Universal Library of Innovative Research and Studies Research Article

ISSN: 3065-0003 | Volume 2, Issue 3

Open Access | PP: 68-74

DOI: https://doi.org/10.70315/uloap.ulirs.2025.0203013

Multimodal Route and Inventory Optimization for the Supply of Inert Materials and Refrigerated Cargoes within the Trans-European Corridors

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Abstract

The study is devoted to a comprehensive investigation and synthesis of optimization models and digital technologies for managing multimodal cargo flows with conflicting logistics regulations, inert materials, and refrigerated cargoes, in the context of the Trans-European Transport Network corridors (TEN-T). The aim of the study is to develop a conceptual framework for integrated management of the specified flows, oriented toward improving the operational performance, resilience, and fault tolerance of logistics chains. The methodological basis includes a systematic review of the scientific literature on vehicle routing problems (VRP) and inventory routing problems (IRP), as well as a content analysis of European Union strategic documents and industry reports. The analysis records a persistent structural imbalance in the modal split of freight transport in the EU: the dominance of road transport contradicts the strategic goals of decarbonization. As a response, a multilayer conceptual architecture is proposed, integrating the Internet of Things (IoT) and blockchain to ensure data integrity and traceability, digital twins for predictive modeling, and multi-agent systems (MAS) for decentralized autonomous coordination. The conclusion of the study is that replacing centralized planning with decentralized orchestration of logistics services is a necessary condition for overcoming existing barriers and unlocking the potential of the TEN-T network. The material presented in the study will be of interest to researchers in logistics and supply chain management, transport planning specialists, and decision-makers in the development of transport infrastructure.

Keywords: *Multimodal Transport, Route Optimization, Inventory Management, Trans-European Transport Network, TEN-T, Refrigerated Cargoes, Inert Materials, Digital Twin, Multi-Agent Systems, Blockchain.*

INTRODUCTION

The strategic role of the Trans-European Transport Network (TEN-T) for economic integration, sustainable development, and strengthening the competitiveness of the European Union is beyond doubt [1]. The TEN-T policy is aimed at forming a single, highly efficient, and multimodal infrastructure—an ensemble of railway lines, inland waterways, maritime routes, and roads—that connects key logistics hubs across the entire continent [2, 3]. At the same time, a comparison of current statistical series on freight transport demonstrates a persistent and significant skew in modal distribution. In 2023, road transport reached 25,3% of the EU's total freight turnover (in tonne-kilometres)—the decade's maximum, the share of maritime transport, while remaining dominant at 67,4%, decreased for the fourth consecutive year, and the rail segment stayed at 5,5% [4]. This dynamic directly diverges from the EU's strategic objective to reorient freight flows in favor of more environmentally friendly modes—rail and inland waterway transport—enshrined within the TEN-T policy and the Sustainable and Smart Mobility Strategy [5, 6]. An additional indicator of the mismatch is the continued high activity of road freight, which added another 0,6% in 2024 [7]. The gap between political goals and actual operational trends constitutes the central problem underlying this study.

The complexity of logistics optimization problems increases when analyzing commodity flows with mutually conflicting constraints. On the one hand, the European refrigerated transport market, estimated at USD 4,74 billion in 2024 with a projected compound annual growth rate (CAGR) of 4,32%, serves high-value and time-sensitive cargoes with strict temperature regimes — primarily food and pharmaceuticals [8]. For this category, optimization priorities are the minimization of delivery time and the unconditional maintenance of cold chain integrity [9]. On the other hand, inert materials belonging to the subclass of dry bulk cargoes (21,6% of the EU's total port cargo throughput [10]) are characterized by substantial volumes, low margins, and high

Citation: Yurii Gerasymov, "Multimodal Route and Inventory Optimization for the Supply of Inert Materials and Refrigerated Cargoes within the Trans-European Corridors", Universal Library of Innovative Research and Studies, 2025; 2(3): 68-74. DOI: https://doi.org/10.70315/uloap.ulirs.2025.0203013.

demand elasticity with respect to cost per tonne-kilometer. Here, optimization criteria shift toward maximizing load factor and reducing the share of empty runs. The joint management of these heterogeneous flows within the same multimodal corridors gives rise to a complex multiobjective optimization formulation, in which the requirements of speed, preservation, and cost inevitably come into acute conflict.

Despite a substantial body of research on vehicle routing and inventory-routing optimization, including modifications for perishable products [11], existing models are generally analyzed in isolation and are rarely adapted to the unique, multifaceted, and technologically heterogeneous environment of the TEN-T corridors. There is a deficit of an integrated conceptual framework that unites advanced optimization methods with modern digital technologies (Internet of Things, blockchain, digital twins, multi-agent systems) to simultaneously address the dual problem of transporting inert and refrigerated cargoes at the scale of a real large network, namely TEN-T. This research gap determines the trajectory of the present study.

The aim of the study is to perform a systematic analysis and synthesis of existing optimization models and digital solutions in order to develop a conceptual framework for integrated management of multimodal transportation of inert and refrigerated cargo in TEN-T corridors.

The author's hypothesis is that a decentralized multi-agent system operating within a digital twin of the transport corridor and protected by blockchain mechanisms can provide the required adaptability, fault tolerance, and efficiency to reconcile the conflicting logistics requirements of the specified classes of cargo, thereby encouraging a modal shift toward more sustainable modes of transport.

The scientific novelty lies in the formation of a coherent, technology-oriented conceptual framework for multi-criteria optimization of heterogeneous freight flows in the specific context of TEN-T, which makes it possible to bridge the gap between operations research theory and the practical challenges of the European logistics infrastructure.

MATERIAL AND METHODS

The methodological framework of the study is designed as an integrated approach that combines a systematic review of scholarly literature with a qualitative analysis of regulatory and industry materials. This two-tier structure simultaneously ensures the theoretical accumulation of knowledge on the optimization of logistics systems and takes into account the applied context shaped by EU policy and prevailing market conditions.

The empirical basis is a systematic review of publications from the peer-reviewed databases Scopus and Web of Science. Within its scope, the following key directions of analysis are distinguished:

Multimodal optimization: studies developing mathematical models and algorithms for route optimization in multimodal transport networks.

Perishable Inventory Routing Problem (PIRP): works addressing the specifics of cold-chain logistics and the modeling of limited product shelf life.

Digital technologies in logistics: publications on the potential and architecture of solutions based on the Internet of Things (IoT), blockchain, digital twins (Digital Twins), and multi-agent systems (MAS) aimed at improving the efficiency and transparency of supply chains.

The second component — a content analysis of authoritative non-academic sources — enables the contextualization of theoretical models within the real operational and regulatory environment. The source base is structured as follows:

Official EU documents and reports: materials from Eurostat, the European Commission, and project implementation reports (e.g., H2020 LEAD) providing empirical data, a policy framework, and examples of practical piloting.

Reports on the development of TEN-T corridors: documents recording progress, problems, and bottlenecks of specific transport corridors, which makes it possible to identify practical barriers to multimodality.

Analytical industry reviews: strategic reports by leading consulting firms (e.g., McKinsey, Deloitte) that highlight market trends, risks (including supply chain disruptions and labor shortages), and strategic imperatives of the logistics sector.

RESULTS AND DISCUSSION

Comparison of official statistical datasets with the corpus of strategic acts shows that the logistics architecture of the European Union contains deep structural dysfunctions that impede progress toward the goals of sustainable development. The predominance of road transport amid chronically low involvement of rail and inland waterway transport is not a theoretical hypothesis but an empirically verifiable fact, reliably recorded in official data (see Table 1).

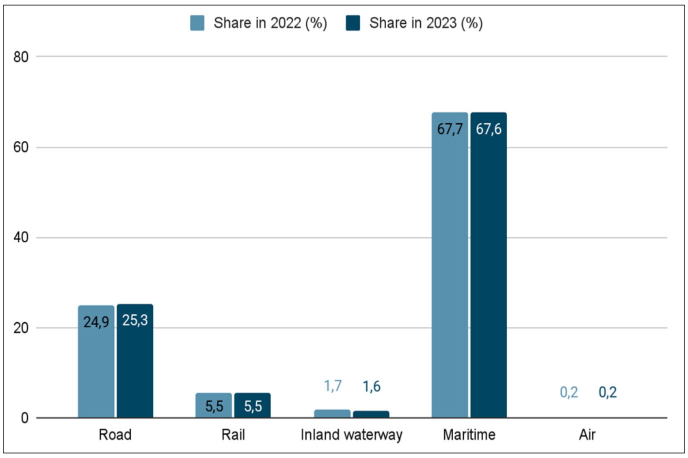

Fig 1. Comparative analysis of modal distribution in EU freight transport (tonne-kilometres, %) (compiled by the author based on [4]).

The data presented in Table 1 reveal a fundamental dissonance: while sustainable mobility is proclaimed as a priority in political declarations, the share of road transport continues to increase, whereas the contribution of more environmentally friendly modes either stagnates (rail) or declines (inland waterway and maritime transport). This statistical skew does not indicate a one-off anomaly but rather persistent systemic defects. The principal barriers are:

1. Infrastructure bottlenecks: reports on the implementation of TEN-T consistently record physical gaps—from missing links and unfinished investments to limited capacity, especially on cross-border sections. Taken together, this directly reduces the speed and predictability of multimodal chains, thereby making them less competitive compared to road transport [6].
2. Interoperability problems: these constitute the most significant constraint on the growth of rail freight in Europe. The historical fragmentation of national networks has produced a mosaic of incompatible standards—from differences in track gauge and power supply systems to more than two dozen signalling systems. The deployment of the European Rail Traffic Management System (ERTMS) is intended to eliminate these discrepancies; however, implementation is progressing slowly and requires substantial capital investment, which delays the creation of a seamless pan-European railway area.
3. Regulatory and digital fragmentation: beyond the physical network, effective multimodal coordination is impeded by the absence of unified digital platforms and data exchange protocols. According to the results of the KEYSTONE project, only 18% of logistics operators transmit data to all relevant public authorities; the key reasons cited are a shortage of appropriate IT tools and privacy concerns. This digital fragmentation mirrors the physical.

The cumulative effect of these factors forms a vicious circle, especially pronounced in the railway segment. A low market share, fueled by interoperability failures and infrastructure constraints, makes rail less reliable and more costly relative to the road alternative, which deters shippers. Shrinking demand and volumes undermine the economic rationale for large-scale public and private investments needed to modernize infrastructure and deploy ERTMS. Underinvestment will preserve the original deficiencies and perpetuate low productivity and competitiveness. Consequently, breaking this circle requires not only financial injections but also a new operational paradigm that maximizes returns on the existing infrastructure and thereby strengthens the case for subsequent investments.

Classical optimization formulations, including the VRP, have historically focused on single-objective minimization, most often total costs or total route length. Contemporary logistics practice, however, requires a multiobjective formulation that simultaneously balances time indicators, costs, carbon footprint, and customer satisfaction metrics [11]. Since the corresponding problems are NP-hard, obtaining an exact global solution within acceptable time frames at realistic scales is unattainable; this drives the widespread use of metaheuristics—Tabu search, simulated annealing, and genetic algorithms—providing high-quality approximate solutions under limited computational budgets [20, 23].

In the cold chain domain, the perishable inventory-routing problem (PIRP) is fundamentally complicated by the presence of a hard shelf-life constraint. Such models require the joint optimization of delivery routes and inventory levels at customers in order to minimize not only transportation and warehousing costs, but also losses due to product spoilage [12]. Dimensionality growth with an expanding assortment and longer shelf-life horizons leads to the curse of dimensionality, where the solution space inflates exponentially. State-of-the-art methods counter this via decomposition schemes that separate inventory control and routing, as well as through the use of dynamic pricing to regulate demand under disruptions [12].

For bulk cargo, the objective function is typically formulated as minimizing unit cost per ton-kilometer. Optimization priorities are shifted toward maximizing the loading of rolling stock, selecting the economically preferred mode of transport (over long hauls predominantly rail or waterborne), and reducing terminal handling time and cost. In such models, hard time windows play a secondary role compared to capacity utilization and the extraction of economies of scale.

A comparative analysis of model requirements for these two cargo classes reveals a fundamental gap in their information profiles. For refrigerated shipments, high-resolution real-time telemetry is critical: temperature, humidity, residual shelf life, precise coordinates, and near-term demand forecasts [12, 22]. Their value is determined primarily by timeliness and metrological accuracy. In contrast, the optimization of shipments of inert materials relies on more stable, aggregated datasets: terminal throughputs, mode-specific tariffs, vehicle payload capacities, and demand volumes; here the key value of data is correctness for cost calculation. Consequently, a unified digital management system must be designed to process two qualitatively different streams: high frequency with minimal latency for time-sensitive cargo, and low frequency but voluminous for bulk cargo. It follows that the base digital infrastructure (for example, IoT sensors and data platforms) cannot be a universal key; it must be modular and adaptable to the specific information physics of the cargo being served.

To overcome the stated limitations, a multilevel conceptual model is proposed that sequentially integrates advanced digital technologies into a unified, intelligent, and adaptive system for managing multimodal transportation. The model comprises three interrelated layers: foundational (data collection and protection), analytical (modeling and forecasting), and decision-making (decentralized coordination) [18, 21].

The foundational layer is based on a combination of IoT and blockchain as a mechanism for ensuring data integrity. The objective of this layer is the guaranteed acquisition of reliable real-time information and the establishment of trust in a multi-stakeholder environment.

The Internet of Things (IoT) acts as the nervous system of the logistics chain, providing a continuous flow of information on location, cargo condition, and environmental parameters (in particular, temperature and humidity for the cold chain).

Blockchain serves as an immutable distributed ledger: when data streams from IoT sensors are recorded, the data become tamper-resistant and transparent to participants with appropriate access rights [20]. This eliminates the critical problem of trust and integrity and establishes a verifiable supply chain for sensitive categories such as pharmaceuticals and fresh products.

Smart contracts enable the automatic execution of predefined actions — from quality inspections to payments — based on validated IoT events. For clarity, the solution architecture will be presented in Figure 2.

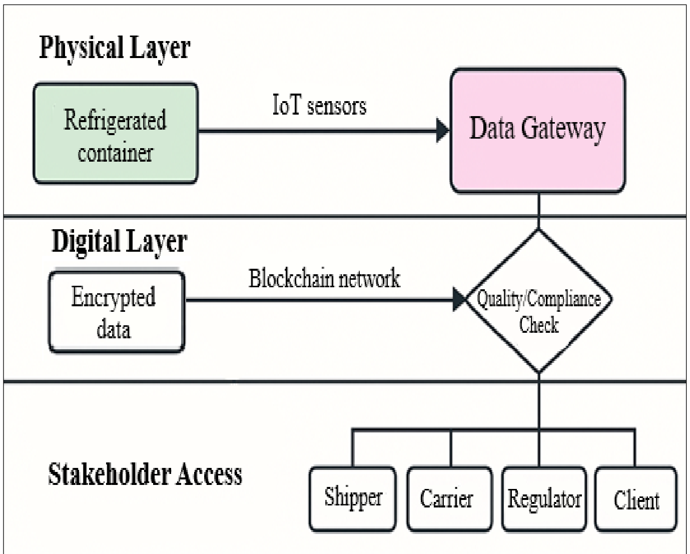

Fig.2. IoT and blockchain integration architecture for cold chain traceability (compiled by the author based on [6, 15, 17, 19, 24]).

The H2020 LEAD project empirically confirmed the viability of the approach by establishing digital twins of urban logistics across six TEN-T nodes and testing solutions such as urban consolidation centers and new delivery schemes; this demonstrated the effectiveness of DT as a tool for collaborative, data-driven governance [24]. The conceptual model of the aforementioned digital twin is presented in Fig. 3.

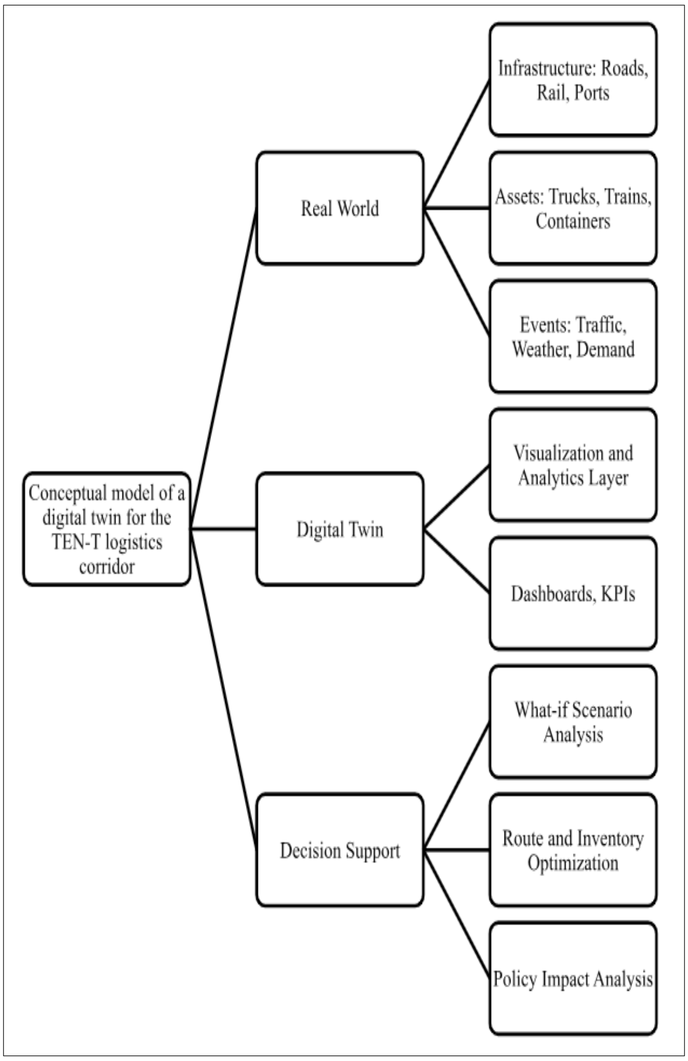

Fig.3. Conceptual model of a digital twin for the TEN-T logistics corridor (compiled by the author based on [6, 13, 14, 16]).

As an example of operation, consider the following case: a refrigerated cargo agent publishes a transportation request with strict time and temperature constraints. Several carrier agents (road, rail) offer services, and a smart contract on the blockchain automatically concludes a contract with the agent whose offer best satisfies the specified criteria. This results in a dynamic, self-organizing market for logistics services. The architecture is inherently scalable and fault tolerant: in the event of the failure of one agent (e.g., the unavailability of a specific railway segment) other agents can dynamically replan routes without the involvement of a central dispatcher. This approach constitutes a practical step toward implementing the concept of the Physical Internet — a global open logistics system

Despite its high potential, the proposed conceptual model encounters serious obstacles in practical implementation. The key technological problem is the absence of unified standards for data representation and semantic interoperability among heterogeneous information systems. The viability of a digital twin directly depends on the quality, completeness, and consistency of incoming data streams; consequently, the fragmentation of formats and ontologies provokes error accumulation, increases transaction costs, and undermines trust in analytical results.

Organizational constraints are associated with the reluctance of private companies to disclose confidential operational information due to competitive risks. Building the trust required for interfirm interaction within a multi-agent architecture (MAS) is not reducible to the deployment of exchange protocols: it is a long-term institutional task that requires contractual frameworks, transparent access rules, and mechanisms for distributing benefits and risks, which cannot be guaranteed by technological means alone.

Financial barriers manifest themselves in substantial upfront capital expenditures on sensor capabilities, software platforms, and digital infrastructure. For small and medium-sized enterprises, such investments are often prohibitive, which slows the diffusion of innovations and exacerbates structural asymmetry between large and small market participants.

The personnel shortage in the logistics sector amplifies the above challenges: there is a deficit of specialists with advanced digital competencies capable of designing, administering, and operating complex cyber-physical solutions based on digital twins and MAS [28]. The lack of relevant competencies reduces implementation quality and increases the likelihood of operational failures.

At the same time, the potential effects of deploying the model directly correlate with the strategic priorities of the European Union. From the standpoint of operational efficiency, dynamic, decentralized optimization makes it possible to markedly reduce the share of empty mileage, shorten transit time, and increase asset utilization, which collectively leads to lower total costs and higher productivity.

In the sustainability domain, the system incentivizes an effective modal shift and route optimization, thereby directly contributing to the decarbonization of logistics and the achievement of the targets of the European Green Deal.

Finally, the decentralized nature of the multi-agent architecture enhances the flexibility and resilience of supply chains: in the face of infrastructure disruptions or geopolitical shocks, autonomous agents are able to adapt to changing conditions and devise alternative solutions, reducing the vulnerability of the system as a whole.

Implementing such an architecture entails a radical transformation of the very logic of conducting the logistics business. The current paradigm rests primarily on vertically integrated operators that own and manage infrastructure. The MAS/DT model, in contrast, forms a flexible multi-sided market in which logistics resources — transport capacities, warehouse space, handling services — are tokenized and become the subject of transactions among autonomous agents. In this target state, competitive advantage will belong not to the owners of the largest stock of physical assets, but to the holders of the most advanced agent systems capable of composing complex, multi-partner service chains in real time. This implies a shift of emphasis from asset ownership to the primacy of data and algorithms. Such a shift simultaneously lowers entry barriers for new, agile participants and compels large, established operators to rethink their value proposition, moving from the role of asset providers to that of service orchestrators within the shared open ecosystem envisaged by the Physical Internet concept.

CONCLUSION

The analysis conducted demonstrates that the persistent gap between the declared ambitions of the EU regarding multimodality and the de facto dominance of road transport is rooted in systemic fragmentation — infrastructural, operational, and digital. Localized, isolated optimizations of individual links in the supply chain are fundamentally unable to synchronize divergent requirements for handling heterogeneous freight flows, including refrigerated and inert.

The research objective has been achieved: a conceptual framework has been formed that integrates IoT, blockchain, digital twins, and multi-agent systems. The results obtained confirm the hypothesis that a decentralized, data-driven, and autonomous architecture is a viable pathway to fault-tolerant and efficient multimodal logistics. The proposed model sets out a strategic roadmap for key stakeholders: for regulators, a plan for deploying digital ecosystems; for infrastructure managers and logistics operators, a delineation of the forthcoming competitive field in which digital orchestration, rather than mere asset ownership, becomes the decisive factor.

The practical significance of the work lies in a systems approach to modernizing logistics in the TEN-T corridors, capable of increasing the return on existing capacity and bringing closer the achievement of decarbonization targets.

Further research should focus on the applied implementation of the proposed model. Priorities include:

- Development of unified data ontologies and communication protocols for logistics agents as a necessary condition for their interoperability.
- Design and experimental validation of specific multi-agent reinforcement learning (MARL) algorithms to solve routing and pricing negotiation tasks in a dynamic environment.
- Conducting pilot projects in operational TEN-T corridors to quantitatively validate the effectiveness of the model and to elaborate the socio-technical aspects of its deployment under real-world conditions.

REFERENCES

1. Trans-European Transport Network (TEN-T) [Electronic resource]. - Access mode: https://transport.ec.europa.eu/transport-themes/infrastructure-and-investment/trans-european-transport-network-ten-t_en (date of access: 17.08.2025).
2. New EU Transport Report: Current trends and issues - European Commission [Electronic resource]. - Access mode: https://transport.ec.europa.eu/news-events/news/new-eu-transport-report-current-trends-and-issues-2024-06-27_en (date of access: 19.08.2025).
3. Revised Trans-European Transport Network (TEN-T) Regulation enters into force - CEDR [Electronic resource]. - Access mode: https://www.cedr.eu/news-data/4091/Revised-Trans-European-Transport-Network-TEN-T-Regulation-enters-into-force (date of access: 19.08.2025).
4. Freight transport statistics - modal split Statistics Explained [Electronic resource]. - Access mode: https://ec.europa.eu/eurostat/statistics-explained/SEPDF/cache/1142.pdf (date of access: 20.08.2025).
5. Transport statistics at regional level Statistics Explained - European Commission [Electronic resource]. - Access mode: https://ec.europa.eu/eurostat/statistics-explained/SEPDF/cache/14273.pdf (date of access: 19.08.2025).
6. THE TRACK TO A SUCCESSFUL TEN-T - Community of European Railway and Infrastructure Companies (CER) [Electronic resource]. - Access mode: https://www.cer.be/images/publications/reports/221205_CER_Publication_The_Track_to_a_Successful_TEN-T.pdf (date of access: 19.08.2025).
7. EU road freight transport sees 0.6% increase in 2024 - News articles - Eurostat [Electronic resource]. - Access mode: https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20250709-1 (date of access: 22.08.2025).
8. Europe Refrigerated Transport Market Report by Mode of Transportation (Refrigerated Road Transport, Refrigerated Sea Transport, Refrigerated Rail Transport, Refrigerated Air Transport), Technology (Vapor Compression Systems, Air-Blown Evaporators, Eutectic Devices, Cryogenic Systems), Temperature (Single-Temperature, Multi-Temperature), Application (Chilled Food Products, Frozen Food Products, and Others), and Country 2025-2033 [Electronic resource]. - Access mode: https://www.imarcgroup.com/europe-refrigerated-transport-market (date of access: 19.08.2025).
9. Europe Refrigerated Transport Market Size & Share Analysis - Growth Trends and Forecast (2025 - 2030) [Electronic resource]. - Access mode: https://www.mordorintelligence.com/industry-reports/europe-refrigerated-transport-market (date of access: 19.08.2025).
10. Maritime transport of goods - annual data - Statistics Explained - Eurostat [Electronic resource]. - Access mode: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Maritime_transport_of_goods_-_annual_data (date of access: 19.08.2025).
11. Peng Y., Yong P., Luo Y. The route problem of multimodal transportation with timetable under uncertainty: Multi-objective robust optimization model and heuristic approach //RAIRO-operations Research. – 2021. – Vol. 55. – pp. 3035-3050.
12. Khalili G. Perishable Inventory Routing Problem Under Uncertainty : diss. – University of Waterloo, 2023. - pp.25-34.
13. Yavari M., Enjavi H., Geraeli M. Demand management to cope with routes disruptions in location-inventory-routing problem for perishable products //Research in Transportation Business & Management. – 2020. – Vol. 37. https://doi.org/10.1016/j.rtbm.2020.100552.
14. Udomwannakhet J. et al. A review of multimodal transportation optimization model //2018 5th International Conference on Business and Industrial Research (ICBIR). – IEEE, 2018. – pp. 333-338.
15. Taran I. et al. Structural optimization of multimodal routes for cargo delivery //Archives of Transport. – 2023. – Vol. 67 (3). – pp. 49-70. https://doi.org/10.5604/01.3001.0053.7076.
16. Peres I. T. et al. Optimization in inventory-routing problem with planned transshipment: A case study in the retail industry //International Journal of Production Economics. – 2017. – Vol. 193. – pp. 748-756.
17. Gavrilova M. L. et al. Multi-modal motion-capture-based biometric systems for emergency response and patient rehabilitation //Research Anthology on Rehabilitation Practices and Therapy. – IGI Global Scientific Publishing, 2021. – pp. 653-678.
18. Fareed A. G. et al. Role and applications of advanced digital technologies in achieving sustainability in multimodal logistics operations: A systematic literature review //Sustainable Futures. – 2024. – Vol. 8. https://doi.org/10.1016/j.sftr.2024.100278.
19. Azevedo P., Gomes J., Romão M. Supply chain traceability using blockchain //Operations Management Research. – 2023. – Vol. 16 (3). – pp. 1359-1381.
20. Pretel E. et al. Multi-agent systems in support of digital twins: A survey //International Work-Conference on the Interplay Between Natural and Artificial Computation. – Cham : Springer International Publishing, 2022. – pp. 524-533.

21. Wang Y., Sarkis J. Emerging digitalisation technologies in freight transport and logistics: Current trends and future directions //Transportation Research Part E: Logistics and Transportation Review. – 2021. – Vol. 148. https://doi.org/10.1016/j.tre.2021.102291.

22. Galkin A. et al. Digital twins in logistics: a comprehensive bibliometric analysis for advancing smart cities and sustainable development //Discover Sustainability. – 2025. – Vol. 6 (1). – pp. 1-25.

23. van Weenen R. L., Burgess A., Francke J. Study on the implementation of the TEN-T regulation–the Netherlands case //Transportation Research Procedia. – 2016. – Vol. 14. – pp. 484-493.

24. Boira J. V., Berzi M. Liberalization, Trans-European Corridors and EU Funds: A New Scenario in the Relationship between Rail Networks and Mediterranean Cities //Land. – 2023. – Vol. 12 (11). https://doi.org/10.3390/land12111986.