. Analiza pokazatelja uspješnosti jasno potvrđuje da su troškovi rada ključni ograničavajući čimbenik profitabilnosti taksi djelatnosti. U promatranom razdoblju taksi sektor, uz uključene troškove zaposlenika, ostvaruje vrlo niske EBITDA marže (Zagreb 1,5%, Hrvatska 4,1%) te negativan povrat na aktivu (ROA od -3,1% u Zagrebu i -1,5% na razini države), dok su istovremeno prosječne marže svih djelatnosti i šireg sektora prijevoza i skladištenja višestruko više. Istodobno, neto profitne marže u taksi djelatnosti ostaju negativne i u Zagrebu (-1,8%) i na razini Hrvatske (-1,0%), za razliku od pozitivnih vrijednosti u svim djelatnostima i u sektoru prijevoza i skladištenja, što dodatno potvrđuje strukturalnu slabost klasičnog poslovnog modela.

Kada se iz računa isključe troškovi zaposlenika, slika se radikalno mijenja. Hipotetske EBITDA marže taksi djelatnosti rastu na oko 29-32%, neto profitne marže na približno 26-27%, a ROA doseže vrlo visoke vrijednosti od oko 45% u Zagrebu i 42% na nacionalnoj razini, čime taksi sektor premašuje profitabilnost prosjeka svih djelatnosti i šireg sektora prijevoza i skladištenja. Veličina jaza između stvarnih i hipotetskih pokazatelja znatno je veća u taksi djelatnosti nego u ostalim promatranim skupinama, što nedvosmisleno upućuje na to da su troškovi zaposlenika glavna stavka koja sektor 'gura' u zonu niske profitabilnosti ili gubitka.

Bitno je, međutim, istaknuti da se tako visoke hipotetske marže ne mogu mehanički preslikati na stvarne rezultate u scenariju prelaska s klasičnog taksi prijevoza na robotaksije. Uvođenje autonomnog prijevoza podrazumijeva znatno veći kapitalni intenzitet poslovanja, uključujući visoku nabavnu cijenu autonomnih vozila, ulaganja u punionice, IT infrastrukturu, nadzorne centre i specijaliziranu opremu, što dio ušteđenih troškova rada pretvara u trošak amortizacije i financiranja. Osim toga, ni u takvom modelu ne nestaje potreba za radom ljudi, jer su i dalje nužni zaposlenici za čišćenje i tehničko održavanje vozila, nadzor i upravljanje flotom i korisničku podršku. Stvarni učinak autonomnog prijevoza na profitabilnost stoga će ovisiti o ravnoteži između uštede na troškovima rada vozača i povećanih troškova kapitala, tehnologije i pratećih usluga, a ne samo o aritmetičkom uklanjanju jedne stavke iz računa dobiti i gubitka.

Prikazani rezultati upućuju na to da je sadašnji poslovni model taksi prijevoza u prosjeku teško održiv, budući da dugoročno ne uspijeva ostvariti razinu profitabilnosti koja bi osigurala stabilno poslovanje i razvoj sektora. Drugim riječima, čak i bez uvođenja autonomnog prijevoza, postojeći model suočen je s temeljnim ograničenjem - ne ispunjava osnovni postulat poslovanja da aktivnosti moraju generirati dostatan i održiv povrat na uložene resurse.

5.4. Šire implikacije uvođenja autonomnog prijevoza

U prethodnom poglavlju pokazano je da sadašnji poslovni model taksi djelatnosti u prosjeku ne ostvaruje profitabilnost koja bi osigurala dugoročnu održivost sektora, te da bi eliminacija ili snažno smanjenje troškova rada vozača bitno promijenila strukturu troškova i potencijalnu profitabilnost. Uvođenje autonomnog prijevoza stoga ne predstavlja samo tehnološku

inovaciju, nego potencijalno duboku strukturnu promjenu načina organizacije usluge, tržišta rada i regulacije taksi djelatnosti.

5.4.1. Učinci na tržište rada u taksi djelatnosti

Uvođenje autonomnih vozila u funkciji robotaksija izravno utječe na potražnju za radom klasičnih taksi vozača. U mjeri u kojoj se vožnje preusmjeravaju s vozila s vozačem na autonomna vozila, smanjuje se broj radnih mjesta koja su danas najvećim dijelom vezana uz relativno niskokvalificirani rad, s nižim plaćama i ograničenim mogućnostima napredovanja. Time se otvara pitanje koliko će postojećih taksista moći dugoročno zadržati svoj status samostalnih poduzetnika ili zaposlenih vozača u tradicionalnim tvrtkama, a koliko će ih biti prisiljeno napustiti djelatnost ili se prilagoditi novim ulogama.

Istodobno, autonomni prijevoz generira novu potražnju za drugačijim profilima radne snage. Umjesto velikog broja vozača, raste potreba za radnicima angažiranima na održavanju i čišćenju vozila, tehničarima za dijagnostiku i servis autonomnih sustava, IT stručnjacima za upravljanje flotom i razvojem softvera, kao i operaterima u nadzornim centrima koji prate vozila i interveniraju u izvanrednim situacijama. Posljedica je strukturni pomak u traženim kvalifikacijama - dio niskokvalificiranih radnih mjesta nestaje ili se smanjuje, dok raste važnost tehničkih i informatičkih znanja. U takvom okruženju rizik dugoročne nezaposlenosti najviše pogađa starije vozače i one s nižom razinom obrazovanja i vještina, što otvara pitanje potrebe za mjerama prekvalifikacije i aktivne politike tržišta rada.

5.4.2. Promjena organizacijskog modela usluge

U klasičnom modelu taksi prijevoza tržište karakterizira velik broj mikro i malih poduzetnika s jednim ili nekoliko vozila, često uz relativno slabu kapitaliziranost i ograničene mogućnosti ulaganja u novu tehnologiju. U 2024. godini od 1.157 poslovnih subjekata u taksi djelatnosti koji su poslovali u sustavu poreza na dobit nije bilo velikih poduzetnika, jedan je bio srednje veličine, šest malih, a preostalih 1.150 svrstava se u kategoriju mikropoduzeća. Na području Grada Zagreba djelovalo je 424 poslovna subjekta u taksi djelatnosti i svi su redom bili mikro poduzetnici. Uvođenje autonomnog prijevoza naginje prema suprotnom obrascu - centraliziranim flotama kojima upravljaju tehnološke platforme ili veći operateri s bitno višim kapitalnim zahtjevima po vozilu. Nabava autonomnih vozila, uspostava infrastrukturnih kapaciteta i razvoj potrebnih IT rješenja zahtijevaju znatno veći početni ulog od onoga koji je potreban za ulazak u klasičnu taksi djelatnost.

Takav pomak pogoduje ekonomiji razmjera i koncentraciji tržišta. Veći operateri mogu rasporediti fiksne troškove tehnologije, razvoja platforme i marketinških aktivnosti na veći broj vozila i vožnji, čime ostvaruju niži trošak po jedinici usluge od disperzirane mreže malih prijevoznika. Posljedica može biti smanjenje broja samostalnih taksi poduzetnika i jačanje uloge integriranih platformi koje istodobno upravljaju voznim parkom, cijenama i korisničkim sučeljem. Time se mijenja i pregovaračka moć pojedinih sudionika - u klasičnom modelu vozači i mali prijevoznici barem formalno nastupaju kao samostalni poduzetnici, dok u autonomnom modelu ključnu ulogu preuzimaju vlasnici flota i nositelji platformi. U takvom okruženju tradicionalni taksisti mogu ostati uključeni tek kao podizvođači u segmentima gdje je i dalje potreban ljudski rad (npr. usluge više dodane vrijednosti ili specifični oblici prijevoza), ali gube mogućnost samostalnog oblikovanja cijena i poslovne politike.

5.4.3. Regulatorni izazovi i preraspodjela rizika

Širenje autonomnog prijevoza otvara niz novih regulatornih pitanja koja nadilaze klasični okvir za licenciranje taksi prijevoznika. Potrebno je jasno definirati odgovornost u slučaju prometnih nesreća i drugih incidenata (proizvođač vozila, operater flote, pružatelj softverskog rješenja ili vlasnik infrastrukture). Istodobno, regulator mora osigurati da sigurnosni standardi za autonomna vozila budu barem usporedivi s postojećim standardima za vozila s vozačem, uz uvažavanje specifičnih rizika vezanih uz kibernetičku sigurnost i moguće zlouporabe sustava.

Drugo ključno pitanje odnosi se na uvjete pristupa tržištu i zaštitu konkurencije. S obzirom na visoke ulazne barijere i snažnu ulogu platformi, postoji rizik da nekoliko velikih operatera preuzme dominantan položaj na tržištu, što bi moglo dovesti do smanjenja konkurencije i dugoročno nepovoljnijih uvjeta za korisnike. Regulator stoga mora pronaći ravnotežu između poticanja inovacija i izbjegavanja prekomjerne koncentracije tržišne moći, primjerice kroz zahtjeve za transparentnost algoritama određivanja cijena, obveze nediskriminatornog pristupa infrastrukturi ili ograničavanje vertikalne integracije u pojedinim segmentima lanca vrijednosti.

6. ZAKLJUČAK

Analiza je pokazala da je taksi djelatnost u Gradu Zagrebu, ali i na razini Hrvatske, dugoročno opterećena visokim i rastućim troškovima rada, uz istodobno nisku i volatilnu razinu profitabilnosti. U razdoblju 2020.-2024. EBITDA marže i neto profitne marže taksi sektora u pravilu su niske ili negativne, dok je povrat na aktivu često ispod nule, što upućuje na to da postojeći poslovni model ne osigurava zadovoljavajući povrat na uložene resurse. Takva je situacija osobito izražena u Zagrebu, gdje je broj taksi vozila posljednjih godina snažno porastao nakon liberalizacije tržišta, uz istodobno jačanje konkurencije i pritisak na cijene.

Rezultati simulacije u kojoj se iz financijskih izvještaja isključuju troškovi zaposlenika pokazuju da bi u hipotetskom scenariju bez troškova rada vozača taksi djelatnost ostvarivala vrlo visoke razine profitabilnosti. U prosjeku razdoblja 2022.-2024. EBITDA marže i ROA u takvom scenariju višestruko premašuju prosjek svih djelatnosti i šireg sektora prijevoza i skladištenja, pri čemu je jaz između stvarnih i hipotetskih marži znatno veći u taksi djelatnosti nego u usporedivim skupinama. To upućuje da su troškovi zaposlenika ključni ograničavajući čimbenik profitabilnosti taksi sektora, dok se problem ne može svesti na opću neučinkovitost ili nedostatnu razinu prihoda.

Ipak, tako visoke hipotetske marže ne mogu se izravno preslikati na očekivane rezultate u scenariju prelaska na autonomni prijevoz. Uvođenje robotaksija podrazumijeva znatno veći kapitalni intenzitet poslovanja, uključujući visoka ulaganja u autonomna vozila, punionice, IT infrastrukturu i nadzorne centre, čime se dio uštede na troškovima rada pretvara u troškove amortizacije i financiranja. Osim toga, ni u autonomnom modelu ne nestaje potreba za radom ljudi, budući da su i dalje nužni zaposlenici za održavanje i čišćenje vozila, nadzor flote te korisničku podršku, pa stvarni učinak autonomnog prijevoza na profitabilnost ovisi o ravnoteži između smanjenih troškova rada i povećanih troškova kapitala, tehnologije i pratećih usluga, kao i o intenzitetu tržišne konkurencije.

Šire implikacije uvođenja autonomnog prijevoza protežu se na tržište rada, organizacijsku strukturu sektora i regulatorni okvir. Očekuje se smanjenje potražnje za klasičnim vozačkim radnim mjestima i rast potrebe za novim profilima zaposlenih u održavanju, IT-u i upravljanju flotom, uz rizik dugotrajnije nezaposlenosti za dio postojećih taksista i potrebu za programima prekvalifikacije. Istodobno, prelazak na kapitalno intenzivne, centralizirane flote pogoduje koncentraciji tržišta u rukama tehnoloških platformi i većih operatera, čime se mijenjaju odnosi tržišne moći i otvaraju nova regulatorna pitanja vezana uz sigurnost, odgovornost i zaštitu konkurencije.

Na temelju provedenog istraživanja može se zaključiti da je sadašnji, radno intenzivan model taksi djelatnosti u prosjeku teško održiv te da autonomni prijevoz otvara mogućnost značajnog poboljšanja troškovne učinkovitosti, ali uz cijenu povećanih kapitalnih zahtjeva i dubljih strukturnih promjena u sektoru. Za javne politike i regulatore ključan će izazov biti oblikovati okvir koji će omogućiti iskorištavanje potencijalnih učinkovitosti autonomnog prijevoza, a istodobno ublažiti negativne redistribucijske učinke na postojeće taksiste, potaknuti tržišnu konkurenciju i očuvati sigurnost korisnika.

Dobiveni rezultati potvrđuju polaznu hipotezu H1 da je visoki udio troškova rada vozača ključni uzrok niske profitabilnosti taksi djelatnosti u Gradu Zagrebu te da bi njihova

eliminacija ili značajno smanjenje znatno povećala profitabilnost sektora. Kvalitativna analiza dodatno ukazuje na to da uvođenje autonomnog prijevoza može promijeniti strukturu troškova i organizacijski okvir taksi djelatnosti, ali i otvoriti nova pitanja u pogledu tržišta rada, tržišne koncentracije i regulatornog okvira.

Ograničenje ovog istraživanja proizlazi iz činjenice da scenarijska analiza pretpostavlja eliminaciju troškova zaposlenika bez istodobnog modeliranja dodatnih kapitalnih i tehnoloških troškova povezanih s uvođenjem autonomnih vozila. U stvarnim uvjetima prelazak na robotaksi model doveo bi do značajnog povećanja kapitalne intenzivnosti poslovanja, što bi dio uštede na troškovima rada pretvorilo u troškove amortizacije i održavanja tehnološke infrastrukture, a vjerojatno i financiranja. Buduća istraživanja stoga bi trebala razviti detaljnije modele troškovne strukture autonomnog prijevoza.

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Preliminary Communication

LABOR COSTS AND PROFITABILITY IN THE TAXI INDUSTRY UNDER CONDITIONS OF AUTONOMOUS TRANSPORT

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ABSTRACT

This paper analyses the effects of introducing robotaxis into the taxi market, with a particular focus on labour costs and sector profitability. In Croatia, especially in urban areas such as Zagreb, taxi activity is characterised by high and rising labour costs that account for a significant share of total operating expenses. The sector is also marked by a large share of micro and small enterprises, which are the most vulnerable to cost increases and market shocks. Financial indicators point to structural weakness, reflected in very low EBITDA and net profit margins as well as weak returns, which raises questions about long-term sustainability. In this context, robotaxis represent an important technological shift because automation can substantially reduce or eliminate driver labour costs and thereby improve cost efficiency and profitability within new business models. At the same time, such development may further weaken the position of traditional taxi operators, especially smaller firms that lack the capacity to invest in new technology. The paper also conceptually discusses broader implications of robotaxis for urban service provision, labour markets, organisation of the service and market concentration. Overall, the introduction of robotaxis may significantly reshape the cost structure and profitability of taxi services, while actual outcomes will depend on implementation, regulation and the adaptation of existing market participants.

Key words: *autonomous transport, labor costs, profitability, robotaxi, taxi industry*

Review

TRAFFIC CONGESTION AS A FACTOR IN TOURIST DESTINATION MANAGEMENT

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ABSTRACT

Traffic congestion has become an increasingly significant challenge for tourist destination management due to its complex environmental, social, and economic implications. This paper aims to examine traffic as a multidimensional factor influencing the sustainability, attractiveness, and competitiveness of tourist destinations. The objective of the study is to analyze how traffic congestion affects environmental sustainability, visitor satisfaction, and economic performance within tourism destinations. The research is based on a comprehensive literature review encompassing transport studies, tourism management research, urban mobility theories, and empirical case studies. The findings indicate that inefficient transport infrastructure and unmanaged traffic congestion negatively affect destination attractiveness, reduce visitor satisfaction, and generate economic losses through increased travel time, pollution, and operational inefficiencies. Conversely, integrated traffic management, sustainable mobility planning, and the implementation of intelligent transportation systems contribute to improved accessibility, enhanced tourist experiences, and more resilient destination development. The study further highlights the importance of coordinated land-use planning, public transport development, and smart mobility solutions in mitigating congestion-related challenges. By synthesizing multidisciplinary research, this paper contributes to a deeper understanding of traffic congestion as a critical managerial dimension in tourism destination management and provides a conceptual foundation for future empirical research and evidence-based policy development aimed at sustainable tourism growth.

Key words: *traffic congestion, tourist destination management, sustainable mobility, visitor satisfaction, intelligent transportation systems.*

1. INTRODUCTION

Tourism destinations are increasingly challenge by traffic congestion. How does traffic congestion affect the environmental sustainability, visitor satisfaction, and economic outcomes of tourist destination management? This question is crucial to tourism research and management, as congestion has a wide-ranging influence in environmental, social, and economic fields. The paper seeks to review traffic congestion and its multidimensional impact on the overall success of a tourism destination.

Review deals with traffic as a multidimensional factor in tourist destination management. Since tourism depends heavily on transportation infrastructure and mobility, it comes to no surprise that transportation systems affect the attractiveness of tourism destinations. Jebrane (2020) and Gavurova et al. (2023) state the role of transport in supporting tourism. Traffic congestion leads to further degradation, lower visitor satisfaction, and inefficiency in economic gains. In fact, some studies highlight losses of $159 billion per year caused by traffic congestion in particular urban settings (Cheng, Pang et al., 2019). Thus, the recognition of traffic as a multidimensional factor is essential for the improvement of sustainable tourism destination management.

The main focus of this review is to evaluate and analyze the impact of traffic congestion on environmental sustainability, visitor satisfaction, and economic outcomes in tourist destination management. Additionally, the review evaluates the role of traffic congestion on the components of tourism and how traffic and tourism management can enhance sustainable destination development. The review further synthesizes findings from studies on the relationships between public transport, travel behavior, and traffic congestion in tourism destinations (Amézquita-López et al., 2021; Nguyen-Phuoc et al., 2020). The integrated review and analysis of tourism management, transport, urban, and environmental science literature highlight both current challenges and suggested solutions in traffic congestion of tourism.

Recent research addresses the effects of tourism traffic congestion on environmental, social, and economic factors. However, there are some gaps in the understanding of the impacts of congestion and tourism interactions on tourism destinations. Studies often address issues related to the relationship of tourism mobility and carrying capacity (Liu et al., 2022; Wang et al., 2020). Intelligent transportation systems (ITS) and smart city interventions are discussed (Ristama, 2023; Shafieea et al., 2023) as effective remedies; however, their applications and outcomes in tourism destinations may require further analysis. Further, researchers debate the associations between traffic congestion, visitor satisfaction, and economic outcomes (Nian et al., 2023; Moyano et al., 2021). This paper adresses the identified research gaps through synthezing literature that adresses the interrelationship between traffic congestion and various factors in tourism destination management.

The following chapters review these aspects, starting by introducing the theoretical framework of this research in which different topics of transport infrastructure and tourism destination attractiveness will be discussed. Then the multilevel system theory and traffic flow theory are presented. After that, traffic congestion will be viewed under the aspects of tourism experience, tourism attractiveness, and tourist satisfaction. The next chapter reviews smart tourism traffic management that supports the destination's sustainability through smart technology implementation and sustainable mobility policies. Finally, the findings and concluding remarks for future destination management and research suggestions are given.

2. THEORETICAL FRAMEWORK OF TRAFFIC AND TOURISM DESTINATION MANAGEMENT

The theoretical interrelation between transport infrastructure and tourism destination attractiveness underpins an effective traffic-tourism management system. A tourism destination can be defined as an amalgam of tourism products and services that collectively create the visitor experience (Buhalis, 2000). According to the World Tourism Organization, a tourism destination is a physical space where visitors spend at least one night and which contains tourism products, services and attractions (UNWTO, 2019). A tourism destination is generally understood as a physical space in which visitors spend at least one night and which contains tourism products, services, attractions and supporting resources within a specific geographical area (UNWTO, 2019). In tourism research, destinations are also interpreted as complex systems composed of multiple interconnected elements that together create the overall tourist experience (Buhalis, 2000). In this context, destinations represent integrated structures of attractions, tourism services, infrastructure and stakeholders whose interaction determines the competitiveness and attractiveness of a tourism area. From the perspective of destination management theory, a tourism destination represents a spatial unit of tourism supply that must possess sufficient elements of tourism offer, be oriented towards tourism demand and the needs of visitors, and function independently of administrative boundaries. Furthermore, destinations require coordinated management in order to ensure the effective development of tourism resources and services (Magaš, Vodeb and Zadel, 2018). Accessibility and transport infrastructure therefore represent important components of tourism destinations, as they enable tourist mobility and influence the overall attractiveness and competitiveness of destinations. Empirical evidence indicates a significant correlation

between transport infrastructure and the attraction level of tourist destinations. Studies have shown how an efficient infrastructure system, such as airports, highways, and railway stations, enhances the attractiveness level of tourist destinations. For example, in the case of Marrakesh, empirical research clearly demonstrates the relationship between transport infrastructure development and tourism destination attractiveness. Using time-series data for the period 2000-2018, Jebrane (2020) compared the evolution of tourist overnight stays with major transport indicators such as airport passenger traffic, highway traffic, and railway mobility. During this period, the number of overnight stays in Marrakesh increased from approximately 3.15 million in 2000 to more than 8 million by 2019, indicating a substantial growth in tourism activity. At the same time, passenger traffic at Marrakesh Menara Airport increased from around 1.4 million passengers to more than 3.2 million passengers annually, while the opening of the Casablanca - Marrakesh A7 motorway (2007) and the modernization of the Marrakesh railway station (2008) significantly improved accessibility to the destination. Statistical analysis showed a strong positive correlation between overnight stays and airport traffic (r=0.947) and a positive correlation between overnight stays and highway traffic (r=0.811). These results suggest that improvements in transport infrastructure directly contribute to tourism growth and destination competitiveness by facilitating mobility and increasing tourist flows. Accessibility to destinations is two-pronged and can be attained if there is the willingness to travel to the destination using the existing resources and time, and also if the mode of transport offers the required connectivity to move to the destination. If any of these elements is absent, travel remains a challenge. However, only a mere increase in transport infrastructure capacity is not sufficient to sustain a robust tourism system. If the growth in capacity is not matched to the expected growth of demand, infrastructural obsolescence leads to traffic congestions. Therefore, policymakers have the responsibility to adopt an integrated approach by incorporating environmental, social, and economic values in the development of transport infrastructures to not only alleviate existing traffic conditions but also sustain tourism growth in the future (Jebrane, 2020). In addition, transport infrastructure should be seen as a managerial tool in the destination management process. Therefore, ist implications should be holistically viewed and integrated in the tourism destination management decision-making process.

Figure 1. Traffic congestion as a structural constraint of tourism destination accessibility

Source: Authors' own illustration based on urban mobility and tourism transport literature

Adopting multilevel and dynamic systems theory to traffic-tourism management significantly provides the benefit of holistic destination management. The Multilevel Transport System (MST) system provides an analytical framework in traffic management within a tourism destination. For example, the implementation of MST in the urban mobility management in Gdynia, Poland, demonstrated its effectiveness in facilitating communication between policymakers and the wider society and provides detailed explanations as to why such transport policy interventions were required (Okraszewska et al., 2018). In the tourism

context, the levels of planning for MST are the levels of urban mobility planning for tourists in a specific area, destination planning that incorporate mobility planning for tourists, and the regional tourism planning by regions or states that are composed of mobility plans for tourists in each of the destinations. The System Dynamics (SD) methodology enables the development of models that show feedback interactions of various socioeconomic, environmental, and policy variables with the aim of understanding the causal effect of interventions such as congestion pricing or investments in public transport (Sedarati et al,, 2019). Also, System Dynamics models can be used to predict the outcomes and trade-offs of interventions using scenarios by taking into account multiple dynamic and complex systems with many feedback loops and relationships at different timescales (Shafieea et al., 2023). Thus, MST and SD underpin the development of Sustainable Urban Mobility Plans (SUMPs), which allow interventions to alleviate congestion within the tourism area whilst considering their impact on the larger community to lessen stress on the destination as a whole (Okraszewska et al., 2018). Adopting MST and SD as an intervention strategy allows decision makers to dynamically adapt transport policy options based on traveler preferences to improve destination adaptability over time. Also, MST and SD can allow for cross-sectoral coordination and interdependencies by eliminating compartmentalisation to better manage multiple sectors within the system with the aim of enhancing resilience.

Analyzing traffic patterns and urban mobility provides useful insights into enhancing tourist experiences. Studies using big data sources, such as GPS, mobile tracking data, and traffic flow detection data, have revealed significant correlations between mobility and tourist satisfaction. Mobility is a critical factor that can affect tourist satisfaction (Moya-Gómez et al., 2015). Also, the accessibility and attractiveness of tourists depend not only on periodical variations, such as weather and location-based attraction, but also on the actual traffic and mobility congestion around urban centres, especially during peak hours of tourist activities (Xu et al., 2020) For example, studies conducted in urban cities like Madrid showed that traffic congestion during peak traffic periods negatively affected accessibility to various tourist attractions, and these effects are relatively stronger than those of periodical variations (Moya-Gómez et al., 2015; Xu et al., 2020). Agent-based model simulations revealed that tourist agent decision-making strategies, such as route choice, traffic evasion strategies, and congestion avoidance, are the most determinant factors that affect congestion in the system. Policy intervention strategies designed to promote traffic-evasion strategies through real-time traffic information in route selection and congestion avoidance could reduce traffic by up to 70%, depending on the level of adoption. Thus, it can be seen that human behavior plays a significant role in congestion dynamics. Combining trajectory and network analyses identifies major areas of congestion not accounted for by network connectivity, and this shows that combining behavior with informational factors is useful in developing tourism mobility intervention strategies In this case, real-time traffic information helps facilitate destination efficiency and attract quality tourists who can pay for an optimal tourism experience, thus increasing the value of the destination as a whole (Amézquita-López et al., 2021).

Examining the empirical relationships between tourism land use and traffic systems is important in managing tourism mobility systems. The case study of Xiamen Island showed a linear relationship between the spatial distribution of tourism land and traffic flows during peak periods. However, changes in peak traffic patterns-delayed morning peaks and increased early evening peaks-illustrate the need for strategic adaptations in traffic intervention plans, taking into consideration the impact of these changes on the destination. Traffic flows around major tourist attractions surge during holidays, and this underscores the necessity of synchronizing land use and traffic flow intervention policies for optimal tourism development. It is also important to distinguish between the tourism and non-tourism period flow patterns, as these periods have significantly differing traffic dynamics (Gao et al., 2021). Strategic information campaigns and real-time traffic monitoring improve tourist mobility systems by allowing for dynamic and responsive policies. For example, (Xu et al., 2020) developed a real-time monitoring system that predicts traffic flows on roads and around

attractions within urban centres based on periodical tourism patterns to alert potential bottlenecks. Such real-time data systems allow intervention measures to be in place to tackle anticipated bottlenecks, which increases tourism efficiency (Xu et al., 2020) This information then enables policymakers to adopt efficient land use traffic flow intervention strategies to sustain tourism an its contribution to GDP without negatively affecting tourists experiences.

Examining the cost and security implications of tourism traffic demand is critical to building an effective management system. The economic costs of tourism traffic congestions lead to trillions of dollars in productivity loss due to extra travel time, unreliability, fuel consumption, and other societal impacts. Intelligent transportation systems (ITS), like the 511 Systems employed in the United States, represent smart travel technology systems that can achieve great economic, time, and environmental savings in transportation management. The US 511 system showed the effectiveness of technology in providing real-time traffic information. Thus, using ITS can significantly reduce inefficiencies in tourism mobility, thereby minimizing economic costs (Cheng et al., 2019). Traffic management strategies are an essential aspect of tourism development. Travel disruption affects social stability, security, and the economic competitiveness of any state (Thang and Thang-ThongAdhen, 2015). An effective management strategy must provide seamless tourist movement and ensure the security of tourists. Investments in infrastructure projects and systems offer benefits that extend beyond economics. A well-developed road system improves not only tourism mobility but also boosts the destination's brand image, reduces environmental problems, and promotes an attractive tourism atmosphere to potential visitors (Cheng et al., 2019). Combining industrial and security management frameworks enables new ways of prioritizing infrastructure investments and intervention strategies in managing tourism traffic and mobility within a destination.

To conclude, the theoretical aspect of traffic and tourism destination management offers relevant empirical explanations of the interrelation among infrastructure, systems theories, traffic patterns, land use, cost, and economic and security implications.

3. TRAFFFIC CONGESTION AND TOURIST EXPERIENCE

The tourist experience is significantly influenced by traffic congestion, which in turn affects visitor satisfaction and how appealing a destination is perceived to be. It is essential to understand the ways in which transportation problems affect accessibility, feelings of overcrowding, and general perceptions for the development of efficient management strategies. An exploration into the complex relationship existing between tourism success and traffic conditions is conducted in this section, with focus given to the significance of integrated planning within sustainable destination development's wider framework.

3.1. Impact on Destination Acttractiveness and Visitor Satisfaction

Transport infrastructure has a great influence on the attractiveness of the destination since the improvement of the infrastructure of highways, airports and railway stations creates great accessibility that increases the attractiveness of destinations, and thus more tourists will visit these destinations. An example of how improvements to transport infrastructure lead to greater tourism can be seen in the increase in overnight stays in Marrakesh as a consequence of investments in the transportation network (Jebrane, 2020). Therefore, it should be taken into consideration the fact that not only does the quality of the infrastructure in itself matter, but it should also be a forward-looking process. Thus, if there is a demand for visitors, the infrastructure should be able to cope with that demand. If this is not considered, the lack of infrastructure will cause visitor congestion and will, as a result, impact destination attractiveness negatively. In essence, infrastructure links centres and peripheries and has significant impacts on regional development and the geographical distribution of tourism. This ensures that more areas benefit from tourism flows and thus helps to relieve concentration pressure on top destinations. For instance, investments in high-speed trains and in airports increase regional connectivity and reduce the time spent travelling to visit

more peripheral sites. This improves the attractiveness of destinations and, as a result, increases regional connectivity in tourist sites. However, improvements to transport infrastructure need to be complemented by careful management of the destination to protect its environmental and cultural resources. If such investments lack care and strategy, they can lead to increased congestion and overcrowding.

North Macedonia provides a clear example that lack of quality roads and long journey times are significant challenges for increasing the level of destination attractiveness, since this restricts movement between destinations and contributes to congestion (Milenkovski et al., 2020). According to data, after the construction of highways that reduced travel times, the number of visitors in the destination increased, demonstrating that congestion and poorly constructed roads directly impact destination attractiveness. Poor road quality and longer journey times can become a barrier to travel because they cause congestion and decrease the value of the travel experience, thus diminishing the levels of attractiveness. On the other hand, destination attractiveness depends on the quality of the transport infrastructure because travellers want efficient and stress-free connections. Thus, destinations with inefficient transport will see fewer visitors coming to them.

Travel within the tourism destination is a part of the visitor experience, so destinations should avoid the occurrence of congestion as it is a strong determinant of travel satisfaction. For example, destinations that have poor transport links, high congestion, poorly designed transport terminals and expensive fares make for a more unpleasant experience. Congestion has little effect on visitor satisfaction in destinations with many attractions if the level of perceived crowding is low (Nian et al., 2023). But if congestion leads to extreme levels of perceived crowding, visitor satisfaction will decline. International level attractions can withstand some levels of congestion and still attract tourists. However, these attractions need to carefully monitor visitor flow and implement management techniques, such as pre-booking and timed tickets, to reduce crowding. Moreover, negative visitor reviews online due to high congestion may deter others from visiting, and as a result, the attractiveness of the destination will decrease over time.

Transport infrastructure and destination competitiveness cannot be enhanced without the coordination of the tourism, economic, environmental and traffic planning sectors. The change in development approach from scattered to integrated improves visitor experiences and the effect of spatial agglomeration (Chen et al., 2021). Thus, tourism and traffic flows tend to shift and balance so there will be fewer areas that are highly congested and more evenly dispersed tourists throughout the region, improving tourism attractiveness and promoting the sustainable development of the sector. Areas with higher levels of tourism infrastructure will generate multiple effects that make visitors feel that they can visit most sites quickly and simply; that will increase attractiveness, boost satisfaction and generate repeat visitors. If all destinations and regions are connected in this way, that enhances attractiveness and makes repeat visitation more likely. Coordinated regional tourism development leads to a network effect where those areas less popular become more attractive because they can be easily visited from well-developed zones. A dynamic management system improves the ability to adapt to external shocks such as pandemics or economic downturns, as well as enables effective visitor dispersal through congestion management practices. As a result, visitors will be more satisfied and the attraction levels in different regions will improve, as will the sustainability of the destination.

Visitor congestion causes frustration and lowers the likelihood that tourists will visit again. Thus, the community's reaction is important because their opinion is a factor of destination attractiveness (Kanwal et al., 2020). Therefore, the views and reactions of the community and tourism entrepreneurs are crucial to manage the flow of tourists. If the community agrees that the transport infrastructure benefits both them and the tourist sector, they will actively work to improve the visitor experience, generating greater attraction of the destination. If

visitors in tourist spots of a community cause disturbance or restrict people living or working in the area by increasing traffic congestion and disruption, this leads to negative attitudes toward tourism and, thus, can reduce the attractiveness of the destination.

If the tourist region experiences extreme congestion or the attractions are difficult to reach, then the attractiveness is affected because, in the first instance, the visitors tend to get less access to more destinations, and, in the latter case, they spend less time and money in the destinations. In fact, post-crisis transport patterns in the metropolitan area of Madrid were marked by increased congestion (Moyano et al., 2021; Gavurova et al., 2023). During peak visitor months, the attractiveness level of destinations became unequal and tourist traffic tended to become congested around the centres of tourist activity. It must be taken into account that the higher costs and time to connect with various destinations can lead to a less satisfying tourist experience. Thus, the implementation of integrated mobility management can improve this situation.

Large-scale events are of considerable significance in the urban tourism market. One such event, the Australian Formula 1 Grand Prix, shows the potential of major events in Melbourne to be negatively impacted by congestion, resulting in substantial economic costs (Fernando, 2021). The effects of congestion are the lack of movement to other zones and increases in accident risk for both tourists and local residents. Solutions must take into account traffic rerouting for cars and buses, as well as increased train frequency on both metropolitan and regional lines, to provide seamless, safe travel routes between different locations during and after these events. Effective solutions will improve the visitor experience and make the urban destination more attractive and sustainable to visitors and residents.

For destinations that are reliant on inbound international travel, the system bottleneck is more complex. Bottlenecks that arise within the airline-airport-destination system cause congestion and impact attractiveness negatively since it takes longer to reach the final destination (Papatheodorou, 2021). Congestion within an airline-airport-destination system tends to accumulate because there is poor flow, the lack of efficient handling of arriving visitors and the poor connection between the terminal and the rest of the city (last-mile connectivity). The main causes are inefficiencies in security procedures, a lack of handling capacity or low number of personnel resources for baggage and customs handling, and poor connections, like the lack of metro and trains. Therefore, for international destinations that need to be attractive to visitors, investments should be done on streamlining airport security and on last-mile connectivity so visitors feel at ease from arrival to the hotel or the attractions.

Moreover, traffic caused by congestion gives rise to several problems. The high volume of traffic also leads to an increase in congestion-related pollution, causing poor air quality. Higher air and noise pollution, as a result of traffic congestion, also reduced visitor numbers in the long term, especially in environmentally sensitive destinations (Nepal et al., 2019). Air pollution from congestion caused by vehicle traffic will impact the environment, reducing visitor numbers and, consequently, the attractiveness of the destinations.

Carrying capacity in tourism shows that destinations will encounter problems when they exceed their optimal numbers of tourists, which causes environmental harm and poor visitor satisfaction (Wang et al., 2020). Therefore, investments are needed to ensure the system can cope with the varying volume of tourists and that it can adapt, not collapse. Investment into increasing the size and scale of tourism infrastructure, especially transit, can accommodate fluctuating capacity loads within a system that is already constrained. Thus, an investment strategy for traffic infrastructure is more than just about accomodating congestion; it also allows the tourist sector to better whitstand capacity shoyks, ensuring that the sector is robust and sustainable.

Furthermore, not all elements are as essential when it comes to what determines tourists' destination choice: tourist security and cultural diversity seem to affect the satisfaction of travellers more than their choices. Other research showed that transport efficiency and price competitiveness seem to be more important than environmental concerns or natural scenery and wildlife (Khan et al., 2020). Lack of efficiency in local transport and highly priced fares influence the destination's attractiveness and, in turn, tourist experiences.

In conclusion, by developing and improving transport infrastructure in an appropriate manner, the attractiveness of destinations will increase, thus enabling visitors and local people to make the most of the zone in sustainable and long-term tourism.

4. TRAFFIC MANAGEMENT STRATEGIES FOR SUSTAINABLE TOURISM DEVELOPMENT

The application of intelligent transportation systems (ITS) is an effective approach to alleviating traffic congestion in tourism areas. An example of ITS application is the 511 Systems in the US, which provide traffic information in real time, and adaptive control of traffic signals, which are especially useful during peak tourism season. More than $4.7 billion are saved yearly due to decreased travel time and fossil fuel consumption thanks to 511 Systems across the US, demonstrating the ability of ITS to reduce costs significantly regardless of destination size. It must be noted, though, that ITS are beneficial only if proper care is taken to effectively implement and use the technology. Proactive planning, stakeholder involvement, and maintenance are necessary for the effective application of ITS for congestion management in tourism. Over-reliance on IST can also result in negative consequences such as dependency on technology and unequal application of resources, as areeas with low internet access have limited benefit from the implementation of ITS (Cheng et al., 2019).

Eco-smart cities offer a holistic approach to addressing both congestion and environmental concerns through the integration of smart technologies in urban tourism management. These eco-smart cities use digital platforms, IoT sensors, and big data to optimise traffic flow, reduce emissions, and provide multimodal mobility options (Asrifan et al., 2024). Such smartness features appeal to the increasingly environmentally conscious tourist population. Car-free zones, real-time routing and navigation, and dynamic pricing for buses are some of the features that support smart tourism mobility. The use of eco-smart technologies, which includes collaborative governance and community-based programmes, can increase social acceptance of sustainable tourism development plans. The limitation of eco-smart tourism mobility includes the risk of digital exclusion, for persons or communities with less accessibility to technology, as well as environmental concerns such as electronic waste, requiring smart tourism initiatives to adopt the circular economy to be more sustainable.

Sustainable and inclusive mobility solutions for peripheral tourism regions with low public transport access focus on eliminating last-mile connectivity challenges through integrated solutions which can connect with public transport. Electric bike and car rental systems are frequently included as part of these programmes to improve accessibility and reduce the ecological footprint of tourism. The Białowieża Forest in Poland implemented an intermodal mobility system to overcome this last-mile transport barrier by integrating rail with e-bike and e-car rentals to accommodate the lack of a local transport system. Innovative mobility services in peripheral tourism regions not only improve accessibility but also create jobs in rural communities. According to the survey results in (Szymańska et al., 2021)., 40% of respondents prefer this type of intermodal transport to traditional forms. However, these mobility solutions must be tailored to the local environment to accommodate seasonal changes as well as tourism activities in specific periods. If implemented in the wrong amount, innovative mobility solutions can lead to significant financial costs from over-provision or environmental damage from undersupply.

Mobile applications that provide real-time traffic data alert tourists to existing traffic congestion in a specific region and are useful for informing tourist mobility choices. For self-driving tourists, in the moment when they find out traffic will be worse than predicted at the site, they may consider other nearby points of interest or postpone the journey to the point of interest. Using Yatsugatake, Japan, as a case study, (Aoyagi et al. 2020) found that approximately 40% of all tourists changed their itinerary or added another stop because of the information from this application. This diversion of tourist demand through mobile traffic applications reduces traffic at peak times at popular sites, and it can divert traffic and stimulate economic benefits into other, less frequently visited areas of the region. With real-time information providing tourists with an enhanced sense of service quality, visitor satisfaction increases, which encourages repeat visitation. The effective application of such applications depends on the presence of sufficient digital literacy to ensure that individuals can navigate and use them effectively and that strong partnerships exist between local businesses and tourism authorities to encourage appropriate usage.

The introduction of public transport is a means to reduce congestion and improve mobility in tourist regions by increasing its service capacity and accessibility, though many congestion studies ignore the importance of such measures. More specifically, increasing the frequency of service, expanding network coverage, and improving reliability will significantly reduce the utilisation of private transport, encouraging tourists to use sustainable alternatives to travel more effectively in the tourism region (Nguyen-Phuoc et al., 2020). These approaches, which directly tackle traffic volume, and can reduce congestion significantly. As a result, policies can be introduced to promote the utilisation of public transport systems in a region by reducing costs and increasing convenience through the introduction of weekly or seasonal passes and integrated fare systems. By introducing a system with integrated transport options, which offers discounted rates for public transport for those who stay more than a day, many visitors may be incentivised to choose public transport over driving and can avoid paying fees to park. Although such approaches are essential, they do have limitations. The seasonality in transport in certain tourism regions, as well as certain festivals, holidays, or other big events which draw in large quantities of tourists, could overwhelm existing public transport networks in the region. This creates long queues, less reliable services, and overall discomfort for tourists. Additionally, these programmes need sufficient investment, resources, and proper collaboration of various public transport providers to make sure that the system operates effectively and can respond to the ever-changing needs of sustainable tourism.

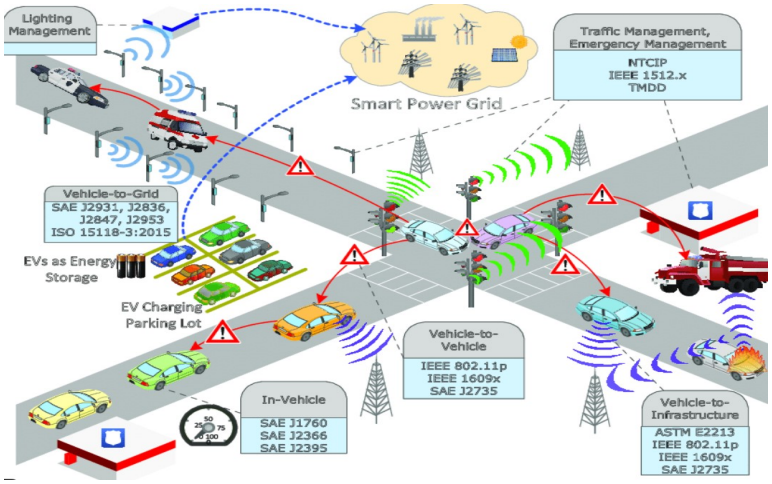
The introduction of green-slow mobility solutions, such as the Ikebus in Ikebukuro, are one alternative approach to solving transport-related problems in areas with dense tourist traffic. Green-slow mobility options can carry many people with minimal emissions and minimal environmental impact (Sano et al., 2024). The availability of several options offers a flexible, accessible, and inclusive mobility service for visitors of any type. Flexible scheduling and route planning ensure that these options can be dynamically tailored to the specific needs of the tourist destination, and the fare and payment mechanisms should be structured to ensure competitive rates while delivering value for the tourists using the transport solution. Integrating green-slow mobility into a broader transport network means that these solutions are not applied in isolation, improving their effectiveness in decreasing congestion and emissions. Ultimately, the effective implementation of green-slow mobility options must be tailored to the specific needs and expectations of tourists and the characteristics of each destination.

Transport and tourism services directly impact 15.76% of tourism’s economic output in China, which is an ideal country in which to study the economic impacts of transport. With the rising traffic volume in tourism areas, it could become detrimental to destination economic development. A continuous increase in tourism growth beyond its optimal range, therefore, may not continuously promote economic gains, and the rise of traffic pressure would decrease the quality of tourism. Thus, each incremental unit of input has lower

efficiency than the previous one. Additionally, the excessive costs imposed on the host destinations would not lead to increased attractiveness. Instead, congestion increases negative externalities of tourism development. The analysis suggests that dynamic control through pricing and capacity management can solve these transport issues. Furthermore, tourism transport should not be separated from the tourism regions; infrastructure investment and construction should not be ignored (Liu et al., 2022). This has the advantage of drawing demand to regions previously neglected. Moreover, evidence-based policy-making could be useful in tourism regions experiencing rapid growth and experiencingt raffic challenges.

The study of Lovina Beach, in Bali, Indonesia, is a valuable case study to explore these impacts on tourism regions with high tourist-generated congestion levels. High traffic volumes in particular periods cause congestion around some sites such as Lovina Beach. According to the V/C results obtained in this study, the routes frequently have a V/C value of 0.95 and above, resulting in low travel comfort. This can be a source of annoyance for many visitors because it limits the accessibility to various tourist attractions and therefore decreases the satisfaction of tourist travel (Ristama, 2023). It should also be emphasised that a congestion reduction strategy for tourism regions must be case-specific and based on sufficient and current data collection, rather than drawing on theoretical and pre-existing interventions. While these interventions offer a framework for the alleviation of tourism congestion, it is not an intervention that can be uniformly applied to every destination, for reasons such as cost, resources, and the practicality and acceptance of the intervention by the host region. It is also important that any future interventions are not only measured by their short-term performance but also their sustainability and ability to be adapted as a tourist destination changes and evolves.

Figure 2. Smart traffic management solutions supporting sustainable tourism mobility



Source: Authors' illustration based on smart mobility and intelligent transportation systems research (e. g. Ristama, 2023; Shafieea et al., 2023; Asrifan et al., 2024).

For tourist destinations to survive in the competitive tourism market, it is essential for the destination to be more sustainable compared to similar tourism regions and be more appealing than their competitors. Sustainability in tourism refers to a concept of balance that is not only about environmental conservation but also about balancing the requirements of environmental conservation with the requirements for improved economic development and social welfare, thus ensuring long-term success. Sustainable transport, for instance, can be more competitive for the destination for the very reason that it addresses issues in the destinations themselves. Multi-modal transport networks not only are more ecologically sensitive and friendly towards tourism regions but also are more efficient at allowing tourists to move in and around the tourist destination (Hall et al., 2025). Transport sustainability

enhances destination competitiveness via buses or train networks that provide acces to transport routes that are designed for the convenience of cyclists and pedestrians, linking them to a host of urban transport facilities.In conclusion, the advanced implementation of ITS traffic management strategies represents a significant shift in managing the movement of tourists in cities while taking into account the need for environmental sustainability and traffic safety. From smart system applications and mobile technology to integrated multi-modal transport solutions and green-slow mobility, effective tourist traffic management strategies must respond to the needs of tourism and transport system demand and supply-side management.

5. CONCLUSION

The objective of this paper was to analyze the relationship between traffic congestion and the various components of tourism destination management, considering environmental sustainability, visitor satisfaction, and economic outcomes. The objective was achieved through an extensive and thorough review of literature, including theoretical papers, case studies, and empirical articles. Therefore, traffic congestion has been proven to play a crucial role in enhancing or diminishing the competitiveness, resilience, and sustainability of destinations. Based on the results of the main analysis, efficient transport infrastructure improves the attractiveness and operability of tourist destinations. For example, efficient and well-organized airports and highways, as well as good connections between different areas within a destination, improve regional development by linking peripheral, rural, and less economically developed regions to urban or central regions. On the other hand, inappropriate and poorly managed transportation systems generate negative externalities, such as air and noise pollution, as well as reduced accessibility and operability of destinations. Moreover, the empirical studies show that congestion diminishes visitor satisfaction, decreases the number of repeat visits, and negatively impacts the overall reputation of destinations. All of these negative results adversely impact destination competitiveness in the long term. Since transport and traffic congestion are intertwined with tourism activity and also with land-use planning, they should all be connected and evaluated by public administrators during decision-making and policies. Real-time traffic control, better planning of tourist flow circulation in and across a destination, and the application of ITS will certainly improve the operation and reduce negative externalities in tourist destinations. By contrast, poor land-use planning will increase traffic congestion and hinder competitiveness.

Smart technologies implemented in tourist destinations greatly improve the efficiency of the transportation systems and the effectiveness of tourism operators and destination managers. They also lower operation and management costs, and are environmentally and financially more effective and sustainable. Intelligent Transportation Systems (ITS), for example, improve the operability of destinations. In general, intelligent systems are cost-effective, as they reduce costs and improve accessibility, leading to better productivity levels in destinations. ITS provide real-time traffic information, which may be crucial for visitors and service providers to organize trips and routes and thereby minimize congestion or delays and increase overall trip satisfaction. In addition, it generates substantial economic benefits and contributes to increased profitability in local economies through better productivity and accessibility. Although this study has contributed to the field of knowledge, there were several limitations: The lack of previous empirical studies and research on the topic, as well as the ever-changing advances in smart technology and mobility, may lead to potential limitations in understanding some aspects of traffic congestion management. Additionally, this research relies solely on literature from other authors, and the generalizability of the results may be limited due to the diversity of tourist destinations around the world and the unique social-cultural contexts in which they operate. Future research should focus on empirical studies on traffic congestion in tourist destinations in specific locations, utilizing new smart transport system technologies. These could offer in-depth information about the

effectiveness of smart mobility, digital, and intelligent mobility systems in sustainable and efficient transport. Other future research directions are to empirically evaluate how visitors perceive mobility in a tourist destination and its relation to their satisfaction or dissatisfaction levels, in order to formulate appropriate policies in sustainable transport systems within tourist destinations. Finally, another aspect of future research can be done on how the tourist carrying capacity may be correlated with the capacity of transport systems in a tourism destination in order to improve tourism destination development.

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Pregledni rad

PROMETNA ZAGUŠENOST KAO ČIMBENIK UPRAVLJANJA TURISTIČKOM DESTINACIJOM

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SAŽETAK

Prometna zagušenost postala je sve značajniji izazov u upravljanju turističkim destinacijama zbog svojih složenih okolišnih, društvenih i ekonomskih implikacija. Cilj ovoga rada jest ispitati promet kao višedimenzionalni čimbenik koji utječe na održivost, privlačnost i konkurentnost turističkih destinacija. Svrha istraživanja je analizirati kako prometna zagušenost utječe na okolišnu održivost, zadovoljstvo posjetitelja i gospodarsku uspješnost unutar turističkih destinacija. Istraživanje se temelji na opsežnom pregledu literature koji obuhvaća prometne studije, istraživanja iz područja upravljanja turizmom, teorije urbane mobilnosti i empirijske studije slučaja.Rezultati upućuju na to da neučinkovita prometna infrastruktura i nekontrolirana prometna zagušenost negativno utječu na privlačnost destinacije, smanjuju zadovoljstvo posjetitelja i uzrokuju gospodarske gubitke kroz produljeno vrijeme putovanja, onečišćenje i operativne neučinkovitosti. Suprotno tome, integrirano upravljanje prometom, planiranje održive mobilnosti i primjena inteligentnih transportnih sustava doprinose boljoj pristupačnosti, kvalitetnijem turističkom iskustvu i otpornijem razvoju destinacije. Istraživanje također naglašava važnost usklađenog prostornog planiranja, razvoja javnog prijevoza i pametnih rješenja mobilnosti u ublažavanju izazova povezanih s prometnom zagušenošću.Sintezom multidisciplinarnih istraživanja ovaj rad pridonosi dubljem razumijevanju prometne zagušenosti kao ključne upravljačke dimenzije u upravljanju turističkim destinacijama te pruža konceptualnu osnovu za buduća empirijska istraživanja i razvoj politika utemeljenih na dokazima, usmjerenih na održivi rast turizma.

Ključne riječi: *prometna zagušenost, upravljanje turističkom destinacijom, održiva mobilnost, zadovoljstvo posjetitelja, inteligentni transportni sustavi.*

Stručni rad

DISTRIBUCIJSKI KANALI U TURISTIČKOM UGOSTITELJSTVU U ERI DIGITALIZACIJE: TRANSFORMACIJA, TRENDOVI I KONKURENTSKE PRILIKE

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SAŽETAK

Svrha rada jest analizirati transformaciju distribucijskih kanala u turističkom ugostiteljstvu pod utjecajem digitalizacije, s posebnim naglaskom na odnos između tradicionalnih posrednika, globalnih distribucijskih sustava, online putničkih agencija i izravnih digitalnih kanala prodaje. Metodološki, rad kombinira pregled recentne i klasične literature s kvalitativnim empirijskim istraživanjem provedenim putem polustrukturiranih fokus intervjua sa 17 sudionika iz hotela, turističkih agencija i turoperatora. Analiza pokazuje da digitalizacija skraćuje distribucijske kanale, povećava brzinu razmjene informacija i omogućuje preciznije upravljanje cijenama, raspoloživošću i odnosima s gostima, ali istodobno povećava ovisnost o digitalnim platformama i složenost višekanalnog upravljanja. Rezultati dodatno upućuju na to da se konkurentnost turističko-ugostiteljskih subjekata sve više temelji na uravnoteženju izravne prodaje i suradnje s posrednicima, integraciji komplementarnih usluga te primjeni analitike i automatizacije. Doprinos rada očituje se u povezivanju teorijskih postavki distribucije s empirijskim uvidima dionika tržišta te u sistematizaciji suvremenih trendova relevantnih za logistiku usluge i upravljanje turističkom ponudom.

Ključne riječi: *digitalizacija; distribucijski kanali; e-distribucija; online rezervacije; turističko ugostiteljstvo*

1. UVOD

Turističko ugostiteljstvo obilježeno je posebnim tržišnim i logističkim značajkama koje ga razlikuju od većine drugih djelatnosti, osobito u području distribucije. Nematerijalna priroda usluga, prostorna vezanost ponude te nemogućnost fizičkog prijenosa ključnih elemenata turističkog proizvoda zahtijevaju specifične distribucijske modele i posredničke odnose. Razvoj informacijsko-komunikacijskih tehnologija, osobito Interneta, dodatno je transformirao načine povezivanja ponude i potražnje, skraćujući distribucijske kanale i jačajući ulogu elektroničkih sustava rezervacija.

U teorijskom smislu, distribucija u turističkom ugostiteljstvu ne obuhvaća samo fizički tok pomoćnih inputa prema objektu nego i organizaciju susreta između gosta i usluge, pri čemu posrednici imaju važnu ulogu u informiranju, rezerviranju i prodaji usluga. U praksi su se tradicionalni oblici posredovanja – turističke agencije, turoperatori i hotelski predstavnici – postupno nadopunili ili transformirali kroz online putničke agencije, rezervacijske servise i globalne distribucijske sustave.

Polazeći od navedenoga, u radu se postavljaju tri radne hipoteze: H1 - digitalizacija skraćuje distribucijske kanale i povećava učinkovitost upravljanja turističko-ugostiteljskom ponudom; H2 - unatoč jačanju izravne online prodaje, digitalni posrednici zadržavaju ključnu ulogu u dosegu tržišta i popunjenosti kapaciteta; H3 - integracija podataka, analitike i komplementarnih usluga povećava konkurentnost subjekata u turističkom ugostiteljstvu.

Cilj rada je analizirati strukturu i transformaciju distribucijskih kanala u turističkom ugostiteljstvu, objasniti ulogu ključnih tradicionalnih i digitalnih posrednika te empirijski ispitati percepcije dionika o koristi i rizicima e-distribucije. Nakon uvoda slijedi prikaz metodologije istraživanja, zatim teorijska i empirijska analiza distribucijskih kanala te rezultati i rasprava, a na kraju se iznose zaključna razmatranja, ograničenja i smjernice za buduća istraživanja.

2. METODOLOGIJA ISTRAŽIVANJA

Rad se temelji na kombinaciji kvalitativnog pristupa i pregleda relevantne literature. Teorijski dio obuhvaća analizu klasičnih i suvremenih izvora o distribuciji u turizmu, e-distribuciji, globalnim distribucijskim sustavima i online putničkim agencijama, dok se empirijski dio zasniva na polustrukturiranim fokus intervjuima.

Terensko istraživanje provedeno je sa 17 sudionika iz područja turističke distribucije, uključujući predstavnike hotela, turističkih agencija i turoperatora. Uzorak je bio namjeran, a kriterij uključivanja odnosio se na iskustvo ispitanika u radu s digitalnim distribucijskim kanalima. Intervjui su trajali približno 20 minuta i analizirani su postupkom tematske analize, s ciljem izdvajanja dominantnih obrazaca, ponavljajućih tema i praktičnih implikacija za upravljanje kanalima prodaje.

Istraživački instrument obuhvatio je pitanja o najvažnijim distribucijskim kanalima, promjenama udjela direktnih rezervacija, utjecaju digitalnih platformi na prodaju, izazovima usklađivanja cijena i raspoloživosti, odnosu koristi i provizija posrednika te očekivanjima u iduće dvije godine. Ovakav pristup omogućio je povezivanje teorijskih pretpostavki s iskustvima sudionika tržišta.

Ograničenje istraživanja proizlazi iz veličine i strukture uzorka te kvalitativne naravi podataka, zbog čega rezultate nije moguće bez zadrške generalizirati na cjelokupni sektor. Ipak, dobiveni nalazi pružaju vrijedan uvid u aktualne trendove, operativne izazove i razvojne smjerove e-distribucije u turističkom ugostiteljstvu.

3. EMPIRIJSKA I TEORIJSKA PODLOGA DISTRIBUCIJSKIH KANALA U TURISTIČKOM UGOSTITELJSTVU

U ugostiteljstvu marketinški posrednici povezuju ponuđače usluga s tržištem, odnosno s drugim posrednicima i krajnjim korisnicima, olakšavajući plasman i prodaju kapaciteta te komunikaciju s gostima (Rantisi et al., 2025). Najčešće vrste posrednika su turističke agencije, turoperatori, specijalizirani posrednici, hotelski predstavnici, državne, regionalne i lokalne turističke zajednice te rezervacijski sustavi na Internetu (Kotler et al., 2003).

Turističke agencije čine poveznicu između tržišne ponude i potražnje. Vukonić (1997) ih definira kao gospodarske subjekte čiji se osnovni zadatak sastoji od organiziranja i prodaje putovanja i boravka te pružanja drugih usluga putnicima i sudionicima turističkog prometa. Prema karakteru poslovanja razlikuju se receptivne i emitivne agencije, pri čemu prve dovoze turiste u receptivna područja i organiziraju njihov boravak, a druge potiču domaće turiste na putovanja u inozemstvo ili unutar vlastite zemlje, uglavnom kao posrednici u pribavljanju usluga (Marin-Pantelescu et al., 2019).

Turoperatori na turističkom tržištu nastupaju kao svojevrsni 'trgovci na veliko', s naglašenom organizatorskom funkcijom. Njihov predmet poslovanja jesu turistički aranžmani, odnosno organiziranje, prodaja i izvršenje paket-aranžmana (George, 2025). Za razliku od agencija, turoperatori kupuju usluge u vlastito ime i za vlastiti račun, kreiraju vlastiti proizvod i preuzimaju rizik za neprodane kapacitete, dok turističke agencije pretežito ostvaruju prihod kroz proviziju i imaju izravniji kontakt s krajnjim klijentima.

Tablica 1. Osnovne razlike između turoperatora i turističkih agencija

TUROPERATOR	TURISTIČKA AGENCIJA
trgovac na veliko poduzetnik i posrednik kupuje usluge u vlastito ime i za vlastiti račun kreira vlastiti proizvod osnovni izvor prihoda: prodaja vlastitih proizvoda snosi rizik za neprodane kapacitete u pravilu nema izravni kontakt s klijentima prodaju svojih proizvoda vrši najčešće koristeći posrednike lokacija nije presudna za uspješno poslovanje glavna funkcija: organizatorska ima specifičnu informativno-savjetodavnu funkciju promocijska funkcija vrlo važna	trgovac na malo posrednik prodaje usluge u svoje ime, ali za tuđi račun plasira na tržištu tuđe proizvode osnovni izvor prihoda: provizija ne snosi rizik za neprodane kapacitete ima izravni kontakt s klijentima vrši izravnu prodaju usluga klijentima lokacija je vrlo bitna za uspjeh poslovanja glavna funkcija: posrednička prevladava opće-informativna funkcija vrlo izražena komercijalno-propagandna funkcija

Izvor: Pirjevec (1998)

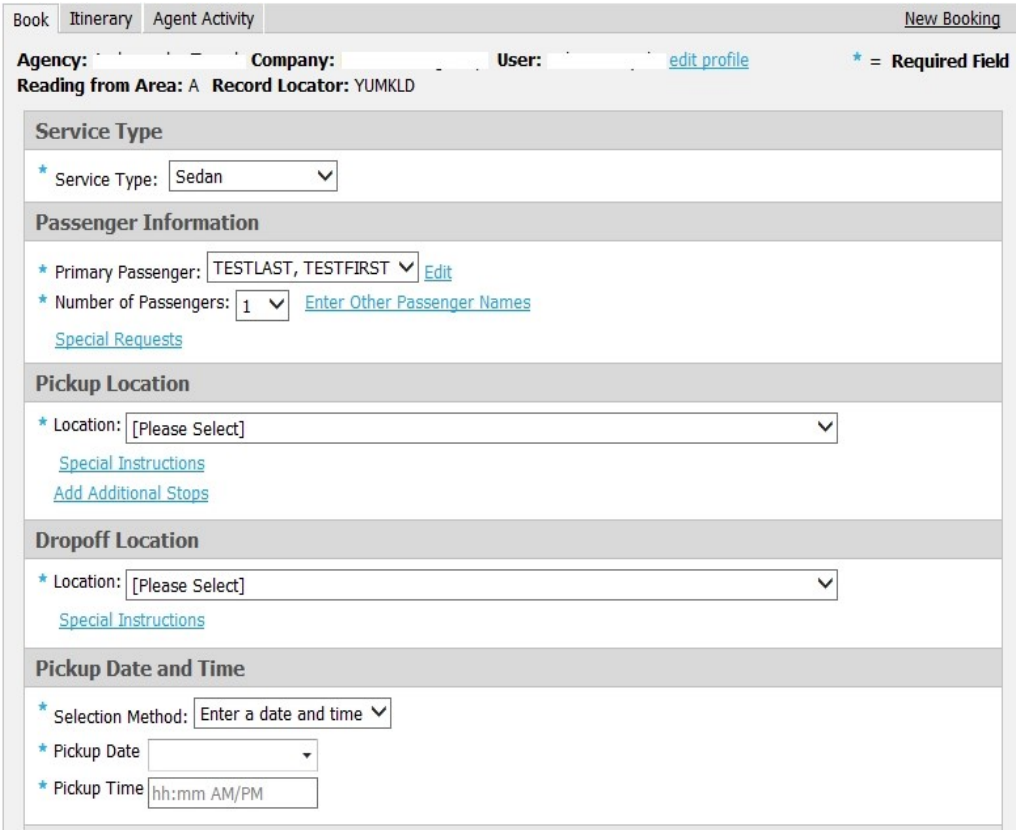
Specijalizirani posrednici predstavljaju turoperatore usmjerene na uži broj tržišnih segmenata, dok hotelski predstavnici prodaju smještajne i druge hotelske usluge na određenom tržišnom području. Državne, regionalne i lokalne turističke zajednice također imaju važnu ulogu u generiranju turističke ponude i potražnje te u promociji destinacije (Fuchs et al., 2025).

Posebno važan oblik suvremenog posredovanja predstavljaju rezervacijski sustavi na Internetu. Internet je u turističkoj industriji postao komunikacijski, transakcijski i distribucijski kanal, a zbog ovisnosti o informacijama i koordinaciji u proizvodnom i distribucijskom lancu turističko ugostiteljstvo pokazalo se vrlo pogodnim za brzo usvajanje informatičkih tehnologija i interaktivnih medija (Özdemir i Türker, 2023). Web-sjedišta i digitalne platforme omogućuju pružanje pisanih, audio i video informacija te čine turističko-ugostiteljski proizvod 'opipljivijim', dok gostima osiguravaju stalnu, brzu i jeftinu komunikaciju s ponuđačima.

E-distribucija označava skup međusobno povezanih organizacija koje sudjeluju u stavljanju proizvoda i usluga na raspolaganje kupcima uz potporu informatičkih tehnologija, osobito Interneta (Leung, 2022). Njezine glavne koristi uključuju smanjenje troškova rada i unosa podataka, brži prijenos informacija, višu kvalitetu podataka, bolje poslovne procese i normizaciju operacija u kanalima distribucije (Raghunathan i Yeh, 2001). U turističkom ugostiteljstvu moguće su dvije osnovne mogućnosti e-distribucije: direktna distribucija preko vlastitog web-sjedišta te distribucija putem e-posrednika (Ibrahim et al., 2022).

Razvoj rezervacijskih sustava na Internetu nadovezao se na ranije zatvorene rezervacijske sustave za zrakoplovne karte i međunarodne hotelske lance. U suvremenom okruženju posebno se ističu globalni distribucijski sustavi Amadeus, Sabre i Travelport, koji omogućuju rezervaciju i kupnju aviokarata, hotelskog smještaja, rent-a-cara i drugih putničkih usluga te i dalje imaju snažnu ulogu u poslovnim putovanjima i profesionalnom posredovanju (Pan, 2025; Yadav, 2025).

Slika 1. Sabre globalni distribucijski sustav



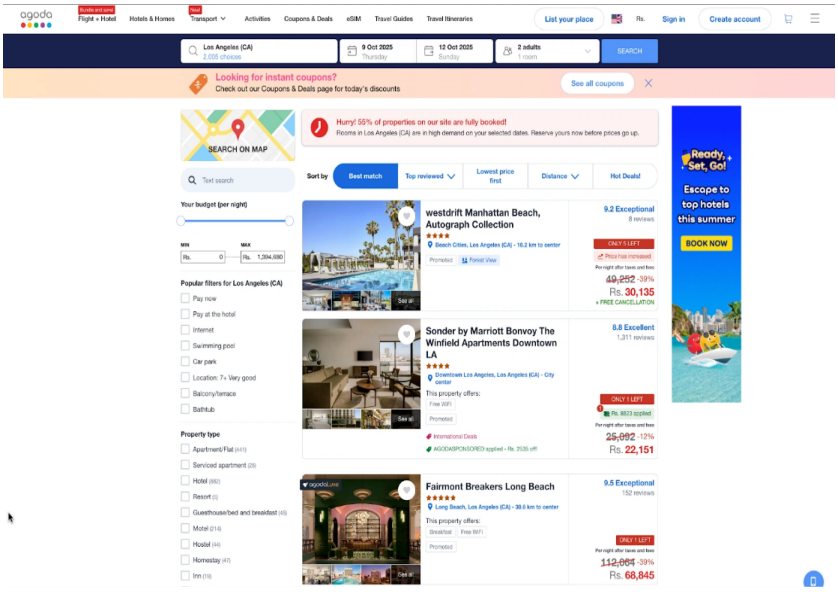
Izvor: autori

Uz GDS sustave, suvremenu distribuciju obilježava snažan rast online putničkih agencija (OTA) kao što su Booking.com, Expedia Group, Airbnb i Trip.com, koje krajnjim korisnicima omogućuju usporedbu cijena, dostupnosti i uvjeta usluga u stvarnom vremenu. Ove platforme nude napredne alate za filtriranje ponude prema cijeni, lokaciji, duljini boravka i preferencijama korisnika, dok se uloga klasičnih agencija zadržava pretežito u segmentu složenijih i korporativnih putovanja.

Suvremeni internetski rezervacijski servisi predstavljaju jedan od ključnih stupova e-distribucije u turističkom ugostiteljstvu. Platforme u vlasništvu Expedia Group i Booking Holdings dominiraju tržištem online rezervacija, dok su servisi poput TripAdvisora snažno utjecali na proces informiranja, formiranja reputacije i usmjeravanja potražnje. Pored univerzalnih OTA platformi razvijeni su i brojni specijalizirani servisi usmjereni na hostel smještaj, privatni smještaj, rent-a-car, kružna putovanja, željeznički prijevoz i putno osiguranje (Ndhlovu et al., 2024; Weerasinghe, 2025).

Novi trendovi uključuju razvoj platformi temeljenih na ekonomiji dijeljenja, mobilnim aplikacijama, personalizaciji ponude, analitici podataka i umjetnoj inteligenciji. U uvjetima globalizacije i snažnih tržišnih promjena sve više dolazi do povezivanja distribucije s opskrbnim lancem, pri čemu Internet omogućuje zajedničke komunikacijske protokole, razmjenu podataka i funkcionalnu povezanost sustava. Takvi poslovni modeli otvaraju prostor za učinkovitije upravljanje turističkim uslugama i stvaranje konkurentske prednosti (Balouei Jamkhaneh et al., 2023; Qiu et al., 2025).

Slika 2. Agoda rezervacijski sustav



Izvor: autori

4. REZULTATI I RASPRAVA

Nalazi fokus intervjua potvrđuju da se distribucija turističko-ugostiteljskih usluga posljednjih godina ubrzano premješta u digitalno okruženje. Sudionici istraživanja kao ključne prednosti digitalnih kanala navode međunarodnu vidljivost, jednostavniju usporedbu ponude, bržu reakciju na promjene potražnje i višu razinu operativne fleksibilnosti. Digitalne platforme pritom nisu percipirane samo kao prodajni kanali, nego i kao akteri koji oblikuju tržišna pravila kroz strukturu provizija, kriterije vidljivosti i sustav ocjena i recenzija.

Ispitanici ističu postojanje dvostruke strategije upravljanja kanalima prodaje. S jedne strane, subjekti nastoje jačati izravnu prodaju putem vlastitih mrežnih stranica i izravne komunikacije s gostima, ponajprije radi smanjenja troškova posredovanja i boljeg upravljanja odnosom s kupcem. S druge strane, odustajanje od posredničkih platformi rijetko se smatra realnom opcijom, osobito pri ulasku na nova tržišta ili u razdobljima slabije potražnje. To upućuje na potrebu strateškog uravnoteženja izravnih i posredovanih kanala.

Jedan od najuočljivijih problema jest operativna složenost višekanalne prodaje. Usklađivanje cijena, raspoloživosti i prodajnih uvjeta po kanalima zahtijeva visoku razinu ažurnosti i standardizacije, a pogreške u sinkronizaciji stvaraju rizik preklapanja rezervacija, nezadovoljstva gostiju i dodatnih troškova. U tom smislu sudionici naglašavaju važnost integriranih digitalnih rješenja, automatizacije i jasnih procedura upravljanja kanalima.

Ispitanici također ukazuju na promjenu u ulozi klasičnih posrednika. Turističke agencije i turoperatori i dalje imaju važnu funkciju u segmentima grupnih, složenijih i korporativnih putovanja, ali u individualnom segmentu prevladava digitalno posredovanje. Vrijednost posrednika sve se više procjenjuje kroz konkretan doprinos popunjenosti, dosegu tržišta, kvaliteti informacija i digitalnoj vidljivosti, a ne samo kroz tradicionalnu prodajnu funkciju.

Posebno je naglašena važnost integracije cjelovitih i djelomičnih usluga radi stvaranja sinergijskih učinaka. Sudionici navode da tržište sve više preferira 'jedno mjesto kupnje', zbog čega raste važnost povezivanja smještaja s prijevozom, dodatnim sadržajima i lokalnim iskustvima. Takvo povezivanje povećava dodanu vrijednost ponude i smanjuje osjetljivost na cjenovnu konkurenciju, ali istodobno zahtijeva standardiziranu razmjenu podataka i pouzdanu koordinaciju među partnerima.

Dobiveni nalazi u cjelini podupiru postavljene hipoteze. H1 je potvrđena jer sugovornici jasno povezuju digitalizaciju s većom učinkovitošću i bržim upravljanjem distribucijom. H2 je

također potvrđena budući da digitalni posrednici, unatoč rastu izravnih rezervacija, ostaju presudni za tržišni doseg i popunjenost kapaciteta. H3 je poduprta kroz naglašavanje važnosti analitike, automatizacije i integracije komplementarnih usluga kao izvora konkurentnosti.

5. ZAKLJUČAK

Distribucija u turističkom ugostiteljstvu predstavlja složen i dinamičan sustav koji se, zbog specifičnosti turističkih usluga, bitno razlikuje od klasičnih distribucijskih modela. Razvoj informacijsko-komunikacijskih tehnologija i Interneta doveo je do snažne transformacije distribucijskih kanala, pri čemu e-distribucija postaje ključni mehanizam povezivanja ponude i potražnje.

Provedena analiza pokazala je da digitalizacija istodobno potiče razvoj izravne online prodaje i jačanje digitalnih posrednika, osobito OTA platformi i globalnih distribucijskih sustava. Stoga konkurentnost turističko-ugostiteljskih subjekata sve više ovisi o sposobnosti uravnoteženja vlastitih kanala prodaje s posredničkim platformama, kvaliteti informacija, upravljanju reputacijom te brzini prilagodbe promjenama na tržištu.

Zaključno, potvrđene su radne hipoteze o skraćivanju distribucijskih kanala, trajnoj važnosti digitalnih posrednika i rastućem značenju integracije podataka, analitike i komplementarnih usluga. Ograničenja rada odnose se na veličinu kvalitativnog uzorka i usmjerenost na percepcije dionika, pa bi buduća istraživanja trebala uključiti veći broj ispitanika, kvantitativne pokazatelje prodaje po kanalima te usporedbe među različitim tipovima smještajnih objekata i emitivnim tržištima.

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Professional paper

DISTRIBUTION CHANNELS IN HOSPITALITY TOURISM IN THE DIGITAL ERA: TRANSFORMATION, TRENDS AND COMPETITIVE OPPORTUNITIES

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ABSTRACT

The purpose of this paper is to analyse the transformation of distribution channels in hospitality tourism under the influence of digitalisation, with a particular focus on the relationship between traditional intermediaries, global distribution systems, online travel agencies and direct digital sales channels. The paper combines a review of relevant classic and recent literature with a qualitative empirical study based on semi-structured focus interviews conducted with 17 participants from hotels, travel agencies and tour operators. The findings indicate that digitalisation shortens distribution channels, accelerates information exchange and improves the management of prices, availability and customer relations, while at the same time increasing dependence on digital platforms and the complexity of multichannel management. The results also show that the competitiveness of hospitality businesses increasingly depends on balancing direct sales and intermediary platforms, integrating complementary services, and using analytics and automation. The paper contributes by linking theoretical perspectives on tourism distribution with empirical insights from market stakeholders and by systematising current trends relevant to service logistics and hospitality management.

Key words: *digitalisation; distribution channels; e-distribution; online booking; hospitality tourism*

Original Scientific Paper

EXPLORING OPERATIONAL FRICTION IN LOGISTICS SYSTEMS: THE IMPACT OF SUPPLY CHAIN DISRUPTIONS AND WEATHER SEVERITY

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ABSTRACT

This study examines how supply chain disruptions affect logistics performance through accumulated operational friction and tests whether weather condition severity changes that relationship. Using a cross-sectional survey of 394 logistics and supply chain professionals across Europe, Asia, and North America, the study applies descriptive statistics, exploratory factor analysis, reliability testing, OLS regression, mediation analysis, moderation analysis, and bootstrap-based conditional process testing. The results show that supply chain risk is positively associated with operational friction and that operational friction is significantly associated with logistics performance. Bootstrap results also support a significant indirect effect of supply chain risk on logistics performance through operational friction, indicating partial mediation. By contrast, the moderating effect of weather condition severity is positive but not statistically significant in the full model. The study contributes by positioning operational friction as a managerially useful and empirically grounded lens for diagnosing how disruption-related inefficiencies accumulate inside logistics systems.

Key words: *Operational Friction, Supply Chain Disruptions, Logistics Performance, Weather Condition Severity, Logistics Resilience, Operational Challenges.*

1. INTRODUCTION

1.1 Problem Background

Global logistics systems operate under frequent disruption, including demand volatility, transport interruptions, infrastructure failures, and environmental shocks. Their performance losses rarely stem from a single event. More often, disruption exposure produces coordination strain, capacity shortages, and process bottlenecks that accumulate and degrade reliability, timeliness, and cost performance. This study treats that accumulated

resistance as operational friction and examines whether it helps explain how supply chain risk translates into logistics performance outcomes.

1.2 Problem Statement

Although prior studies link supply chain risk to logistics performance, many treat that relationship as direct and focus on isolated indicators such as delays, shortages, or cost variance. This leaves less clarity about the internal operational mechanism through which disruption exposure becomes day-to-day performance degradation. The present study addresses that gap by examining operational friction as an intervening construct and by testing weather condition severity as a contextual factor, while keeping the analysis explicitly exploratory rather than causal.

1.3 Practical Importance

For managers, disruption appears as daily operational strain: delayed handoffs, re-planning, congestion, weak visibility, and missed connections. A friction perspective is useful because it focuses attention on how small inefficiencies accumulate across logistics processes instead of treating each symptom as a separate problem. That perspective can support diagnosis and prioritization when firms must respond quickly under uncertainty.

1.4 Research Gap, Objectives, and Research Questions

This study addresses a practical and theoretical gap in explaining how multiple operational inefficiencies accumulate inside disruption-affected logistics systems. It asks three questions: how supply chain risk contributes to operational friction, how operational friction relates to logistics performance, and whether weather condition severity changes that relationship. The objective is to provide an initial empirical assessment of operational friction as a system-level lens for understanding disruption propagation in logistics.

1.5 Scope and Boundaries

The study focuses on short-term logistics execution in disruption-affected contexts such as freight forwarding, warehousing, and shipping. The unit of analysis is operational process and firm-level execution rather than long-horizon network redesign or public policy. Within this scope, operational friction refers to the accumulated resistance created when coordination, capacity, and process constraints interact and reduce efficiency and reliability.

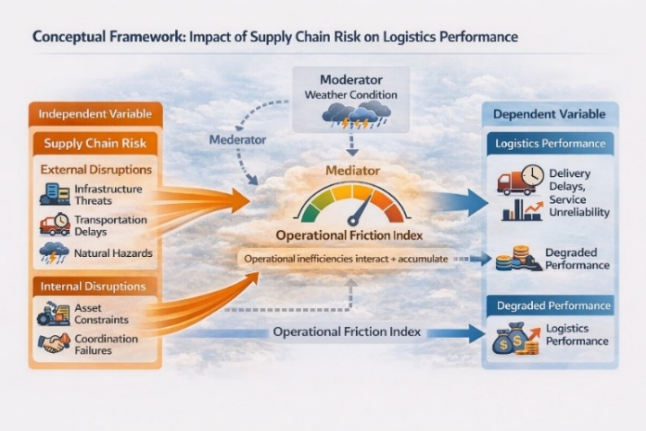
1.6 Contribution of the Study

The paper contributes by introducing operational friction as a concise explanatory lens for how supply chain risk becomes visible as logistics performance degradation. It also offers early empirical evidence that can support resilience-oriented diagnosis in logistics settings, while treating weather severity as an important contextual pressure rather than a statistically confirmed moderator in the present dataset.

2. LITERATURE REVIEW

Figure 1 presents the conceptual framework linking supply chain risk to logistics performance through operational friction, with weather condition severity tested as a contextual moderator.

Figure 1. Conceptual Framework: Impact of Supply Chain Risk on Logistics Performance



Source: Prepared through the authors' collaboration

2.1 Supply Chain Disruptions in Logistics

Supply chain disruptions in logistics are unplanned interruptions that disturb transport, storage, handling, and coordination. External shocks such as weather extremes and infrastructure failures reduce continuity and increase variability, while internal execution problems create delays, congestion, and rescheduling. Prior work documents these performance effects well, but often says less about how multiple pressures accumulate inside operations. That gap motivates operational friction as a complementary explanatory lens.

2.2 Operational Challenges in Logistics Systems

Because logistics systems rely on tightly synchronized actors and processes, disruption quickly produces capacity strain, coordination problems, information gaps, and handling issues. These problems are usually interdependent rather than isolated, which makes them suitable for interpretation through a friction lens. Figure 2 summarizes this compounding logic.

Figure 2. Operational challenges in logistics systems and their compounding effects.

Source: This work is the result of the authors' collaboration

The figure synthesizes four categories of disruption-driven operational challenges—capacity strain, coordination breakdown, information gaps, and handling issues—and shows how they converge through interacting inefficiencies into operational friction, which ultimately degrades logistics performance (e.g., delivery delays and service unreliability). This diagram explains why logistics systems are vulnerable during disruptions: multiple operational challenges can

occur at the same time and reinforce each other. Capacity constraints (e.g., bottlenecks), coordination failures (e.g., misaligned handoffs), limited information/visibility (e.g., delayed updates), and handling problems (e.g., rerouting and weather-related risks) all feed into a central mechanism—operational friction. As these inefficiencies accumulate, the system experiences “drag” that reduces overall performance, leading to degraded logistics outcomes, especially in reliability and timeliness.

2.3 Coordination, Capacity, and Process Frictions

Operational friction can be interpreted through three related domains. Coordination friction reflects weak synchronization and delayed information exchange. Capacity friction reflects shortages or congestion in transport, storage, labor, or infrastructure. Process friction reflects workflow rigidities that generate waiting time, rework, or handling discontinuity. These domains provide a practical language for discussing how disruption exposure accumulates inside logistics operations.

3. DATA AND RESEARCH METHOD

3.1 Data Source and Sample

Survey data were collected from 394 logistics and supply chain professionals in Europe, Asia, and North America across retail, manufacturing, and transportation settings. The study uses a cross-sectional design and a stratified sampling approach to improve representation across firm size, industry, and geographic context. The final analysis uses four reflective constructs measured through multi-item scales: Supply Chain Risk (SCR1–SCR7), Operational Friction (OFI1–OFI8), Weather Condition Severity (WCS1–WCS8), and Logistics Performance (LP1–LP8). These scale scores are the measures used in the reliability tests, factor analysis, regression models, and PROCESS-based mediation and moderation analyses. The design is exploratory, so the findings should be interpreted as associational rather than causal.

Table 1. Sample Characteristics

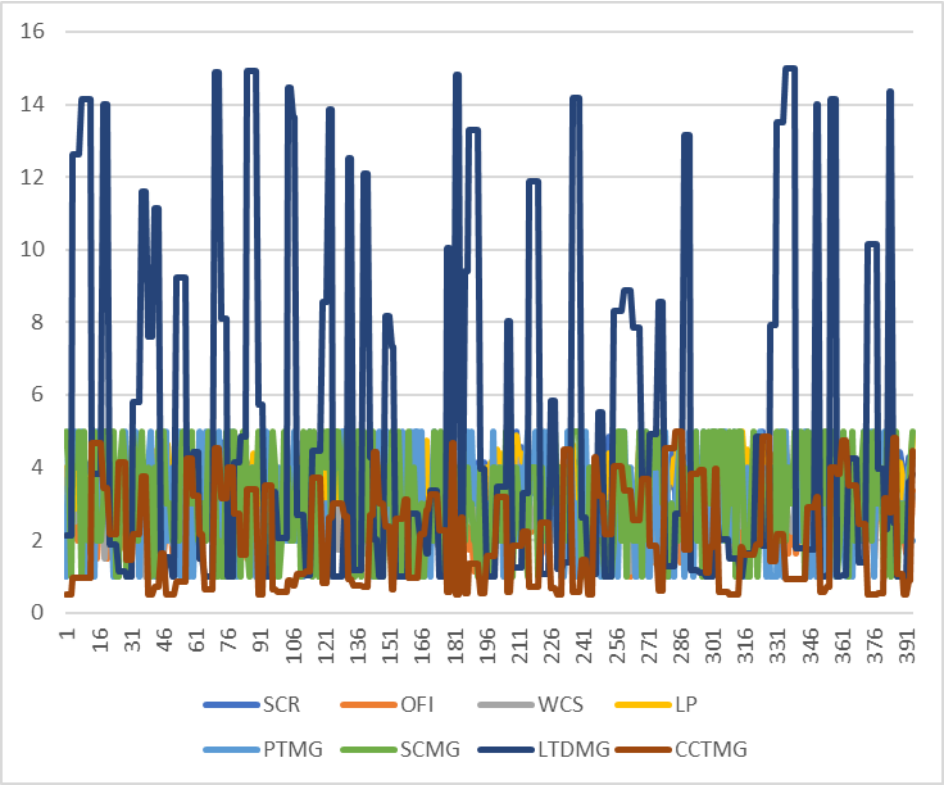
Characteristic	*Details*
Geographical Location	Europe, Asia, North America
Industry Type	Retail, Manufacturing, Transportation
Mean Company Size (Employees)	100.447
Mean Experience (Years)	4.805459

Table 1 summarizes the sample profile. The respondents represent multiple regions and industries, with an average firm size of about 100 employees and average logistics-related experience of about 4.81 years.

3.2 Survey Design

The survey instrument was designed to measure disruption exposure, operational friction, weather severity, and logistics performance using five-point Likert-type items adapted from the literature. After pilot testing and minor wording revisions, the final instrument was administered online to logistics and supply chain professionals through professional networks, email distribution, and industry-related channels. Responses were screened for completeness and consistency before analysis. The final measurement model treats SCR, OFI, WCS, and LP as reflective multi-item constructs, consistent with the reliability and factor-analytic results reported below.

Figure 3. Variation of Key Supply Chain Variables Across Observations



Source: Developed through collaboration among the authors

Figure 3 visualizes the variation of key study variables across observations and is included for descriptive illustration rather than inferential testing.

3.3 Variables and Indicators

The study employs four reflective constructs. SCR captures perceived disruption exposure, OFI captures accumulated coordination, capacity, and process inefficiencies, WCS captures perceived weather-related severity, and LP captures logistics performance outcomes such as reliability and efficiency. Internal consistency and factor loadings indicate that the scales are suitable for exploratory regression and mediation analysis.

Table 2. Reliability and Factor Loadings of Measurement Constructs

Construct	*Number of Items*	*Cronbach's Alpha*	*Factor Loadings (Range)*	*Variance Explained (%)*
Supply Chain Risk (SCR)	7 items (SCR1–SCR7)	≥ 0.70 (acceptable reliability)	0.729 – 0.777	56.22%
Operational Friction (OFI)	8 items (OFI1–OFI8)	≥ 0.70 (acceptable reliability)	0.695 – 0.726	50.22%
Weather Condition Severity (WCS)	8 items (WCS1–WCS8)	≥ 0.70 (acceptable reliability)	0.705 – 0.746	53.52%
Logistics Performance (LP)	8 items (LP1–LP8)	≥ 0.70 (acceptable reliability)	0.736 – 0.794	60.37%

Table 2 reports the reliability and factor structure of the reflective measurement model used in the paper. All constructs meet acceptable thresholds for internal consistency and show satisfactory factor loadings and explained variance.

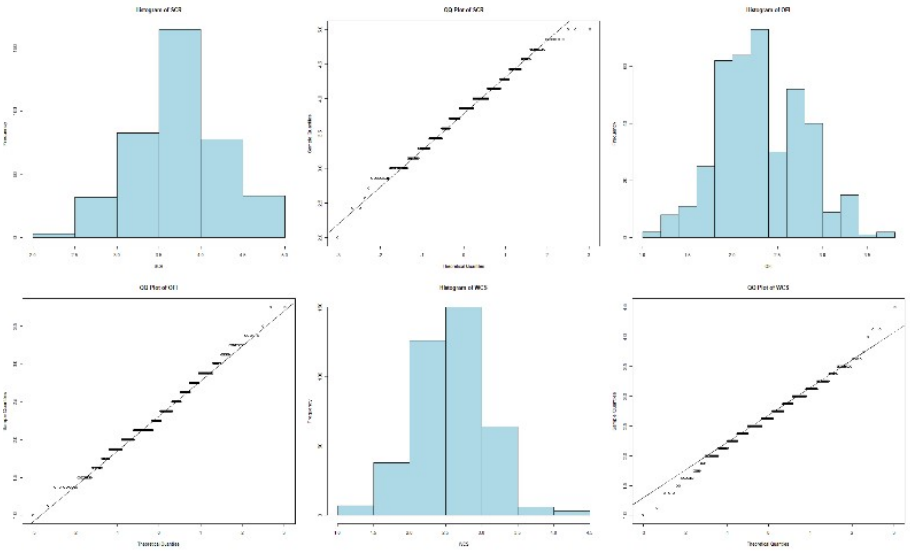
3.4 Analytical Approach

The analysis proceeds in four steps. First, descriptive statistics summarize the main variables. Second, reliability and exploratory factor analysis assess scale quality. Third, OLS regression and PROCESS-based mediation and moderation models test the relationships among SCR, OFI, WCS, and LP using 5,000 bootstrap resamples. Finally, contextual comparisons examine whether OFI differs by product type or supplier country. Analyses were replicated in SPSS and R with matched settings, yielding consistent coefficients and confidence intervals.

4. EMPIRICAL FINDINGS

Table-based descriptive statistics indicate moderate levels of supply chain risk, operational friction, and weather condition severity, alongside generally favorable but variable logistics performance. The distributions appear suitable for parametric analysis, and Figure 5 provides a compact visual normality check for the main constructs.

Figure 5. Distributional Characteristics and Normality Assessment of Key Constructs



Source: This work is the result of the authors' own collaboration

The histograms and Q–Q plots in Figure 5 show approximate normality for the principal constructs, with only minor tail deviations.

To strengthen quantitative validation beyond descriptive interpretation, we estimated a series of regression and bootstrap models using the full sample (N = 394). Supply chain risk (SCR) showed a strong positive association with operational friction (OFI), b = 0.5831, SE = 0.0362, t = 16.1160, p < .0001, explaining 39.8500% of the variance in OFI (R^2 = 0.3985). In turn, when logistics performance (LP) was regressed on both SCR and OFI, both predictors remained significant: SCR, b = 0.5922, SE = 0.0473, t = 12.5130, p < .0001; OFI, b = 0.3802, SE = 0.0512, t = 7.4210, p < .0001. This model explained 58.3063% of the variance in LP (R^2 = 0.5831).

Bootstrap mediation analysis with 5,000 resamples showed a significant indirect effect of SCR on LP through OFI, ab = 0.2216, 95% CI [0.1557, 0.2920]. Because the bootstrap confidence interval excluded zero, the mediation effect was supported. The direct effect of SCR on LP remained significant after including OFI, b = 0.5922, indicating partial rather than full mediation. Substantively, this suggests that supply chain risk is associated with logistics outcomes both directly and indirectly through elevated operational friction.

Table 3. Results Summary Table

Research link / hypothesis	***Test***	***Effect / coefficient***	***95% CI***	***p***	***Conclusion***
SCR → OFI	OLS	b = 0.5831	[0.5119, 0.6542]	< .0001	Supported
SCR → LP (total effect)	OLS	b = 0.8140	[0.7420, 0.8895]*	< .0001	Supported
OFI → LP controlling for SCR	OLS	b = 0.3802	[0.2795, 0.4809]	< .0001	Supported
SCR → LP controlling for OFI (direct effect)	OLS	b = 0.5922	[0.4991, 0.6852]	< .0001	Supported
Indirect effect SCR → OFI → LP	Bootstrap mediation, 5,000 resamples	ab = 0.2216	[0.1557, 0.2920]	—	Supported
OFI × WCS → LP controlling for SCR	Moderated regression	b = 0.0570	[-0.0671, 0.1811]	.3677	Not supported
Product-type group differences in OFI	One-way ANOVA	F(4,389) = 0.4523	—	.7707	Not supported
Supplier-country group differences in OFI	One-way ANOVA	F(4,389) = 0.4876	—	.7449	Not supported

Table 4. Model fit summary

Model	***Dependent Variable***	***Predictors***	***R^2***
Model 1	Operational Friction Index (OFI)	SCR	0.3985
Model 2	Logistics Performance (LP)	SCR, OFI	0.5831
Model 3	Logistics Performance (LP)	SCR, OFI, WCS, OFI × WCS	0.6268

Table 5. Standardized effects

Path	***Standardized Coefficient (β)***	***Significance***
SCR → OFI	0.6313	Significant
SCR → LP (controlling for OFI)	0.5269	Significant
OFI → LP (controlling for SCR)	0.3125	Significant
OFI × WCS → LP	0.0231	p = .3677 (Not Significant)

Table 6. Cronbach's alpha

Construct	***Items***	***Cronbach's alpha***
SCR	7	0.8699
OFI	8	0.8582
WCS	8	0.8758
LP	8	0.9060

Table 7. Factor analysis

Construct	***KMO***	***Bartlett's test p***	***Loading range***	***Variance explained***
SCR	0.9176	< 0.0001	0.7293–0.7774	56.2184%
OFI	0.9112	< 0.0001	0.6950–0.7257	50.2230%
WCS	0.9290	< 0.0001	0.7048–0.7459	53.5205%
LP	0.9429	< 0.0001	0.7363–0.7940	60.3694%

Taken together, the reliability and factor-analysis results support the use of SCR, OFI, WCS, and LP as reflective constructs in the empirical models reported in Tables 3–7.

4.1 Moderation by Weather Condition Severity

We next tested whether weather condition severity (WCS) changed the relationship between operational friction and logistics performance. In the moderated regression including SCR, OFI, WCS, and the OFI × WCS interaction, the interaction term was positive but not statistically significant, b = 0.0570, SE = 0.0632, t = 0.9020, p = .3677. Thus, the data do not provide strong evidence that weather severity significantly alters the OFI–LP relationship in the full model. Although the simple slope of OFI on LP was somewhat larger at higher WCS levels than at lower levels, the interaction pattern was weak and should be interpreted cautiously.

4.2 Group Differences by Product Type and Supplier Country

We also examined whether operational friction differed across product-type groups and supplier-country groups. One-way ANOVA showed no statistically significant differences in OFI across product-type groups, $F(4,389) = 0.4523$, $p = .7707$, or supplier-country groups, $F(4,389) = 0.4876$, $p = .7449$. Accordingly, the present dataset does not support strong mean-level group differences in operational friction across these contextual categories.

4.3 Interpretive Patterns of Operational Friction

The main empirical results support interpreting operational friction as a broad operational condition rather than a single symptom. The strong SCR → OFI coefficient, the significant OFI → LP coefficient, and the significant indirect effect together suggest that disruption exposure is associated with performance deterioration partly through accumulated operational inefficiencies. Weather severity remains substantively relevant as a contextual pressure, but the interaction test is not statistically significant in the full model, so any amplification claim should be treated cautiously. Likewise, the absence of significant group differences suggests that the core friction mechanism may be relatively general across the coded product-type and supplier-country categories in this sample.

5. DISCUSSION AND IMPLICATIONS

5.1 Interpretation of Key Findings

The study's central empirical result is that operational friction partially mediates the relationship between supply chain risk and logistics performance. This supports the view that logistics performance declines not only because firms are exposed to risk, but also because that exposure produces accumulated coordination, capacity, and process strain inside operations. The results also indicate that weather condition severity should be treated carefully in interpretation: it is theoretically relevant and positive in sign, but it is not a statistically supported moderator in the full model.

5.2 Managerial Implications

Three practical implications follow from the main coefficients. First, the significant SCR → OFI relationship suggests that managers should monitor friction indicators early when disruption exposure rises, especially where visibility is weak. Second, the significant OFI → LP relationship indicates value in interventions that improve coordination visibility, increase flexible capacity, and reduce process bottlenecks before they compound. Third, the mediation result suggests that friction diagnosis can be used as a practical tool: identifying where coordination failures, congestion, and workflow delays accumulate may help firms act earlier than performance KPIs alone would allow.

These implications should be framed as operational diagnosis rather than universal prescriptions. The data support targeted attention to friction reduction, but they do not establish causal priority among every managerial action. Even so, the results point to a clear practice agenda built around coordination visibility, flexible capacity, and process agility.

5.3 Resilience Implications

From a resilience perspective, the findings suggest that logistics systems become harder to stabilize when friction accumulates across multiple operational interfaces. Firms that invest in timely information sharing, adaptable capacity arrangements, and simpler recovery routines are therefore better positioned to absorb disruption without allowing operational friction to escalate.

6. CONCLUSION

This study shows that operational friction is a useful explanatory lens for understanding how supply chain risk relates to logistics performance. Empirically, OFI significantly mediates the SCR–LP relationship, while the moderating effect of weather condition severity is not statistically significant in the full model and product-type and supplier-country group differences are also not supported. The practical implication is that managers may benefit from diagnosing disruption-related friction early rather than relying only on outcome KPIs. The research implication is that future studies should refine and test the operational friction construct in broader settings and with stronger causal designs.

The study remains limited by its cross-sectional design, industry and geographic coverage, and reliance on self-reported survey data. Future work could use longitudinal, comparative, or simulation-based designs to test causal pathways more directly and examine whether digital visibility and weather-related planning capabilities reduce operational friction over time.

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ISTRAŽIVANJE OPERATIVNIH POTEŠKOĆA U LOGISTIČKIM SUSTAVIMA: UTJECAJ POREMEĆAJA U OPSKRBNOM LANCU I INTENZITETA VREMENSKIH NEPOGODA

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SAŽETAK
Ovo istraživanje ispituje kako poremećaji u opskrbnom lancu utječu na logističku uspješnost putem akumuliranih operativnih poteškoća te provjerava mijenja li ozbiljnost vremenskih uvjeta taj odnos. Na temelju transverzalnog anketnog istraživanja provedenog na uzorku od 394 stručnjaka za logistiku i upravljanje opskrbnim lancem iz Europe, Azije i Sjeverne Amerike, u radu se primjenjuju deskriptivna statistika, eksploratorna faktorska analiza, testiranje pouzdanosti, OLS regresija, medijacijska analiza, moderacijska analiza te bootstrap uvjetno-procesno testiranje. Rezultati pokazuju da je rizik u opskrbnom lancu pozitivno povezan s operativnim poteškoćama te da su operativne poteškoće značajno povezane s logističkom uspješnošću. Bootstrap rezultati potvrđuju statističku značajnost neizravnog učinka, odnosno potvrđuju da operativne poteškoće djelomično posreduju odnos između rizika u opskrbnom lancu i logističke uspješnosti. Nasuprot tomu, moderirajući učinak ozbiljnosti vremenskih uvjeta pozitivan je, ali nije statistički značajan u cjelovitom modelu. Rad doprinosi literaturi time što operativne poteškoće postavlja kao menadžerski korisnu i empirijski utemeljenu perspektivu za dijagnosticiranje načina na koji se neučinkovitosti povezane s poremećajima akumuliraju unutar logističkih sustava.

Ključne riječi: *operativne poteškoće, poremećaji u opskrbnom lancu, logistička uspješnost, ozbiljnost vremenskih uvjeta, otpornost logistike, operativni izazovi.*

Izvorni znanstveni rad

EKONOMSKA KVANTIFIKACIJA ODRŽIVOSTI PRIJEVOZNOG PONAŠANJA STUDENATA

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SAŽETAK

Istraživanja pokazuju da studentska mobilnost često ovisi o kontekstualnim čimbenicima i atributima planiranog kretanja, no ekonomski aspekt njihovog prijevoznog ponašanja relativno je zanemaren. Konkretizacija odnosa troška i održivosti studentske mobilnosti činila bi snažan argument za urbano prijevozno planiranje, infrastrukturna ulaganja u alternativne modalitete i unapređenja sustava gradskog prijevoza u funkciji poboljšanja kvalitete života u sveučilišnim gradovima. Svrha ovog rada je ekonomska kvantifikacija obrazaca mobilnosti studenata. Cilj istraživanja je utvrditi trošak postojećih obrazaca mobilnosti, kao i napraviti projekciju troška u scenarijima održivijeg prijevoznog ponašanja, sukladno raspoloživim modalitetima, na individualnoj razini i razini populacije. Metodološki pristup uključuje kombinaciju metoda primarnog i sekundarnog istraživanja. Kroz online ispitivanje utvrđeni su obrasci studentske mobilnosti. Metodologijom ugljičnog otiska obrasci mobilnosti su prevedeni u mjeru utjecaja na okoliš, a uvažavanjem stvarnih tržišnih cijena (npr. cijena goriva, cijena prijevoznih karata javnog prijevoza) u odnosu na modalitet kretanja i stvarno prijeđenu udaljenost, izraženi su financijski. Rezultati provedenog istraživanja ukazuju na potencijal za smanjenje ekološkog i ekonomskog tereta studentske mobilnosti. Potvrđeno je da mobilnost modalitetima manjeg ugljičnog otiska implicira i manji trošak mobilnosti, čime ovaj rad, kroz ispunjavanje postavljenih ciljeva, doprinosi području istraživanja studentske mobilnosti šireći raspon aspekata vrednovanja njihova prijevoznog ponašanja kroz istraživanje odnosa okolišnog i ekonomskog aspekta mobilnosti, utemeljeno u kvantifikaciji stvarnih i potencijalnih održivijih obrazaca ponašanja.

Ključne riječi: *obrasci studentske mobilnosti, funkcionalna mobilnost, ugljični otisak, trošak mobilnosti*

1. UVOD

U posljednja dva desetljeća studentska je mobilnost predmet različitih znanstvenih radova, no primarno je fokus na karakterizaciji ponašanja studenata i utvrđivanju determinanti izbora primarnog modaliteta kretanja. U istraživanjima koja se bave održivošću studentske mobilnosti izostaje ekonomski kontekst. Cijena prijevoza razmatra se kao jedan od aspekata mobilnosti studenata (Alomari et al., 2023; Dawood i Rahmat, 2015; Ismael i Duleba, 2023), no trošak se promatra kao faktor subjektivnog odlučivanja, zbog čega nedostaje kvantifikacija. Ovim radom se stoga pokušava sagledati trošak studentske mobilnosti u kontekstu održivosti te odrediti „cijena“ prijevoznog ponašanja studenata u odnosu na trenutno ponašanje i moguće promjene načinske raspodjele k većoj održivosti. S tim ciljem, utvrđuju se trošak i razina održivosti koji su vezani uz pohađanje predavanja, odnosno funkcionalnu mobilnost (eng. *commuting*). Istraživanje je provedeno na uzorku studenata, čije prijevozne navike uvelike odražavaju njihove buduće obrasce (Hasnine et al., 2018;

Kotval-Ket al., 2024; Nash i Mitra, 2019), zbog čega su važni za planiranje urbane mobilnosti.

Mjere i aktivnosti koje se poduzimaju u upravljanju studentskom mobilnošću temelje se na utvrđivanju obrazaca prijevoznog ponašanja i determinanti održivosti (Fondzenyuy et al., 2024; Kovačić i Grofelnik, 2024; Mesarec i Trček, 2024; Ribeiro i Fonseca, 2022). Upravljanje prijevoznom potražnjom studenata je kompleksno, te efekti ponekad potpuno izostaju zbog stavova (Capasso Da Silva et al., 2020; Lowry 2024), navika lii osobnih preferencija studenata (Chavis i Gayah, 2017).

Istraživanje je zasnovano na hipotezi da će više održiva mobilnost studenata, uz manji ekološki utjecaj (manji ugljični otisak), rezultirati i manjim troškom prijevoza za studente te da se razlike u održivosti obrazaca funkcionalne mobilnosti (eng. *commuting*) mogu financijski kvantificirati. Pretpostavka je da bi smanjenje ugljičnog otiska prijevoza do fakulteta značilo i uštede, odnosno smanjeni trošak mobilnosti, na razini pojedinca i studentske populacije. Dokazivanje ove relacije indikativno je za politike urbane mobilnosti i prometno planiranje, te podupire argumentirano uvođenje promjena s ciljem paralelnih restrikcija neželjenom ponašanju i poticaja alternativnim modalitetima. Sukladno postavljenom okviru, nameće se nekoliko ciljeva:

- analizirati udaljenosti i trajanje svakodnevne mobilnosti studenata između lokacije stanovanja i fakulteta,
- procijeniti potencijal za promjenu načinske raspodjele u korist više održivih modaliteta mobilnosti,
- utvrditi ugljični otisak postojećih obrazaca funkcionalne mobilnosti studenata,
- procijeniti uštede emisija CO_2 koje proizlaze iz potencijalne promjene načinske raspodjele,
- utvrditi trošak funkcionalne mobilnosti studenata prema obrascima mobilnosti različite razine održivosti.

Primijenjeni pristup omogućava objektivnu kvantifikaciju ugljičnog otiska, na osnovu stvarno prijeđenih udaljenosti, korištenja preferiranog modaliteta, učestalosti pohađanja predavanja i standardiziranih faktora konverzije emisija, kao i procjenu troškova mobilnosti.

Uvodnom razmatranju slijedi Pregled literature, kojim se ukazuje na kontekst proizašao iz postojećih istraživanja studentske mobilnosti i pronalazi jaz u istraživanjima. Metodološki pristup opisan je u dijelu Metodologija istraživanja. Nakon dijela Rezultati istraživanja, gdje se osim kvantifikacije ugljičnog otiska i troška mobilnosti (individualno, na razini uzorka i na razini sveučilišta; dnevno i godišnje) identificira kriterij za utvrđivanje potencijala promjene, slijedi Diskusija rezultata. Po stavljanju u odnos rezultata istraživanja s postojećom spoznajom, slijedi Zaključak, te se navode bibliografski izvori.

2. PREGLED LITERATURE

Planiranje urbane mobilnosti mora obuhvatiti obrasce ponašanja studenata, njihove navike, stavove i specifična ponašanja (Khattak et al., 2011; Nguyen-Phuoc et al., 2018; Oubahman et al., 2024) kako bi upravljanje prometnom potražnjom bilo usklađeno s nužnošću tranzicije k pametnijoj i održivijoj mobilnosti (European Commission, 2020a). Obrasci mobilnosti studenata razlikuju se od drugih populacijskih skupina (Hafezi et al., 2018; Hamad et al., 2021; Moniruzzaman i Farber, 2018; Taylor i Mitra, 2021), heterogeni su (Kriswardhana i Esztergár-Kiss, 2024), te s velikom vjerojatnošću odražavaju buduće ponašanje i navike (Kotval-Ket al., 2024; Nash i Mitra, 2019) i utjecaj na dugoročnu održivost njihova okruženja (Hossain et al., 2022). Studenti različito percipiraju utjecaj vlastitog prijevoznog ponašanja na okoliš, često ga podcjenjujući (Turay et al., 2024), zbog čega je potrebno utvrditi stvarno ponašanje (za razliku od percepcije) i objektivno kvantificirati njihov ugljični otisak.

Istraživanja studentske mobilnosti ukazuju da je izbor načina prijevoza rezultat kombinacije njihovih stavova te okolišnih i ekonomskih faktora (Whalen et al., 2013), odnosno da proizlazi iz kombinacije latentnih stavova i objektivnih okolnosti (Deneke et al., 2024; Hossain et al., 2022; Saitluanga i Hmangaihzela, 2022). Uz veličinu grada i karakteristike prometnog sustava, lokacija kampusa i dostupni modaliteti kretanja tvore lokalno kontekstualno okruženje koje utječe na mobilnost studenata (Jutz et al., 2024), a udaljenost i trajanje odražavaju se na korisnost putovanja (Al-Salih i Esztergár-Kiss, 2024) te se često razmatraju supstitutivno (Ton et al., 2019). Vjerojatnost odabira određenog modaliteta smanjuje se s povećanjem trajanja putovanja (Lodi et al., 2024; Nguyen-Phuoc et al., 2018), koje se smatra značajnijim utjecajem od troška, odnosno cijene prijevoza (Lodi et al., 2024; Turay et al., 2024). U slučaju nedostupnosti pojedinih modaliteta ograničena mogućnost izbora (Golshani et al., 2018) se odražava na percepciju fleksibilnosti (Fondzenyuy et al., 2024), determinantu usvojenih obrazaca ponašanja povezanu je s postojanjem okolišnih i osobnih ograničenja (Aliari et al., 2020; Maiti et al., 2022).

Cijena prijevoza utječe na lojalnost odabranom prijevoznom modalitetu (Alomari et al., 2023), odražava se na ukupno zadovoljstvo (Ismael i Duleba, 2023), te može odvratiti studente od korištenja (Dawood i Rahmat, 2015). Trošak je jednako važna determinanta izbora načina prijevoza studentima javnih i privatnih sveučilišta (Nasrin, 2020). Uz trošak prijevoza, važan je i trošak parkiranja (Hasnine et al., 2018). Održivost studentske mobilnosti adresirana je brojnim istraživanjima (Azzali i Sabour, 2018; Barros et al., 2018; Mesarec i Trček, 2024; Pérez-Neira et al., 2020; Ribeiro i Fonseca, 2022; Sobrino i Arce, 2021). Ipak, specifični kontekst (poput udaljene ili prigradske lokacije studentskog kampusa) i potreba za postizanjem veće održivosti nalažu potrebu uvažavanja i dodatnih determinanti uz već postojeće (Kovačić i Grofelnik, 2025) ili uvažavanje drugačije perspektive.

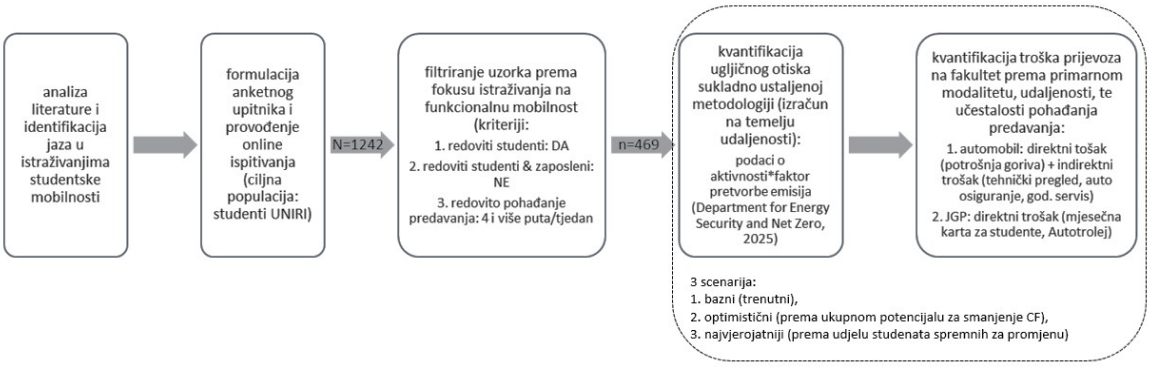
Aktivni modaliteti mobilnosti pozitivno koreliraju s blizinom lokacije sveučilišta (Turay et al., 2024), uz preduvjet postojanja adekvatne infrastrukture (Aliari et al., 2020; Le Pira et al., 2024). Ipak, u praksi se nerijetko događa prijelaz na motorizirane alternative, ako je cijena prijevoza razumna, a usluga posredovana mobilnom aplikacijom (Kotval-K et al., 2024), koja uključuje informacije u stvarnom vremenu te opcije uštede vremena i novca (Coppola et al., 2025), što tehnologije čini sredstvom postizanja održivije mobilnosti (Sottile et al., 2021) ukoliko se njihovi korisnici već ne ponašaju održivo (Kriswardhana i Esztergár-Kiss, 2024). Međutim, studentska populacija nije uvijek sklona promjenama obrazaca mobilnosti, unatoč primijenjenim mjerama (Capasso Da Silva et al., 2020; Lowry 2024; Wiers i Schneider, 2022), čak i kada pokazuju veliku svjesnost i interes za održivost svog okruženja (Abubakar et al., 2016).

Održivost i efikasnost prometnog sustava grada impliciraju promjene načinske raspodjele u korist održivijih alternativa, dijeljenja vožnji (*carpooling*) i rada na daljinu (Victoria Transport Policy Institute, 2014). Mjerama prometnog planiranja i upravljanja prijevoznom potražnjom (Nguyen-Phuoc et al., 2018; Oubahman et al., 2024) moguće utjecati na održivost studentske mobilnosti. Sveučilišta najčešće primjenjuju uvođenje naplate ili povećanje cijene parkiranja, koje utječu na promjenu preferencija i odabir aktivnih modaliteta ili JGP-a (Danaf et al., 2014; Dawood i Rahmat 2015; Hamad et al., 2021; Hasnine et al., 2018; Mesarec i Trček, 2024; Rotaris i Danielis, 2018), pod uvjetom konkurentnosti cijenom i trajanjem putovanja. Uz naplatu, ograničenje broja parkirnih mjesta učinkovit je alat u obeshrabrivanju korištenja automobila (Fernández-Heredia et al., 2014). Ako se realiziraju paralelno s restrikcijama automobilskom prijevozu, manji infrastrukturni zahvati potiču aktivniju i održiviju mobilnost studenata (Nayar i Najafi, 2012) kroz smanjenje prepreka, što je učinkovitije od promicanja prednosti takve mobilnosti (Hamad et al., 2021). S ciljem smanjenja emisija sveučilišta razmatraju i održavanje predavanja online, no ekološki efekti su minimalni zbog realokacije emisija (Jutz et al., 2024). Održivost mobilnosti studenata usko je povezano i sa stambenim pitanjem (Jutz et al., 2024; Mesarec i Trček, 2024; Nash i Mitra, 2019), odnosno s udaljenošću studentskog smještaja od fakulteta.

3. METODOLOGIJA ISTRAŽIVANJA

Metodološki pristup podudara se s postojećim istraživanjima u: 1. uvažavanju funkcionalne mobilnosti (Deneke et al., 2024; Hasnine et al., 2018; Ribeiro i Fonseca, 2022); 2. provedbi putem online ispitivanja (Kotval-K et al., 2024; Lodi et al., 2024; Mesarec i Trček, 2024; Pérez-Neira et al., 2020); 3. fokusu isključivo na studente (Jutz et al., 2024; Le Pira et al., 2024; Lodi et al., 2024; Lowry, 2024; Turay et al., 2024); te 4. analizi održivosti studentske mobilnosti utvrđivanjem emisija CO_2 (Mesarec i Trček, 2024; Kovačić i Grofelnik, 2025; Pérez-Neira et al., 2020; Sobrino i Arce, 2021). Analiza scenarija u ovom istraživanju primjenjuje kriterij primarno određen prijeđenom udaljenošću, preuzet i prilagođen iz istraživanja Ribeiro i Fonseca (2022), sukladno kojem se potencijal promjene načinske raspodjele prema većoj održivosti razmatra u dva scenarija. Optimistični scenarij ukazuje na potencijal za smanjenje CO_2 kada bi svi studenti, kojima to kriterij udaljenosti dozvoljava, zamijenili način prijevoza više održivom alternativom. Najvjerojatniji scenarij ukazuje na potencijal za promjenu i uštedu CO_2 sukladno spremnosti za promjenu studenata, izraženoj tijekom ispitivanja (11 % u konkretnom slučaju). Osim utvrđivanja razlike emisija CO_2 i smanjenja ugljičnog otiska po scenarijima, ovaj rad donosi i monetarnu kvantifikaciju te promjene. Metodološki pristup usmjeren na ostvarenje ciljeva istraživanja i testiranje hipoteze prikazan je Slikom 1.

Slika 11. Istraživački pristup



Izvor: autori

Primarnim istraživanjem obuhvaćeni su studenti u redovitom statusu, koji uz studij nisu zaposleni, kako bi uočeni obrasci mobilnosti što preciznije odražavali putovanja povezana s predavanjima i obvezama na fakultetu. Ovaj rad fokusira se isključivo na funkcionalnu mobilnost, jer su obrasci povezani sa slobodnim vremenom mnogo heterogeniji (Loa i Habib, 2024). Mobilnost povezana s rasporedom predavanja lakše je predvidiva, te visokoobrazovne institucije i gradovi mogu na istu jednostavnije utjecati (Fernandes et al., 2019; Lodi et al, 2024). Fokusom na konkretizaciju troška prijevoza studenata u odnosu s razinom održivosti prijevoznog ponašanja (sukladno korištenom modalitetu, stvarno prijeđenoj udaljenosti i pohađanju predavanja) ovo istraživanje doprinosi širini spektra istraživanja prijevoznih navika i učinaka studentske mobilnosti. Uvaženo je realizirano ponašanje te je na osnovu utvrđenih obrazaca kvantificirana održivost jer istraživanja pokazuju da se percepcija studenata snažno razlikuje kada je u pitanju doživljaj održivosti prijevoznog ponašanja (Turay et al., 2024).

Ispitivanje je provedeno pomoću online upitnika, dostupnog studentima Sveučilišta u Rijeci (UNIRI) putem linka. Strukturu upitnika čini nekoliko tematskih dijelova, počevši sa socio-demografskim obilježjima ispitanika. Slijede segmenti koji se odnose na svakodnevno prijevozno ponašanje, prvo općenito, a zatim u odnosu na različite modalitete mobilnosti (vožnju automobila, korištenje javnog prijevoza, pješačenje, vožnju biciklom, korištenje javnih bicikala, car-sharing, korištenje romobila i multimodalne opcije). Sadržaj upitnika usklađen je

s postojećim pristupom u istraživanjima urbane mobilnosti u smislu utvrđivanja obrazaca, kvalitete i održivosti iste (European Commission 2014, 2020b; WBCSD, 2015), no dopunjen je pitanjima u funkciji preciznog izračuna ugljičnog otiska i troška putovanja (utvrđivanje primarnog modaliteta mobilnosti, marka i tip vozila, godina proizvodnje, vrsta goriva, potrošnja goriva (l/100km), udaljenost od polazišta do fakulteta, trajanje putovanja, te dijeljenje vožnji).

Po provođenju primarnog istraživanja i utvrđivanju obrazaca mobilnosti na razini uzorka, ugljični otisak izračunat je na bazi podataka o aktivnosti (udaljenost, primarni modalitet, karakteristike osobnih automobila (pogonsko gorivo, potrošnja goriva) – ako je primarni modalitet automobil, broj predavanja tjedno i broj radnih dana u akademskoj godini) i faktora konverzije emisija (kg CO_2e) (Tablica 1). Sukladno vrijednostima faktora konverzije, biciklistički prijevoz pokazuje se kao najmanje opterećenje za okoliš.

Tablica 9. Faktori konverzije emisija primarnih prijevoznih modaliteta studenata

Modalitet mobilnosti	kg CO_2e / pkm			
	dizel	benzin	hibrid	Autoplin
Prosječni automobil*	0,173	0,163	0,128	0,196
Prosječni autobus JGP*	0,104			
Bicikl**	0,021			
Pješačenje**	0,056			

Izvori: *Department for Energy Security and Net Zero, 2025; **Cycling UK.org

Kalkulaciji ugljičnog otiska je uslijedila ekonomska kvantifikacija ponašanja studenata, također na osnovu stvarno prijeđene udaljenosti, te objektivno utvrđene potrošnje goriva prema vrsti (za automobile), ili cijene prijevozne karte (mjesečne karte za JGP), odnosno cijene korištenja aktivnih modaliteta. Podaci o potrošnji goriva preuzeti su iz javne baze podataka (Spritmonitor.de) koja sadrži sve modele i tipove vozila ispitanika, budući su se podaci o stvarnoj potrošnji prikupljeni upitnikom pokazali nepouzdanima te velikog udjela odgovora „ne znam“. Za monetarnu valorizaciju obrazaca mobilnosti uvaženi su direktni troškovi (trošak goriva prema vrsti i potrošnji (HAK, 2025) ili cijena prijevozne karte JGP (Autotrolej, n.d.)), te procjena indirektnih troškova koji su dio troška prijevoza automobilima.

4. REZULTATI ISTRAŽIVANJA

4.1 Uzorak

Ukupno je prikupljeno 1242 odgovora studenata Sveučilišta u Rijeci. Uvažavanjem samo pravilno ispunjenih obrazaca, te filtriranjem prema pristupu ovog istraživanja (uvažavanje samo redovitih studenata, te studenata koji uz studij ne rade) uzorak za ovo istraživanje sveden je na 469 studenata, međusobno različitih prema osnovnim socio-demografskim značajkama, lokaciji mjesta stanovanja, te primarnom modalitetu mobilnosti (Tablica 2).

Iz presjeka strukture uzorka moguće je zaključiti da izostaju multimodalni oblici mobilnosti te različiti oblici dijeljenja prijevoznih sredstava (bicikala, romobila, automobila). Većina ispitanih unutar je tipičnog raspona godina starosti za studentsku populaciju, no većinom su ispitane žene. Udio prijevoza automobilima čini otprilike trećinu načinske raspodjele, dok je JGP primarni modalitet.

Tablica 10. Struktura uzorka (n=469)

Odrednica	Svojstvo	Udio (%)
Spol	M	31,56
	Ž	68,44
Starost	18-20	52,03
	21-23	38,38
	24 i više	9,59
Lokacija prebivališta / boravišta	grad	45,63
	prigradsko naselje	54,37
Primarni modalitet mobilnosti	automobil	31,77
	JGP (autobus; autobus i pješačenje)	45,63
	pješačenje	21,32
	bicikl (osobni)	1,28

Izvor: autori

Uzorak je 4,68 % ukupnog broja redovitih studenata Sveučilišta u ak. godini 2024./2025. (Sveučilište u Rijeci, 2024), što omogućava i projekciju ugljičnog otiska i troškova mobilnosti i na sveučilišnoj razini (za redovite studente), budući je udio ispitanih veći nego u postojećim istraživanjima (Ribeiro i Fonseca, 2022) koja primjenjuju takav pristup. Ipak, radi nemogućnosti utvrđivanja udjela zaposlenih studenata u kontingentu redovitih studenata na razini Sveučilišta, kalkulacija ugljičnog otiska i troška mobilnosti za sveučilišnu populaciju prije svega ima indikativni karakter.

4.2 Obilježja funkcionalne mobilnosti studenata

S obzirom da sve sastavnice Sveučilišta i sadržaji Studentskog centra nisu locirani na istoj lokaciji, prevaljene udaljenosti i trajanje putovanja se mogu značajno razlikovati među ispitanim studentima. Prijeđene udaljenosti i vremena putovanja između polazišta i matičnog fakulteta sumirani su 3. i 4. tablicom za prijevozne modalitete koje ispitani studenti koriste.

Tablica 11. Udaljenosti koje studenti prevaljuju na relaciji od lokacije stanovanja do fakulteta prema primarno izabranom modalitetu mobilnosti

prijeđena udaljenost (1 smjer)	primarno izabrani modalitet			
	automobil (n=149)	JGP (n=214)	pješačenje (n=100)	bicikl (n=6)
<1 km	2,68%	3,74%	55,00%	0,00%
>1 - ≤5 km	20,81%	32,24%	39,00%	66,67%
>5 - ≤10 km	39,60%	38,32%	6,00%	16,67%
>10 - ≤20 km	36,91%	25,70%	0,00%	16,67%

Izvor: autori

Rezultati pokazuju da su mnoga putovanja automobilom i autobusom kratka i unutar raspona prikladnog za vožnju biciklom ili čak pješačenje. Pješačenje je treće rangirani izbor studenata i uglavnom se preferira na kraćim udaljenostima. Što se tiče trajanja putovanja (Tablica 4), evidentna je povezanost s prevaljenim udaljenostima.

Tablica 12. Trajanje putovanja studenata od lokacije stanovanja do fakulteta prema primarno izabranom modalitetu mobilnosti

trajanje putovanja (1 smjer)	primarno izabrani modalitet			
	automobil (n=149)	JGP (n=214)	pješačenje (n=100)	bicikl (n=6)
<15 min	26,17%	14,02%	72,00%	16,67%
>15 - ≤30 min	55,03%	35,98%	22,00%	66,67%
>30 - ≤60 min	18,12%	39,25%	6,00%	16,67%
>60 - ≤90 min	0,67%	10,75%	0,00%	0,00%

Izvor: autori

Svedeno na osnovne atribute prijevoza (udaljenost, trajanje, brzina putovanja) funkcionalna mobilnost ispitanih studenata ukazuje da se najveće udaljenosti prevaljuju automobilima, putovanje kojima i najduže traje, bez obzira na najveću utvrđenu brzinu kretanja (Tablica 5). Prevaljene udaljenosti i trajanje putovanja (Tablica 3 i Tablica 4) ukazuju na mogućnost supstitucije motoriziranih modaliteta nemotoriziranim alternativama.

Tablica 13. Podaci o funkcionalnoj mobilnosti ispitanih studenata*

primarni modalitet	ukupna prevaljena udaljenost modalitetom (pkm/dan)	ukupno trajanje putovanja modalitetom (pmin/dan)	prosječna dnevna udaljenost po studentu (km/dan)	prosječno trajanje putovanja po studentu (min/dan)	prosječna godišnja udaljenost po studentu (pkm)**	prosječna brzina (km/h)
automobil	2698	7440	18,10	49,94	2806,64	21,75
JGP	3242	15556	7,57	36,34	1173,35	12,50
pješačenje	425	3690	2,13	18,45	330,15	6,93
bicikl	65	300	5,42	25,00	840,1	13,01

*vrijednost uključuje i odlaznu i dolaznu mobilnost (putovanje u oba smjera)
**na bazi prosječnog trajanja ak. godine na Sveučilištu (30 tjedana) i broja radnih dana (u prosjeku 155 prema kalendarima nastave sastavnica UNIRI)

Izvor: autori

Brzina kretanja biciklom podjednaka je brzini prijevoza autobusom, a otprilike 40 % udaljenosti prevaljenih JGP-om u dohvatu su biciklističkog prijevoza.

4.3 Potencijal za smanjenje ugljičnog otiska studenata

Utvrđivanje potencijala za unapređenje održivosti studentske mobilnosti zasniva se na definiranju četiri razreda sukladno parametrima udaljenosti i trajanja putovanja: 1. pješački, 2. biciklistički, 3. razred JGP-a, te 4. multimodalni razred, koji uključuje i osobna vozila (Tablica 6) (Ribeiro i Fonseca, 2022). Prilagodba za potrebe ovog istraživanja je izvršena u pješačkom razredu, gdje je kriterij udaljenosti promijenjen iz 0,8 km u 1 km, a trajanje iz „do 10 minuta“ u „do 15 minuta“ što dozvoljavaju postojeća istraživanja (npr. Zhan et al., 2016, Lodi et al., 2024).

Tablica 14. Kriterij za utvrđivanje potencijala promjene obrazaca mobilnosti studenata

razred funkcionalne mobilnosti	modalitet	udaljenost	trajanje
kratka putovanja	pješačenje	<1 km	<15 min
	biciklistički prijevoz	<5 km	<20 min
duga putovanja	JGP	>5 km	<30 min
	multimodalne opcije; automobili	>5 km	>30 min

Izvor: prilagodba autora prema Ribeiro i Fonseca (2022)

Prema kriteriju u Tablici 6, a sukladno kvantifikaciji faktora konverzije (Tablica 1), ukupni potencijal za promjenu načinske raspodjele na održivije modalitete u ovom istraživanju iznosio bi ukupno 82,55 % za automobilski prijevoz, ukupno 22,89 % za JGP, te ukupno 35,00 % za pješačenje. Načinska distribucija precizirana je u Tablici 7.

Tablica 15. Potencijal za promjenu obrazaca mobilnosti studenata sukladno utvrđenim kriterijima udaljenosti i trajanja putovanja

potencijalna alternativa / potencijal za promjenu												
primarni modalitet	automobil		JGP		pješačenje		bicikl		Neodređeno		ukupno	
	br.	%	br.	%	br.	%	br.	%	br.	%	br.	%
automobil (n=149)	*26**	*17,45*	88	59,06	2	1,34%	33	22,15	0	0,00	149	100
JGP (n=214)	82	38,32	*55**	*25,70*	5	0,93%	47	21,96	25	11,68	214	100
pješačenje (n=100)	6	6,00	5	5,00	*51**	*51,00%*	35	35,00	3	3,00	100	100
bicikl (n=6)	1	16,67	1	16,67	0	0,00%	*4**	*66,67*	0	0,00	6	100

Napomena: Označeno crvenim ne smatra se potencijalom u smislu povećanja održivosti s obzirom na nedostajuće multimodalne opcije u području i/ili nastavak korištenja istog modaliteta (*broj studenata koji nastavljaju koristiti isti modalitet prijevoza)

Izvor: autori

Sukladno identificiranom potencijalu za promjenu, ukupni ugljični otisak trenutnih obrazaca mobilnosti studenata prikazuje se kroz: 1) optimistični scenarij (Tablica 8), te 2) najvjerojatniji scenarij (Tablica 9). Za svaki je, sukladno potencijalu smanjenja emisija CO_2 prelaskom na održivije načine prijevoza (prema kriteriju u tablici 6 i potencijalu u tablici 7) napravljena i projekcija za cijelu populaciju redovitih studenata Sveučilišta u Rijeci.

Kada bi, sukladno ukupnom identificiranom potencijalu za promjenu prijevoznog ponašanja, studenti prihvatili alternative koje su sposobne zadovoljiti njihove potrebe za prevaljivanjem udaljenosti, ukupne emisije na razini uzorka smanjile bi se za gotovo 70 tona u jednoj akademskoj godini. U idealnom slučaju, na razini Sveučilišta to bi značilo smanjenje ugljičnog otiska za više od 1492,44 tone, odnosno za 41 %. U prosjeku, studenti bi smanjili pojedinačni ugljični otisak za 149,04 kg CO_2e godišnje, no najveći efekt dogodio bi se kada bi studenti koji pri dolasku na fakultet prevaljuju kraće udaljenosti (do 1 km, odnosno do 5 km) automobilom, isti zamijenili pješačenjem ili biciklom.

Tablica 16. Ugljični otisak funkcionalne mobilnosti studenata (kg CO_2e) i potencijalne uštede emisija prijelazom na održivije modalitete – optimistični scenarij*

primarni modalitet	ukupni godišnji CF	godišnji CF po studentu	ukupni CF nakon supstitucije	CF po studentu nakon supstitucije
automobil (n=149)	94 238,37	632,47	47 198,03 (- 49,92 %)	316,77 (- 49,99 %)
JGP (n=214)	70 159,19	327,85	47 579,78 (- 32,18 %)	222,34 (- 32,18 %)
pješačenje (n=100)	5 728,80	57,29	5 450,61 (- 4,86 %)	54,51 (- 4,85 %)
bicikl (n=6)	325,50	54,25	325,5	54,25
Ukupno (n=469)	**170 451,85**	**363,44**	**100 553,91 (- 41,01 %)**	**214,40 (- 41,01 %)**
Ukupno UNIRI (n=10 014)	**3 639 513,54**		**2 147 078,17 (- 41,01 %)**	

*Na bazi prosječnog trajanja nastave u ak. godini na Sveučilištu (30 tjedana; 155 radnih dana)

Izvor: autori

Ipak, vjerojatniji je scenarij u kojem bi promjenu obrazaca mobilnosti ostvarili samo studenti koji su izrazili sklonost promjeni (Tablica 9), pod uvjetom da visokoobrazovna institucija i/ili

jedinice lokalne samouprave, donesu mjere koje bi motivirale njihovu promjenu, a koje ispitanici identificiraju kao: veći izbor i bolja kvaliteta alternativa, restrikcije i naplata parkiranja paralelno sa subvencioniranjem JGP / prostorom za sigurno ostavljanje bicikala, nagrađivanje održivog ponašanja, natjecanje s drugim studentima u uštedama emisija.

Tablica 17. Ugljični otisak funkcionalne mobilnosti studenata (kg CO_2e) i potencijalne uštede emisija prijelazom na održivije modalitete - najvjerojatniji scenarij*

primarni modalitet	ukupni CF	godišnji CF po studentu	ukupni CF - scenarij JGP	ukupni CF - scenarij bicikl	godišnji CF po studentu nakon supstitucije
automobil (n=149)	94 238,37	632,47	89 245,31 (- 5,30 %)	84 761,00 (- 10,06 %)	598,96 (JGP) / 568,87 (bicikl)
JGP (n=214)	70 159,90	327,85	70 159,90	63 719,36 (- 9,18 %)	297,75 (bicikl)
pješačenje (n=100)	5 729,00	57,29	5 729,00	5 695,56 (- 0,58 %)	56,96 (bicikl)
bicikl (n=6)	325,50	54,25	325,50	325,50	54,25
Ukupno (n=469)	**170 452,77**	**363,44**	**165 459,71 (- 2,93 %)**	**154 501,42 (-9,36 %)**	**329,24**
Ukupno UNIRI (n=10 014)	**3 639 513,54**		**3 403 641,38 (- 2,93 %)**	**3 298 926,15 (- 9,36 %)**	

*Na bazi prosječnog trajanja nastave u ak. godini na Sveučilištu (30 tjedana; 155 radnih dana)

Izvor: autori

U scenariju u kojem bi 11 % ispitanika promijenilo izbor primarnog modaliteta najveći potencijal za uštedu CO_2 događa se pri supstituciji motoriziranih oblika prijevoza biciklom. Sukladno kriterijima u Tablici 6, pješačenje nije adekvatna opcija za korisnike motoriziranih modaliteta. Promjenom načinske raspodjele u korist biciklističkog prijevoza, najveće godišnje smanjenje ugljičnog otiska ostvarili bi ispitanici koji trenutno putuju automobilom (-578,22 kg CO_2e / -91,43 %), dok bi na razini skupine korisnika automobila prosječno smanjenje iznosilo 63,6 kg CO_2e ili 10,06 %. Evidentno, u oba scenarija supstitucija prijevoza automobilom alternativama koje zadovoljavaju kriterij prevaljivanja udaljenosti ima najveći potencijal za smanjenje ugljičnog otiska.

4.4 Trošak studentske mobilnosti

Ovim istraživanjem odnos troška i održivosti studentske mobilnosti promatra se kroz prizmu potrebe smanjenja ugljičnog otiska i drugih negativnih utjecaja prometa uvođenjem mjera upravljanja prometnom potražnjom i intervencija u prijevoznom sustavu grada s ciljem. Razlika u troškovima utvrđena je u odnosu na scenarije više održivog prometnog ponašanja. Trošak funkcionalne mobilnosti pješačenjem ili biciklom se učestalo vrednuje kroz uštede u odnosu na korištenje automobila i iskazuje kroz koristi za zdravlje koje aktivni oblici mobilnosti donose. Ne određuje se monetarnom vrijednošću jer je vrijednost jako blizu 0, što podupiru postojeća istraživanja (Van Ommeren i Fosgerau, 2009). Kod automobilskog prijevoza uvaženi su direktni troškovi (cijena goriva (HAK, 2025) - potrošnja prema tipu vozila (Spritmonitor.de) na osnovu dnevno prevaljene udaljenosti od mjesta stanovanja do fakulteta (input ispitanika)), i procijenjeni indirektni troškovi (koji uključuju realne podatke o minimalnom trošku tehničkog pregleda vozila u odnosu na tip i motor vozila (Centar za vozila Hrvatske; HAK, n.d.), prosječni trošak obveznog automobilskog osiguranja u Republici Hrvatskoj (Kompare.hr), i trošak redovitog servisa (input ispitanika), prema dostupnim izvorima za usporedbu. Nisu uključeni troškovi kasko osiguranja, cestarina, parkiranja, nabave i zamjene ljetnih/zimskih guma, koji su proizvoljne naravi.

Kada se godišnji troškovi korištenja preferiranog modaliteta stave u odnos s alternativama, sukladno potencijalu za promjenu prema primijenjenom kriteriju moguće je izvesti određene zaključke o odnosu održivosti (ugljičnog otiska) i cijene mobilnosti u oba scenarija.

Tablica 18. Trošak funkcionalne mobilnosti studenata (u EUR) prema utvrđenim obrascima i projekcija troška - optimistični scenarij*

primarni modalitet	ukupni godišnji trošak mobilnosti	prosječni godišnji trošak mobilnosti po studentu	prosječni dnevni trošak mobilnosti po studentu	ukupni godišnji trošak mobilnosti nakon supstitucije	prosječni dnevni trošak mobilnosti po studentu nakon supstitucije
automobil (n=149)	91.225,57	612,25	3,95	45.178,56 (- 50,48 %)	0 – 3,95
JGP (n=214)	71.155,00	332,50**	2,14**	53.865,00 (- 24,30 %)	0 - 2,14**
pješačenje (n=100)	0	0	0	0	0
bicikl (n=6)	0	0	0	0	0
Ukupno (n=469)	**162.380,57**	**346,23**	**2,24**	**99.043,56 (- 39,01 %)**	**1,36 (- 39,28 %)**
Ukupno UNIRI (n=10 014)	**3.467.158,64**			**2.114.620,01 (- 39,01 %)**	

*Na bazi prosječnog trajanja nastave u ak. godini na Sveučilištu (30 tjedana; 155 radnih dana)
**Pod uvjetom kupnje mjesečne karte

Izvor: autori

Rezultati istraživanja gledani sumarno ukazuju da primarni izbor sredstava s manjim ugljičnim otiskom (i s njima povezana mobilnost) znači i manji trošak mobilnosti za studente. Kako su poduzete sve mjere da kvantifikacija troškova mobilnosti bude objektivna, u slučaju optimističnog scenarija hipoteza istraživanja se smatra potvrđenom za ispitanike čiji su primarni izbor motorizirani oblici prijevoza. S obzirom da je za pješačenje i vožnju biciklom trošak mobilnosti 0 €, nije moguće testirati pretpostavku hipoteze na međusobnom odnosu tih modaliteta. Iako su emisije vožnje biciklom niže od emisija pješačenja, benefiti oba načina aktivne mobilnosti nadilaze negativne utjecaje na pojedince i društvo u cjelini.

Iskorištavanjem maksimalnog potencijala supstitucije modaliteta održivijim alternativama zbirni troškovi mobilnosti studenata smanjili bi se za 39 %, što je gotovo proporcionalno smanjenju ukupnih emisija (41 %). Najveće uštede ostvarili bi studenti čiji je primarni izbor trenutno automobil, no koji prevaljuju kraće udaljenosti i/ili čije putovanje traje do 30 minuta, te bi za svoje odlaske na fakultet mogli odabrati modalitet manjeg ugljičnog otiska. U tom slučaju, dnevni trošak mobilnosti bio bi u rasponu od 0 € (bicikl, pješačenje) do 2,14 € (JGP), što bi na razini akademske godine činilo uštedu od 612,25 €, odnosno 279,75 €.

Tablica 19. Trošak funkcionalne mobilnosti studenata (u EUR) prema utvrđenim obrascima i projekcija troška - najvjerojatniji scenarij

primarni modalitet	ukupni godišnji trošak mobilnosti	prosječni godišnji trošak mobilnosti	prosječni dnevni trošak mobilnosti	Trošak mobilnosti - scenarij JGP		Trošak mobilnosti – scenarij bicikl	
				ukupni	pros. dnevni	ukupni	pros. dnevni
automobil (n=149)	91.225,57	612,25	3,95	86.640,44 (- 5,03 %)	2,14 - 3,95	81.190,76 (- 11,00 %)	0 - 3,95
JGP (n=214)	71.155,00	332,50**	2,14**	71.155,00	2,14**	63.327,95 (- 11,00 %)	0 - 2,14**
pješačenje (n=100)	0	0	0	0	0	0	0
bicikl (n=6)	0	0	0	0	0	0	0
Ukupno (n=469)	**162.380,57**	**346,23**	**2,24**	**157.795,44 (- 2,82 %)**	**2,17**	**144.518,71 (- 11,00 %)**	**1,99**
Ukupno UNIRI (n=10 014)	**3.467.158,64**			**3.369.257,33 (- 2,82 %)**	**2,17**	**3.085.771,33 (- 10,99 %)**	

*Na bazi prosječnog trajanja nastave u ak. godini na Sveučilištu (30 tjedana; 155 radnih dana)
**Pod uvjetom kupnje mjesečne karte

Izvor: autori

Kada bi se 11 % ispitanih studenata, koji primarno izabiru automobil za kretanje do fakulteta, odlučilo za prijevoz JGP-om, na razini ukupnog troška dogodilo bi se smanjenje od 2,82 %. Na individualnoj razini to bi značilo uštedu od 279,75 € u akademskoj godini. Ukupni trošak mobilnosti bio bi mnogo manji (0 €) kada bi se isti udio studenata odlučio za prijevoz biciklom. U scenariju najvjerojatnije supstitucije to indicira smanjenje ukupnih troškova studentske mobilnosti za 11 %, te potencijalnu uštedu od 346,23 € u jednoj akademskoj godini.

5. DISKUSIJA REZULTATA ISTRAŽIVANJA

Determinante prijevoznog ponašanja studenata treba identificirati prije uvođenja mjera upravljanja mobilnošću (Chavis i Gayah, 2017; Dawood i Rahmat, 2015), a kako bi analiza obrazaca mobilnosti imala svrhu, primarno istraživanje uvažava potencijal za promjenu, u funkciji unaprjeđenja ekološke i ekonomske održivosti ponašanja ove populacijske skupine.

U konkretnom slučaju raspon dostupnih modaliteta je ograničen, a studenti su većinom skloni „klasičnim“ oblicima mobilnosti. Unatoč načinskoj raspodjeli u korist JGP, najveće ukupne emisije CO_2 povezane su s korištenjem automobila – kao i u prethodnim istraživanjima (Sobrino i Arce, 2021). Uz izbor automobila kao primarnog modaliteta za odlazak na fakultet veže se i najveći potencijal za smanjenje utjecaja na okoliš, što je u skladu s istraživanjem Ribeiro i Fonseca (2022). Primarno istraživanje potvrđuje i da je supstitucijom automobila s alternativama na kraćim udaljenostima potencijal smanjenja godišnjih emisija CO_2 veći od 40%, što potvrđuje zaključke istraživanja Mesarec i Trček (2024).

Ovim istraživanjem dokazano je da trošak prijevoza studenata pokazuje potencijal smanjenja u slučaju smanjenja emisija CO_2. Najveći potencijal za uštede predstavlja supstitucija automobilskog prijevoza alternativama. Trošak goriva osnova je kalkulacije direktnog troška automobilske mobilnosti, no indirektni troškovi, koje vozači često značajno podcjenjuju (Andor et al., 2020), utječu na odnos veličina s troškovima prijevoza alternativama. Vrijednost indirektnog troška prijevoza automobilom određena je konzervativno (prema dostupnim izvorima), čime je minimiziran potencijalni utjecaj subjektivizma na formirane odnose među modalitetima i izvedene zaključke.

Rezultati provedenog istraživanja imaju ekološku, ekonomsku i društvenu važnost jer indiciraju da i u slučaju vjerojatnijeg scenarija iskorištavanje potencijala za promjenu prijevoznog ponašanja studenata ostvaruje pozitivne efekte. Trošak prijevoza u ovom istraživanju nije se pokazao kao primarna determinanta izbora modaliteta, kao ni u postojećim istraživanjima (Lodi et al., 2024; Turay et al., 2024). Ipak, trošak prijevoza smatra se mjerom urbanog prometnog planiranja u poticanju društvene održivosti (El-Geneidy, et al., 2016), a kvantifikacija troška u ovom istraživanju potvrđuje da su održivije opcije jeftinije za pojedinca, kao što su i manje opterećenje za društvo (EEA, 2023).

Jedno od ograničenja istraživanja čini prostorna disperzija Sveučilišta u Rijeci te različite (gradske i prigradske) lokacije pojedinih sastavnica, studentskog smještaja i drugih sadržaja, što se odražava na potrebu za prevaljivanjem udaljenosti i mogućnost izbora modaliteta. Korelacija aktivnih modaliteta i kratkih udaljenosti (Turay et al., 2024) ukazuje na izrazitu ograničenost potencijala pješačenja u primarnom istraživanju (nije adekvatna opcija za većinu korisnika motoriziranih modaliteta). Pitanje lokacije stanovanja u odnosu na matični fakultet bitan je utjecaj na obrasce mobilnosti u smislu udaljenosti i trajanja putovanja, troškova i izbora načina prijevoza budući postoje sastavnice Sveučilišta na prigradskoj lokaciji, gdje ne postoji studentski smještaj, zbog čega sadržaje smještaja i prehrane studenti koriste u kapacitetima Studentskog centra u Rijeci, kao što postoje i studenti s adresom na prigradskoj lokaciji, koji zbog studija redovito putuju u grad.

Izostanak multimodalnosti među studentima u primarnom istraživanju implicira smanjenu vjerojatnost supstitucije automobila modalitetima manjeg ugljičnog otiska (Lowry, 2024), a potencijalni doprinos smanjenju ugljičnog otiska i troškova mobilnosti do 50 % (C2ES, n.d.) koji je moguće ostvariti dijeljenjem vožnji uvelike je zanemaren. Razlika objektivnog potencijala za održiviju mobilnost (ukupno 85 % na razini automobilskog prijevoza) i stvarne spremnosti na promjenu (11 % studenata) produkt je izostanka upravljanja prijevoznom potražnjom na razini Sveučilišta, te nedostajuće ponude alternativa. Nepostojanje adekvatne infrastrukture i pratećih sadržaja, te vrlo mali udio biciklističkog prijevoza u uzorku, potvrđuje se i važnost fizičkih preduvjeta za promjenu ponašanja studenata (Aliari et al., 2020; Le Pira et al., 2024) unutar udaljenosti koje određuju potencijal za promjenu (Hossain et al., 2022).

S obzirom da online ispitivanja imaju svojih nedostataka, koji se mogu odraziti na kvalitetu podataka zbog samoprocjene i potrebe za davanjem društveno prihvatljivih odgovora, studenti nisu ispitivani o percepciji vlastitog ponašanja. Fokus pitanja je na objektivnim parametrima mobilnosti, postavljena su neutralnim stilom, a ispitivanje je anonimizirano. Anulirani su odgovori u kojima je utvrđena nekonzistentnost ili čiji je unos trajao kraće od vremena potrebnog za pročitati pitanja. Svi prezentirani rezultati (prevaljene udaljenosti, trajanje putovanja, ekološki otisak, potencijal za smanjenje emisija CO_2, troškovi povezani s različitim obrascima mobilnosti) šire spoznaju prethodnih istraživanja i potencijalno dodatno informiraju prometne politike i prometno planiranje u gradovima. U konkretnom slučaju jasno je koji bi modalitet mobilnosti studenata bio okolišno i ekonomski najprihvatljiviji. Uvjeti u okruženju i neprepoznatost aktivne mobilnosti kao ravnopravnog modaliteta među studentima djeluju limitirajuće.

Percepcija predanosti javnih vlasti održivosti, uz vlastite vrijednosti i društvene norme, snažna je determinanta usvajanja održivih prijevoznih opcija (Zhang et al, 2026). U konkretnom slučaju potrebno je primijeniti sustavni pristup promjeni obrazaca mobilnosti, koji integrira planiranje, politike, nove tehnologije i stvaranje infrastrukture alternativama, te omogućiti dostupnost i povezanost (Sobrino i Arce, 2021; Sottile et al., 2021), diversificirati ponudu prijevoza (Lowry, 2024) i povećati zadovoljstvo korisnika (Stojić et al., 2020) paralelno sa smanjenjem emisija CO_2. Održiviji prijevoz otporniji je na nestabilne cijene energenata, podupire društvenu jednakost i dugoročno stabilniji urbani razvoj (UNDP, 2025).

6. ZAKLJUČAK

Većina istraživanja studentske mobilnosti koja uključuju aspekt troška isti promatraju kao utjecajni faktor odlučivanja o izboru modaliteta. Ovim istraživanjem kvantificirane su razlike u troškovima mobilnosti u odnosu na promjene razine održivosti obrazaca funkcionalne mobilnosti studenata. Cilj istraživanja je ostvaren kvantifikacijom troška postojećih obrazaca mobilnosti (dnevnih i na bazi akademske godine), i mogućih obrazaca u kontekstu dva scenarija više održivog prijevoznog ponašanja. Iako mobilnošću ispitanih studenata ne dominira automobil, najviše ukupnih emisija CO_2 koje proizlaze iz putovanja na predavanja generira upravo prijevoz automobilima. Uz to, mnogo dnevnih putovanja realizira se modalitetima koji ne odgovaraju potrebi za prevaljivanjem udaljenosti, te proizlazi kako ni trošak ni održivost nisu primarne determinante izbora modaliteta za većinu ispitanih studenata.

Analizom je identificiran neiskorišteni potencijal za promjenu obrazaca mobilnosti prema održivijim (aktivnim) modalitetima, što implicira emisijske i monetarne uštede, kojima bi promjena prijevoznog ponašanja doprinijela. Ovim radom kvantifikacija troškova prijevoza stavljena je u odnos s razinom održivosti, što je bitnije od utvrđenih apsolutnih vrijednosti troškova, koji su također dio rezultata primarnog istraživanja. Potvrđeno je da održiviji obrasci mobilnosti sa sobom nose manje troškove, što je bitan argument u ostvarivanju promjene ponašanja (različitim mjerama i politikama definiranim na razini pojedinog grada), a potvrđuje postavljenu hipotezu.

U kontekstu utjecaja na društvenu zajednicu, mnogo postojećih istraživanja potvrđuje koristi (i potrebu) smanjenja udjela automobila u načinskoj raspodjeli. Prijevozno ponašanje studenata izravno se odražava na lokalnu i regionalnu održivost, a objektivne okolnosti (npr. dostupne alternative, izgrađeni okoliš, individualni aspekti) oblikuju mobilnost studenata u obrascima koji ukazuju na njihove buduće preferencije. S ciljem tranzicije prema održivijim obrascima mobilnosti studenata, potrebno je uzeti u obzir razloge izbora primarnog modaliteta prijevoza i sukladno inputima koje generiraju podaci o stavovima, preferencijama i faktorima ponašanja definirati mjere politike upravljanja prijevoznom potražnjom, kao i politika koje adresiraju stanovanje i zdravlje.

S obzirom na učinjenu kvantifikaciju ugljičnog otiska te troška prijevoza studenata, bilo bi svrhovito proširiti istraživanje u smjeru raspoloživog budžeta studenata i utvrditi ulogu troškova mobilnosti u odnosu na raspoloživi budžet. U kontekstu urbane mobilnosti, utvrđeni odnos ekološke i ekonomske kvantifikacije obrazaca mobilnosti bilo bi zanimljivo istražiti u odnosu na funkcionalnu mobilnost radno aktivnog dijela populacije, čiji su obrasci uvjetovani radnim vremenom i manje subvencionirani od prijevoza studenata. Potencijalno, obuhvatom ovih dviju velikih skupina, urbano prometno planiranje bi dobilo mnoge inpute o slabostima i potencijalu trenutnog stanja prometnog sustava. Širenje obuhvata ovog istraživanja omogućilo bi preciziranje ekonomskog utjecaja promjene obrazaca mobilnosti, budući je društveni kontekst ovim radom razmotren, no kvantifikacija troška najpreciznija je na razini pojedinca.

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Original Scientific Paper

ECONOMIC QUANTIFICATION OF THE SUSTAINABILITY OF STUDENTS' TRAVEL BEHAVIOR

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ABSTRACT

Research indicates that student mobility is frequently contingent on contextual factors and attributes of planned mobility. Nevertheless, the economic dimension of their transport behaviour has received comparatively little attention. The establishment of a relationship between the financial implications and environmental impact of student mobility would provide a strong rationale for the development of urban transportation planning, infrastructure investments in alternative transportation modes, and enhancements to the urban transportation system, while contributing to the enhancement of the quality of life in university cities. The purpose of this paper is to undertake an economic quantification of student mobility patterns. The objective is twofold: to ascertain the cost of prevailing mobility patterns, and to make a cost projection in scenarios of more sustainable transport behaviour, according to the available modalities, at the individual and student population levels. The methodological approach incorporates a combination of primary and secondary research methods. The determination of student mobility patterns was achieved through the implementation of an online survey. Utilising the carbon footprint methodology, mobility patterns were translated into a measure of environmental impact. A financial valuation of student mobility incorporates real market prices (e.g., fuel prices, public transport fees) in relation to the mode of mobility and the actual distance travelled. The findings of the research indicate the potential for reducing the environmental and economic burden of student mobility, and that adopting lower carbon footprint modalities also implies lower mobility costs. This work contributes to the field of student mobility research by expanding the range of evaluation aspects.

Key words: *student mobility patterns, commuting, carbon footprint, cost of mobility*

Original Scientific Paper

DETERMINANTS OF SUSTAINABLE AND ATTRACTIVE RAILWAY TOURISM EXPERIENCE

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ABSTRACT

Railway tourism as a form of sustainable tourism is gaining importance due to the environmental benefits and possibility of experiencing variety of natural and cultural attractions, landscape, thematic routes, gastronomy and authenticity. In addition, it contributes to development of unique tourism offer that captures heritage and identity elements (e. g., historical trains and historical railway routes). The purpose of this study is to examine the determinants of railway tourism attractiveness and to point out the potential of railway tourism as important factor of sustainable tourism development. In particular, the present study aims to empirically explore the importance of elements that determine the attractiveness of railway tourism, focusing on potential tourists/passengers' perspective. Based on literature review, measurement variables from past research were adopted. Data was gathered with online and onsite questionnaires and analysed with univariate and bivariate statistical methods. The results indicate that travel comfort, staff, reliability, safety and security, accessibility, landscape along the route, and adventure and exploration are important determinants of railway tourism attractiveness. Therefore, the results imply that the focus on these service elements may enhance railway tourism experience and contribute to development of attractive tourism offer of a high quality.

Key words: *railway tourism, sustainable tourism development, tourism attractiveness elements, tourists' importance perspective*

1. INTRODUCTION

The contemporary tourist is increasingly aware of the need for sustainable development and the preservation of limited resources, with the aim of tourism attractiveness protection. Changes in tourism demand are continuous, therefore, tourism supply stakeholders must devote significant attention to researching tourism demand and designing offerings capable of responding to the constantly evolving needs of contemporary tourists. In this context, rail travel is gaining strategic importance in tourism, as it enables the development of environmentally responsible tourism offerings while creating opportunities for new and distinctive tourism products and services.

Recent research highlights that railways and train travel do not merely constitute a more sustainable mode of transport, but also represent a potentially strong element of tourism product differentiation (Peira et al., 2022). In this context, the revitalization of neglected and underutilized railway lines creates opportunities for the development of innovative, experience-oriented, and interpretively rich tourism products.

Although transport, as a distinct scientific discipline, is widely acknowledged as a key driver of tourism development and a critical factor in linking tourism demand and supply, railway transport in Croatia continues to play a marginal role in tourist mobility patterns. This can be

attributed primarily to outdated infrastructure, the lack of competitive and attractive tourism products, and an insufficient recognition of the need to establish synergies between the tourism product and the railway sector (ETC, 2020).

Despite these limitations, railway transport demonstrates considerable development potential, particularly within the framework of sustainable tourism and the enhancement of destination accessibility, which is widely regarded as a prerequisite for strengthening the overall competitiveness of Croatia's tourism sector. Building on these assumptions, this study seeks to explore the possibilities of integrating railway transport into the existing tourism product of the Republic of Croatia, by evaluating the perceived attractiveness of railways as a component of tourism offerings design and development.

2. RAILWAY TOURISM EXPERIENCE

According to Jensen and Bird (2024), the concept of railway tourism encapsulates the experience and/or symbolic consumption, related to traveling by train, including the experience of railway architecture and visiting railway museums. Rail tourism studies acknowledge the heritage value as well as the social, cultural, and experiential significance of train travel. In addition, railway tourism encompasses railway heritage, attractions management, slow tourism, and low-carbon tourism transitions (Jensen and Larsen, 2021).

A systematic literature review suggests that railways in tourism perform a multifaceted function: as critical infrastructure underpinning destination accessibility, as a mechanism for fostering territorial cohesion, and as a tourism product itself (Peira et al., 2022). Notably, the adaptive reuse of abandoned railway lines into tourism itineraries can act as a catalyst for the revitalization of rural and peripheral areas, generating new development opportunities and extending visitors' length of stay (Ristić et al., 2024). In this context, railway infrastructure is reconfigured from a passive asset into an active instrument of destination development.

In addition, modern tourism trends place emphasis on the importance of experience, authenticity, and emotional connection with the destination. In line with the concepts of experiential and slow tourism, rail travel, particularly along scenically unique and historically important routs, enables a slower mode of mobility, direct sensory engagement with the landscape, and the development of a "journey through time" experience (Bayraktar and Selçuk, 2022). Instead of being passive consumers of destinations' offerings, these forms of mobility allow tourists to actively co-create place-based experiences.

Similarly, according to Cavallaro et al. (2022), emotional factors play a significant role in the decision-making process related to railway travel, including nostalgia for past times and the pursuit of authentic experiences. These factors also have a big effect on the perceived value of the tourism product.

However, despite the identification of key determinants of attractiveness, the examination of tourists' perceptions regarding the importance of individual elements remains insufficiently addressed in the existing scientific literature (Cavallaro et al., 2022). In order to create a sustainable tourism product, it is essential to understand how potential tourists assess various aspects of railway tourism. Namely, these perceptions have a direct impact on travel decisions and destination choice. Therefore, analysing the perceived importance of specific elements represents a critical step in the development of competitive tourism offer.

Furthermore, tourism research consistently confirms the existence of significant differences in preferences and perceptions across various demographic groups, influenced by factors such as age, education, and prior travel experience, all of which affect the evaluation and attractiveness of tourism products (Taylor, 2015). These differences may be particularly pronounced in the context of railway tourism, as it attracts heterogeneous groups of tourists,

ranging from railway enthusiasts, to those motivated by sustainability aspects or the experiential dimension of travel (UIC, 2024b).

3. STUDY METHODOLOGY

Following previously described theoretical framework, the present study aims to empirically explore the importance of elements that determine the attractiveness of railway tourism. For this purpose, following research questions are intended to be addressed:

RQ1: How potential tourists perceive the importance of elements that determine the attractiveness of railway tourism?

RQ2: Are there significant differences between different demographic groups regarding the perceived levels of importance for attractive railway tourism elements?

To answer research questions, following literature-based elements of attractive railway tourism experience were adopted (Taylor, 2015; Lee, Chen, 2016; Ristić et al., 2024; UIC, 2024a; Naletina et al., 2025): accessibility, authenticity, complementary amenities along the route, railway heritage interpretation, cooperation with local community, uniqueness, sustainability, personalized experience, landscape along the route, security and safety, adventure and exploration, novelty, reliability, innovation and digital content, travel comfort, staff, basic services on train, complementary services on train, complementary services at railway station, and attractiveness.

The questionnaire consisted of two parts. The first part measured the importance of each element of attractive railway tourism experience, using Likert-type scale with 5 scores, from “very unimportant” (as 1) to “very important” (as 5). To ensure that respondents clearly understood the meaning of each element, the list of attractiveness elements was accompanied by brief explanations of the individual terms. The second part consisted of questions for describing demographic profile of the respondents.

The questionnaires were distributed online and onsite during the two-month period from December 2025 to January 2026 to potential tourists/passengers in Croatia. Data collection was based on convenience sampling procedure and ended with 152 valid responses.

Univariate and bivariate statistical analyses were used to analyse collected data. Descriptive statistical analysis was performed to describe the respondents’ profile and to empirically evaluate the level of importance for each element of railway tourism attractiveness. In addition, significance of difference in the levels of importance regarding different demographic groups of the respondents was tested using independent samples t-test.

4. STUDY RESULTS

This section presents the results of descriptive and bivariate statistical analyses, as follows. Firstly, sample demographic information is described, followed by the presentation of perceived importance of railway tourism attractiveness elements mean scores. Finally, the results of testing the significance of difference between different demographic groups regarding perceived importance mean scores are shown.

Sample structure consisted predominantly of female respondents (59.2 per cent). On average, respondents were 32 years of age, mostly from bigger cities in Croatia (64.5 per cent). More than half of them (51.3 per cent) completed high level of education. Respondents were predominantly employed (61.8 per cent). The majority of them (72.4 per cent) was familiar with the railway tourism as specific tourism product, and 25 per cent of the respondents reported previous experience with railway tourism.

The results of descriptive analysis for each element of railway tourism attractiveness are summarized in Table 1.

Table1. Descriptive statistics for railway tourism attractiveness elements

Attractiveness elements	Mean	Standard deviation
Accessibility	4.40	0.871
Authenticity	4.05	0.933
Complementary amenities along the route	4.03	1.038
Railway heritage interpretation	3.66	1.122
Cooperation with local community	4.03	1.003
Uniqueness	4.04	1.022
Sustainability	3.72	1.123
Personalized experience	3.93	1.014
Landscape along the route	4.24	0.935
Security and safety	4.51	0.780
Adventure and exploration	4.23	0.938
Novelty	3.94	1.050
Reliability	4.55	0.796
Innovation and digital content	3.80	1.069
Travel comfort	4.63	0.697
Staff	4.58	0.742
Basic services on the train	4.31	0.937
Complementary services on train	3.42	1.310
Complementary services at railway station	3.47	1.179
Attractiveness	3.80	1.100

Note: mean scores range from 1 (very unimportant) to 5 (very important)

Source: Authors

As reported in Table 1, perceived importance means scores ranged from 3.42 to 4.63, implying medium to very high importance of individual railway tourism attractiveness elements. Respondents assessed travel comfort, staff, reliability, and security and safety with the highest mean scores (from 4.51 to 4.63), implying that fundamental service quality and safety aspects are the most important determinants of attractive railway tourism experience.

Relatively high mean scores (from 4.23 to 4.40) were recorded for accessibility, basic services on the train, landscape along the route, and adventure and exploration, indicating that respondents valued the importance of scenic and experiential aspects of the railway tourism journey. Elements related to authenticity, uniqueness, complementary amenities along the route, cooperation with the local community, personalized experience, and novelty were observed as important (mean scores from 3.94 to 4.05). As moderately important were assessed elements considering attractiveness, innovation and digital content, sustainability, and railway heritage interpretation (mean scores from 3.66 to 3.80). The lowest mean scores (from 3.42 to 3.47) were given to complementary services on the train and to complementary services at railway station, suggesting that these services are perceived as less important for railway tourism attractiveness.

Next, the comparison of importance mean scores between different demographic groups was performed. The analysis comprises mean scores comparisons regarding the respondents' gender, age and place of residence. The results are demonstrated in Table 2.

The analysis of difference in perceived importance mean scores for railway tourism attractiveness elements indicated higher scores in the female sample for most of the elements. Only for five elements (railway heritage interpretation, uniqueness, complementary services on train, innovation and digital content, and attractiveness) the scores were higher in the male sample. However, the t-test results showed that in 3 out of 20 elements these differences were significant. These results indicated that female respondents perceived adventure and exploration, travel comfort, and staff as significantly more important than male respondents.

In terms of different age groups, the comparison of mean scores revealed differences in level of importance for attractiveness elements between respondents aged 30 years or less, and respondents that are older than 30 years. Higher mean scores for the majority of elements were recorded by the respondents above 30 years of age. For six elements (railway heritage interpretation, personalized experience, novelty, complementary services on train, complementary services at railway station, and attractiveness) the scores were higher in the sample of younger respondents. In contrast, the t-test results revealed that in 5 out of 20 elements these differences were significant. These results implied that respondents above 30 years of age gave significantly higher scores to the accessibility, authenticity, cooperation with local community, and landscape along the route than younger respondents. In addition, respondents bellow 30 years of age observed innovation and digital content as significantly more important than those who are older than 30 years.

Finally, the analysis of difference in perceived importance mean scores regarding the place of residence indicated higher scores in the sample of town residents for majority of the elements. For eight elements (uniqueness, novelty, innovation and digital content, travel comfort, staff, basic services on the train, complementary services on train, complementary services at railway station) the scores were higher in the sample of city residents. However, the t-test results showed that in 2 out of 20 elements these differences were significant. These results indicated that town residents perceived cooperation with local community and sustainability elements as significantly more important than city residents.

Table 2. The comparison of perceived importance mean scores for railway tourism attractiveness elements

Attractiveness elements	Gender			Age			Place of residence		
	Male	Female	T-value	30 years and less	Above 30 years	T-value	City	Town	T-value
Accessibility	4.27 (0.890)	4.49 (0.851)	-1.500	4.22 (0.989)	4.59 (0.681)	-2.747**	4.37 (0.913)	4.46 (0.794)	-0.647
Authenticity	3.92 (0.946)	4.14 (0.919)	-1.467	3.87 (0.958)	4.24 (0.873)	-2.494*	3.96 (0.930)	4.22 (0.926)	-1.673
Complementary amenities along the route	3.95 (1.078)	4.09 (1.013)	-0.800	3.96 (1.156)	4.11 (0.900)	-0.875	4.03 (1.069)	4.04 (0.990)	-0.036
Railway heritage interpretation	3.82 (1.000)	3.54 (1.191)	1.557	3.72 (1.150)	3.59 (1.097)	0.676	3.62 (1.089)	3.72 (1.188)	-0.523
Cooperation with local community	3.85 (1.099)	4.14 (0.919)	-1.762	3.83 (1.098)	4.23 (0.853)	-2.477*	3.78 (1.005)	4.28 (0.751)	-2.045*
Uniqueness	4.08 (1.045)	4.01 (1.011)	0.411	3.90 (1.135)	4.19 (0.871)	-1.784	4.06 (1.024)	4.00 (1.028)	0.352
Sustainability	3.71	3.73	-0.127	3.63	3.82	-1.083	3.58	3.90	-2.012*

Attractiveness elements	Gender			Age			Place of residence		
	Male	Female	T-value	30 years and less	Above 30 years	T-value	City	Town	T-value
	(1.165)	(1.100)		(1.229)	(0.998)		(1.154)	(1.071)	
Personalized experience	3.77 (1.062)	4.04 (0.970)	-1.623	3.94 (1.036)	3.92 (0.998)	0.021	3.90 (1.050)	4.00 (0.952)	-0.592
Landscape along the route	4.19 (1.084)	4.28 (0.821)	-0.545	4.01 (1.051)	4.49 (0.726)	-3.247**	4.23 (0.928)	4.26 (0.955)	-0.155
Security and safety	4.44 (0.880)	4.57 (0.704)	-1.019	4.41 (0.918)	4.62 (0.590)	-1.698	4.48 (0.852)	4.57 (0.633)	-0.713
Adventure and exploration	3.98 (1.123)	4.40 (0.747)	-2.554*	4.13 (1.085)	4.34 (0.745)	-1.394	4.21 (1.018)	4.26 (0.782)	-0.282
Novelty	3.92 (1.091)	3.96 (1.027)	-0.208	3.96 (1.062)	3.92 (1.044)	0.249	3.97 (1.010)	3.89 (1.127)	0.437
Reliability	4.45 (0.899)	4.62 (0.712)	-1.248	4.49 (0.922)	4.62 (0.635)	-1.052	4.55 (0.801)	4.56 (0.793)	-0.034
Innovation and digital content	3.89 (0.994)	3.73 (1.120)	0.871	4.10 (0.891)	3.47 (1.149)	3.760**	3.83 (1.065)	3.74 (1.085)	0.472

Attractiveness elements	Gender			Age			Place of residence		
	Male	Female	T-value	30 years and less	Above 30 years	T-value	City	Town	T-value
Travel comfort	4.47 (0.824)	4.74 (0.572)	-2.291*	4.63 (0.723)	4.64 (0.674)	-0.061	4.66 (0.703)	4.57 (0.690)	0.754
Staff	4.39 (0.930)	4.71 (0.546)	-2.467*	4.49 (0.879)	4.68 (0.552)	-1.592	4.58 (0.798)	4.57 (0.633)	0.060
Basic services on the train	4.15 (0.989)	4.42 (0.887)	-1.806	4.22 (0.989)	4.41 (0.875)	-1.235	4.37 (0.890)	4.20 (1.016)	1.031
Complementary services on train	3.53 (1.352)	3.34 (1.282)	0.868	3.62 (1.282)	3.22 (1.317)	1.894	3.50 (1.262)	3.28 (1.393)	1.001
Complementary services at railway station	3.34 (1.200)	3.56 (1.162)	-1.115	3.53 (1.181)	3.41 (1.181)	0.627	3.49 (1.133)	3.43 (1.268)	0.319
Attractiveness	3.82 (1.000)	3.78 (1.169)	0.246	3.94 (0.902)	3.65 (1.265)	1.604	3.80 (1.055)	3.80 (1.188)	-0.002

Note: values in parentheses are standard deviations; * $p < 0.05$; ** $p < 0.01$

Source: Authors

5. CONCLUSION

The present study was conducted to highlight the determinants of attractive and sustainable railway tourism experience. The results provide the perceptions of importance of railway tourism attractiveness elements, as well as comparison of perceived importance levels between selected demographic groups of respondents. In particular, the role of respondents' gender, age and place of residence was examined.

Addressing the first research question (RQ1), study results demonstrate medium to very high importance of railway tourism attractiveness elements. The greatest emphasis was placed on core service quality and safety-related elements. Namely, the highest importance was assigned to travel comfort, staff, reliability, and security and safety, confirming that the fundamental operational service performance is the key determinant of an attractive railway tourism experience. In addition, scenic and experiential components such as accessibility, landscape, and opportunities for adventure, were also highly valued. What is more, authenticity-related and innovative elements were perceived as moderately important. In contrast, the additional services offered on the train and at the railway stations were rated as less important, although positive, indicating they have secondary role in shaping the overall attractiveness perceptions.

With respect to second research question (RQ2), the results reveal that significant differences between selected demographic groups exist, although they are limited to specific elements. This means that in general, different groups of respondents reported similar assessments of perceived importance and that general perceptions of attractiveness are relatively consistent across observed demographic groups. However, in some cases significant differences are detected, showing that specific attractiveness elements are significantly influenced by demographic characteristics. In particular, female respondents placed significantly higher importance on adventure and exploration, travel comfort, and staff compared to males. Respondents above 30 years valued accessibility, authenticity, cooperation with local community, and landscape significantly more strongly, whereas younger respondents emphasized innovation and digital content. Furthermore, town residents assigned significantly greater importance to cooperation with local community and to sustainability compared to city residents.

Given the multidisciplinary nature of railway tourism, these findings have important implications for both the transport and tourism sectors. Managers can create more specialized and competitive railway tourism products, tailored to different groups of potential tourists. Additionally, these insights help stakeholders to better align service attributes with the preferences of various market segments.

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ODREDNICE ODRŽIVOG I ATRAKTIVNOG TURISTIČKOG ISKUSTVA U ŽELJEZNIČKOM PROMETU

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SAŽETAK

Željeznički turizam kao oblik održivog turizma dobiva na važnosti zbog ekoloških prednosti i mogućnosti doživljavanja raznih prirodnih i kulturnih atrakcija, krajolika, tematskih ruta, gastronomije i autentičnosti. Osim toga, doprinosi razvoju jedinstvene turističke ponude koja obuhvaća elemente baštine i identiteta (npr. povijesni vlakovi i povijesne željezničke rute). Svrha ove studije je ispitati odrednice atraktivnosti željezničkog turizma i istaknuti potencijal željezničkog turizma kao važnog čimbenika održivog razvoja turizma. Posebno, ova studija ima za cilj empirijski istražiti važnost elemenata koji određuju atraktivnost željezničkog turizma, s naglaskom na perspektivu potencijalnih turista/putnika. Na temelju pregleda literature usvojene su mjerne varijable iz prošlih istraživanja. Podaci su prikupljeni putem online i upitnika na licu mjesta te analizirani univarijatnim i bivarijatnim statističkim metodama. Rezultati pokazuju da su udobnost putovanja, osoblje, pouzdanost, sigurnost i zaštita, dostupnost, krajolik duž rute te avantura i istraživanje važne odrednice atraktivnosti željezničkog turizma. Stoga rezultati impliciraju da fokus na ove elemente usluge može poboljšati iskustvo željezničkog turizma i doprinijeti razvoju atraktivne turističke ponude visoke kvalitete. Ključne riječi: željeznički turizam, održivi razvoj turizma, elementi turističke atraktivnosti, perspektiva važnosti turista

Ključne riječi: *željeznički turizam, održivi razvoj turizma, elementi turističke atraktivnosti, perspektiva važnosti turista*