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Methodology for Organizing and Managing Cross-Border Transportation Under Conditions of Digital Transformation and Global Instability

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Abstract

The study is devoted to a systemic analysis of the contemporary methodology of cross-border transportation, in which instruments of spatial macro-modeling, the contours of digital transformation, and principles of sustainable development are integrated. The period of 2024–2025, marked by pronounced turbulence in the global trade and transport architecture and by instability in routing, intensifies the need to abandon inertial linear management schemes in favor of adaptive ecosystem-based models capable of promptly recalibrating the parameters of coordination and flow allocation. Within the framework of the work, approaches to weakening the barrier effect of state borders are examined through the deployment of technological solutions of Industry 4.0, including artificial intelligence algorithms, distributed ledgers based on blockchain approaches, and Internet of Things infrastructures that ensure end-to-end observability and operational consistency.

A central place is occupied by an analysis of Eurasian transport corridors, including the International North–South Transport Corridor and the Middle Corridor, with an emphasis on comparing their operational effectiveness, capacity constraints, and geopolitical role in the reconfiguring logistics of interregional trade. The methodological toolkit employed includes evaluative Petri nets as a formal instrument for describing the dynamics of freight flows, identifying bottlenecks, and testing scenario robustness under changes in network parameters, as well as stochastic risk-assessment methods for territories with elevated conflict potential, which make it possible to account for the probabilistic nature of disruptions, delays, and route redistribution. The results obtained indicate that coupling digital management instruments with green standards generates a synergy effect: cost rationalization is achieved while simultaneously strengthening the long-term resilience of supply chains, expressed in increased adaptability, transparency, and capacity for recovery after external shocks. The conclusions presented are oriented toward the professional communities of logistics, international relations, and public administration, for which the priority is the introduction of innovative mechanisms into the practice of cross-border interaction.

Keywords: *Cross-Border Transportation, Multimodal Corridors, The International North–South Transport Corridor, Digital Transformation, Artificial Intelligence, Blockchain In Logistics, Sustainable Development, Green Logistics, Risk Management, Petri Nets.*

CONTENT

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INTRODUCTION

The contemporary configuration of international transport systems is undergoing a phase of profound structural reconfiguration that has the character of tectonic shifts. By 2024, cross-border transportation had lost the status of a purely technological operation for moving commodity flows and had acquired the significance of an instrument of geopolitical positioning, as well as a means of maintaining the economic security of states and integration groupings. According to the Bureau of Transportation Statistics, March 2025 was recorded as a record period in terms of the value volume of freight transportation between the United States, Canada, and Mexico: the indicator reached 144.8 billion dollars, exceeding the level of March 2024 by 8.4% and the 2019 values by 35% [1]. In the Eurasian macroregion, a dynamic comparable in significance manifested itself in the growth of rail transportation along the International North–South Transport Corridor (INSTC): in 2024, the volume increased by 19% and amounted to 26.9 million tons, indicating a stable reorientation of part of trade flows in favor of alternative routes and nodes [2].

In the presence of a substantial body of empirical observations, a pronounced methodological deficit is recorded: the contemporary research agenda does not possess an integral interdisciplinary framework capable of simultaneously accounting for the probabilistic nature of cross-border delays, the dynamics of digital reformatting, and the imperatives of environmental neutrality. Under conditions of a VUCA environment, defined by volatility, uncertainty, complexity, and ambiguity, traditional approaches to planning and coordination prove insufficiently sensitive to nonlinear disturbances and cascading effects, which in practical terms reduces the effectiveness of seamless logistics solutions and increases transaction losses.

In this connection, the **objective** is formulated as the development and substantiation of a comprehensive methodology for managing cross-border transportation, relying on intelligent automation of processes and the strategic development of multimodal corridors as the infrastructural foundation of sustainable connectivity.

The scientific novelty consists in substantiating the concept of digital soft infrastructure as the predominant factor in increasing border throughput capacity, within the framework of which investments in algorithmic management, data interoperability, and the coherence of digital protocols ensure a higher ROI in comparison with the predominantly extensive expansion of physical capacities.

The authorial hypothesis proceeds from the assumption that a transition to decentralized management models on the basis of blockchain and federated training of artificial intelligence is capable of reducing the duration of cross-border transit by 40–60% and decreasing administrative costs by 20%, while simultaneously increasing the environmental sustainability of the transport and logistics system by minimizing empty runs.

CHAPTER 1. THEORETICAL AND METHODOLOGICAL FOUNDATIONS OF SPATIAL MODELING OF CROSS-BORDER SYSTEMS

Within Chapter 1, the theoretical and methodological foundations for spatial modeling of cross-border systems were established. It was shown that in 2024 the state border is interpreted not as a static line, but as a dynamic interface of interaction, and that the barrier effect is decreasingly reducible to tariffs and is increasingly determined by incompatibility of digital protocols, asymmetry of cybersecurity requirements, and differences in environmental regulation. This configuration necessitates multilevel analysis of actor linkages, value chains, and institutions, and it relies on hybrid measurement approaches, including gravity models, quasi-experiments, and high-frequency digital traces of logistics, with a decomposition of the border wedge into administrative, technological, and regulatory components.

The applicability of evaluative Petri nets for macro-modeling international transport corridors under conditions of fragmented data was substantiated, including the decomposition of the corridor into nodes and arcs, the parameterization of delay distributions, a multicriteria key performance indicator system (economics, operations, environment, social effects), parameter identification procedures, and sensitivity analysis. This makes it possible to obtain not only mean values, but also distributions of risks of deadline failures and cascading delays, and to conduct what-if scenarios of digitalization.

Finally, the financial and institutional contour of cross-border infrastructure development in 2024–2025 was disclosed, in which budget resource deficits and the energy transition strengthen the role of public–private partnerships, blended finance, and credit enhancement mechanisms, including guarantees, subordinated tranches, availability payments, and foreign-exchange risk hedging, under the key importance of interstate framework agreements on tariffs, access, digital document management, and dispute resolution. Taken together, these factors increase the resilience of project decisions to macro-shocks and accelerate technological modernization.

Economic Geography and the Concept of the Barrier Effect in 2024

The traditional representation of state borders as immobile demarcation lines in 2024 was definitively replaced by an interpretation of borders as dynamic interfaces of interaction, in which regimes of control, exchange, and coordination are simultaneously co-present. Within the framework of classical economic thought, borders for a long time were described predominantly through the category of transaction costs, and trade liberalization was interpreted as an almost universal mechanism for increasing efficiency [4]. However, the results of contemporary research in economic geography demonstrate the limitations of such a reduction and emphasize the necessity of a multilevel analysis that includes relational ties among regional actors, the configuration of value chains, and the characteristics of the institutional environment [4].

Within the current agenda, the barrier effect is increasingly less reducible to customs tariffs and is to a growing extent determined by the lack of alignment of digital protocols, the asymmetry of cybersecurity requirements, as well as differences in climate and environmental regulatory regimes. Even within the European Union, data arrays on cross-border movements of labor and freight remain not fully harmonized, which generates latent obstacles to the formation of a unified transport space and complicates the comparability of statistics across corridors and nodes [4]. In 2024, the research focus shifted noticeably toward the microlevel, namely the analysis of the functioning of individual firms in border areas, which makes it possible to identify specific logistics resources, institutional windows of opportunity, and channels for the diffusion of innovations under conditions of heterogeneous regulation [4].

The quantitative assessment of cross-border barriers in 2024–2025 increasingly relies on combining traditional gravity specifications with instruments of causal identification, including quasi-experimental designs (discontinuities in regulatory regimes, asynchronous reforms, changes in control procedures) and high-frequency proxy indicators of delays. Additional precision is provided by digital traces of logistics processes: fleet telematics, AIS data for maritime transportation, logs of checkpoint passage, as well as information on the processing time of electronic documents, which makes it possible to decompose the aggregate border wedge into components: administrative, technological, and regulatory.

The substantive interpretation of measured barriers requires taking into account that the border performs not only a restrictive function but also a selectively stimulating function: the strengthening of requirements for security and the resilience of supply chains may raise entry costs while simultaneously creating demand for compliance competencies, certification services, and technological solutions for traceability. In this logic, border territories begin to function as platforms for the institutional and technological stitching of markets, where competitive advantages are formed through the ability of firms to integrate heterogeneous standards, ensure data interoperability, and minimize regulatory risks while maintaining the speed and reliability of delivery.

Table 1 is presented below, systematizing the main types of barriers in cross-border transportation and the methods of their quantitative assessment in 2024–2025.

Table 1. Main Types of Barriers in Cross-Border Transportation and Methods of Their Quantitative Assessment in 2024–2025 (compiled by the author based on [4, 5, 6, 7]).

Barrier type	Core determinants	Assessment methodology (KPI)	Impact on logistics 2024
Institutional	Customs regulations; sanctions regimes	Border crossing clearance time (dwell time); Logistics Performance Index (LPI)	Increase in processing time by 15-20% in regions characterized by instability
Technical	Disparities in track gauge width; weight control standards	Transshipment delay coefficient	Increase in operational costs by 12%
Digital	Absence of a unified single window; incompatibility of electronic data interchange (EDI) standards	Share of electronic document circulation across the supply chain	Reduction in throughput capacity by 30%
Infrastructure	Wear and deterioration of rail infrastructure; shortage of terminal capacities	Throughput capacity (TEU per year); port utilization rate	Constraint on export growth from developing countries by 18%

The analysis of the barrier effect indicates that the most dynamically developing border territories transform their peripheral position into a source of competitive advantages by institutionally formalizing cross-border regional innovation systems (CBRIS), which function as a mechanism for reproducing cooperative ties and generating new forms of economic integration.

Application of Evaluative Petri Nets for Macro-Modeling of Corridors

At the early stages of planning international transport corridors (ITC), the initial information, as a rule, is characterized by fragmentation, high variability, and incompleteness, as a result of which classical deterministic modeling methods often lose reproducibility and prognostic validity. In this situation, the methodology of evaluative Petri nets (E-Nets) acts as a methodologically justified instrument of simulation analysis of complex logistics processes, making it possible to formalize uncertainty without artificially simplifying the structure of the system [8]. Petri nets provide simultaneous visualization and mathematical description of parallel, asynchronous, and stochastic events that arise during the passage of control procedures, changes of transport modes, and the crossing of state borders.

The construction of an E-Net model of an ITC in the practices of 2024 relies on the sequential unfolding of the corridor structure into elementary components: nodes (ports, dry ports, terminals) and links between them in the form of arcs (rail segments, road directions, maritime lines) are delineated, which sets the skeleton of the flow topology and ensures the comparability of alternative routes [9]. Next, a taxonomy of performance indicators integrated into the model across four dimensions, economic, operational, environmental, and social, is formed, so that the modeling is not confined to speed and cost but reflects the multicriteria nature of infrastructure decisions [9]. The final element of the basic specification is the parameterization of time delays: for each transition in the net, a distribution function of waiting time is specified that can account for random factors (meteorological conditions, enhanced inspections, queues at border crossing points), thereby moving the model from a descriptive plane to a prognostic and experimental plane [8].

Under conditions of limited observability of parameters, a correct procedure for identifying delay distributions and aligning them with available empirical traces becomes of key importance. In practice, combined strategies are used: aggregation of historical logs of operation passage (if they are available), expert elicitation with the protocoling of assumptions, as well as iterative refinement of parameters as new observations appear, which makes it possible to reduce a priori uncertainty without destroying the integrity of the model. A substantial role is played by sensitivity analysis, which reveals which elements of the network determine the main share of variation in the final key performance indicators and where exactly it is expedient to concentrate efforts on data collection.

An E-Nets-based model makes it possible to obtain not only mean estimates of transit time and cost but also distributions of outcomes that are critical for analyzing the reliability and resilience of an ITC: the probabilities of deadline failures, the frequency of queue accumulation, and the risk of cascading delays under local disruptions. Such a formulation creates a foundation for comparative evaluation of regulatory scenarios and infrastructure interventions (changes in control procedures, digitalization of document management, redistribution of throughput capacity), as well as for identifying bottlenecks and hidden sources of losses in supply chains. As a result, E-Nets function as an instrument that links the engineering decomposition of the corridor with multicriteria performance indicators and allows for consistent increases in precision as input data are refined (see Fig. 1).

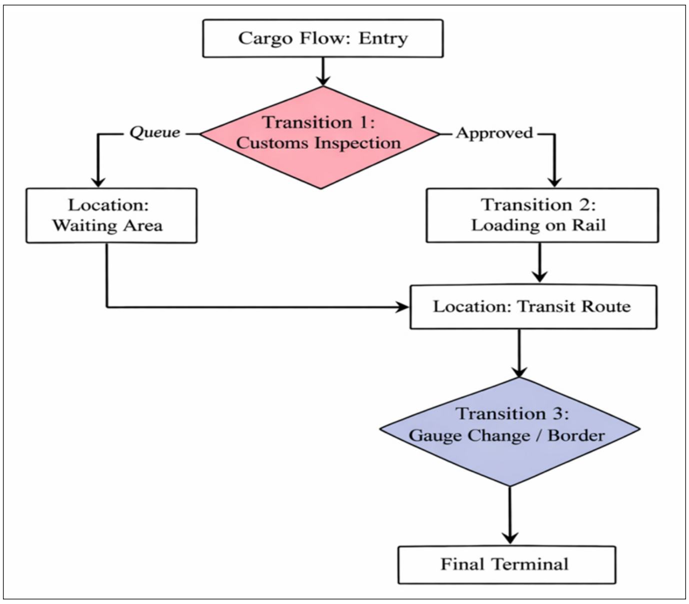

Fig. 1. Description of the E-Nets Architecture (compiled by the author based on [8, 9]).

The practical implementation of the proposed methodological framework enables simulation what-if scenarios, making it possible, in particular, to quantitatively assess the effect of introducing digital pre-notification mechanisms on the integral throughput capacity of a transport corridor and the resilience of its operational contour. Empirical results presented in specialized studies demonstrate that the use of Petri nets in modeling terminal, warehousing, and border processes increases the accuracy of resource allocation and ensures a 22% reduction in downtime.

Financial Modeling and Public–Private Partnership Mechanisms in Cross-Border Infrastructure

The development of cross-border infrastructure in 2025 is increasingly constrained by a deficit of budgetary resources, which intensifies competition among projects for public appropriations and increases the significance of off-budget mechanisms. In the United States, a plateau of federal transportation spending is observed, as a result of which the financial burden shifts to the level of states and municipalities, and compensatory solutions under consideration include vehicle miles traveled fees and special taxes on electric vehicles [10]. At the global level, accelerated financialization of the sector is observed: private capital (private equity) is strengthening its presence in infrastructure, and it is noted that in 2024, 22% of deals in advanced industries were associated with private equity funds, while the volume of investment in transport infrastructure was 35% higher compared with the previous decade [11].

Approaches to attracting investment into an ITC in 2024–2025 are formed as a portfolio of complementary instruments combining risk allocation, adaptation to the energy transition, and the enhancement of project credit quality. Cross-border public–private partnerships implemented by consortia from several countries make it possible to diversify political and operational risks while simultaneously extracting synergistic effects from the alignment of standards and procedures. Return modeling under conditions of the energy transition acquires independent significance, because the growth of the share of electric transport undermines the sustainability of traditional sources of road revenues; in California, for example, a 31% decline in proceeds from fuel excise taxes is expected by 2035, which requires a reassessment of long-term cash flows and a revision of tariff assumptions [10]. Alongside this, the application of green financing through concessional loans from international development banks (AIIB, ADB) expands, provided that environmental requirements and reporting procedures are met [12].

An additional layer of the methodology is the institutional architecture of cross-border projects, because for an ITC the compatibility of legal regimes, the predictability of tariff regulation, and the robustness of dispute resolution mechanisms are critical. Practice shows that investment attractiveness increases substantially when interstate framework agreements are in place that fix the principles of access to infrastructure, the procedure for indexing payments, standards for digital document management, and minimum requirements for service reliability. In such arrangements, risks are expediently structured according to the principle whoever controls bears: operational risks are assigned to the concessionaire or operator, regulatory and political risks are partially covered by state guarantees, stabilization clauses, and insurance, while currency risks are addressed through hedging instruments and the use of multi-currency revenue.

Under conditions of pressure on traditional revenue bases, the role of blended finance and credit enhancement instruments increases, allowing capital to be assembled from sources with different requirements regarding risk and return. In infrastructure transactions, subordinated tranches, partial coverage guarantees, availability payment revenue agreements, as well as contractual models in which payments are tied not only to traffic but also to measurable indicators of quality and resilience, are increasingly used, which reduces cash-flow volatility and increases the project debt capacity. Coupling with environmental financing programs and standardized environmental, social, and governance indicators facilitates the attraction of concessional resources and lowers the cost of capital while preserving requirements for environmental standards [12]. Table 2 below provides a comparison of traditional and innovative financing models for cross-border nodes.

Table 2. Comparison of Traditional and Innovative Financing Models for Cross-Border Nodes (compiled by the author based on [10-12]).

Financing model	Source of capital	Primary risk	Advantage
Direct public financing	Budget appropriations	Political volatility; budget deficit	Full state control
Institutional public-private partnership (PPP)	Private funds plus state guarantees	Long-term payback period (20-30 years)	Managerial efficiency and acceleration of construction timelines
Mileage-Based Fees (MBF)	Users (payment per mileage)	Technological complexity of data collection	Equity in cost allocation
Green bonds	Institutional investors	Strict emissions reporting requirements	Low interest rate

Integrating the specified financial instruments into a coherent methodological construct for managing international transport corridors forms an additional contour of adaptability that increases the resilience of project decisions to macroeconomic shocks and technological shifts. Through diversifying sources of capital, aligning financing parameters with the life cycle of infrastructure assets, and embedding risk-oriented hedging mechanisms, stabilization of investment flows is achieved amid changes in interest rates, foreign-exchange conditions, and demand for transportation services. At the same time, a financial architecture synchronized with digital transformation accelerates technological renewal and reduces the likelihood of disruptions in project delivery, because it enables the rapid reallocation of resources toward critical modernization directions and supports the required level of operational reliability.

CHAPTER 2. DIGITAL TRANSFORMATION AND INTELLIGENT MANAGEMENT OF TRANSPORTATION

In Section 2, the complex of digital transformation and intelligent transportation management was examined as an end-to-end contour for increasing the efficiency and resilience of international transport corridors. It was shown that in 2024–2025 artificial intelligence evolved from isolated pilots to industrial deployment within the operational platforms of carriers and logistics operators, enabling queue forecasting and dynamic routing, predictive maintenance of infrastructure, and shift optimization, with early adopters reporting productivity gains of 30–50%. At the same time, a durable effect is achievable only in the presence of a mature integration layer and rigorous data governance, including master data management, data lineage, and drift control, as well as embedded practices of machine learning operations and model risk management that account for cybersecurity risks and safe rollback scenarios.

Next, the role of blockchain was substantiated as a protocol of decentralized trust in cross-border logistics, forming an immutable event ledger for insurance, customs, and environmental, social, and governance auditing, further strengthened through coupling with the Internet of Things, where losses decline to 1.2% versus 4.5% in traditional schemes, through smart contracts for multimodal settlements, and through federated learning that enables risk-model construction without transferring primary datasets. In 2025, the emphasis shifts toward interoperability and open standards in order to avoid vendor lock-in.

Finally, the methodology of corridor digital twins was disclosed as continuously updated virtual models of assets and flows in a near real-time mode, built on sensor (Internet of Things), integration (Warehouse Management Systems, Transportation Management Systems, Enterprise Resource Planning systems, and reference-data harmonization), and analytical layers (artificial intelligence forecasting and simulation of black swan events). In this architecture, the key constraints are semantic compatibility, a single source of truth for core entities (container, shipment, vehicle, route segment), and access security, while blockchain is applied as a mechanism for fixing the integrity of critical operational event logs, thereby increasing trust and the reproducibility of managerial decisions.

Artificial Intelligence and Autonomous Systems in 2024–2025

Digital transformation in logistics has evolved from basic tracking services to integrated digital platforms in which machine learning algorithms and intelligent analytics are embedded within the loops of planning and execution. In 2024, a transition is observed from limited pilot deployments of artificial intelligence solutions to industrial-scale rollout, in which such instruments become the core of the operating systems of major logistics operators [10]. The practical effect manifests in reduced border downtime through more accurate queue forecasting and dynamic reconfiguration of flows, as well as in the optimization of infrastructure maintenance schedules on the basis of predictive failure models [10]. Additional confirmation of economic effectiveness is provided by the World Economic Forum: companies that implemented artificial intelligence early in the marketing and sales of logistics services report productivity growth of 30–50% [14].

Within the current methodological framework of 2025, emphasis shifts toward governed autonomy and higher decision accuracy under conditions of high demand variability and resource constraints. Agentic artificial intelligence is considered as a class of autonomous software agents capable of negotiating freight rates, allocating capacity, and adjusting routes in real time, relying on multicriteria models of cost, time, and risk. At the same time, ALICE AI White Paper forecasts that by 2027, 40% of such projects will be discontinued because of the complexity of integration into existing information technology landscapes and operating processes; however, successful implementations are capable of forming a sustainable competitive advantage through faster response and lower transaction costs [16]. In parallel, the role of artificial intelligence in workforce management is strengthening: algorithmic optimization of shift scheduling at terminals and in ports makes it possible to align labor demand with the actual volatility of cargo flows, which is especially significant amid personnel shortages and rising labor costs [17]. A substantial contribution to accelerating border and terminal procedures is provided by computer vision at border crossing points, which automates the recognition of license plates, container markings, and indicators of damage; the stated reduction of inspection time per vehicle to 10 minutes reflects the potential of such solutions to increase throughput capacity and reduce operational losses [15, 18].

A critical condition for a durable return on artificial intelligence is data quality and the maturity of the integration layer. In logistics, the principal losses in model accuracy arise from heterogeneity of sources (transportation management systems and warehouse management systems, port and customs systems, telematics, electronic data interchange messages), misalignment of reference directories, and delays in status updates. Therefore, practices of data governance, master data management, and observability move from auxiliary functions to the foundation of the reliability of digital solutions: without formalized rules for data lineage, drift control, and the reproducibility of computational pipelines, autonomous scenarios inevitably degrade and lose predictability.

A distinct layer of requirements is formed by cybersecurity risks and operational resilience: the expansion of application programming interface integrations and the connection of field devices increase the attack surface, while dependence on algorithmic recommendations raises the cost of errors and failures. As a result, the industrial deployment perimeter incorporates machine learning operations and model risk management mechanisms, including model version control, validation procedures, monitoring of prediction quality, safe rollback scenarios, and the allocation of responsibility between automation and the dispatch control layer. Such an architecture makes it possible to increase the degree of autonomy while preserving process controllability under border constraints, weather disruptions, infrastructure overload, and other supply chain shocks (see Table 3).

Table 3. Matrix of Effects and Technological Complexity of Applying Artificial Intelligence in International Transport Corridors (compiled by the author based on [10, 14, 15, 16, 18]).

AI application in international transport corridors (ITC)	Business effect (ROI)	Technological complexity
Route optimization (Dynamic Routing)	Reduction in fuel costs by 15-20%	Medium
Predictive maintenance of infrastructure	Reduction in downtime by 25%	High
Automation of customs declarations	Acceleration of clearance processing by 3.4 times	High
Demand forecasting	Planning accuracy up to 95%	Medium

The transformation of personnel functional roles under the influence of artificial intelligence instruments is regarded as an organic component of the methodological contour, because the implementation of artificial intelligence is accompanied by a redistribution of tasks toward hybrid practices grounded in collaboration with artificial intelligence. Labor market dynamics confirm the institutionalization of this shift: in 2024, the number of vacancies in sales and marketing directly oriented toward the presence of skills for interacting with artificial intelligence increased by 340%.

Blockchain and Decentralized Trust Protocols

Blockchain in the context of cross-border logistics is often interpreted as a universal instrument capable of radically reducing the trust deficit among participants in the transportation process operating in different jurisdictions. Its implementation in 2024 makes it possible to form an immutable register of events and transactions, which acquires fundamental significance for insurance procedures, customs control, and verifiable environmental auditing. 19 Research findings indicate that the application of blockchain solutions is associated with a reduction in administrative costs by 15–20% and a shortening of customs clearance time by 50–70%, which reflects the effect of standardizing the evidentiary base and reducing the number of manual approvals [19, 20].

The implementation of blockchain within the methodological contour presupposes coupling with Internet of Things infrastructure: telemetry from temperature and humidity sensors is recorded in the distributed ledger directly, thereby limiting the possibility of falsifying information about compliance with transportation conditions and cargo integrity; in 2024, the frequency of losses in such systems is estimated at 1.2% versus 4.5% in traditional configurations, which illustrates the practical value of an immutable registration environment [20]. A significant element is represented by smart contracts for multimodal chains, ensuring automated settlement among a rail operator, port infrastructure, and a maritime carrier upon the occurrence of a predefined control event, which reduces lags in financial clearing and lowers the probability of disputed interpretations of performance conditions. An additional level of resilience is achieved through federated learning: the SafeLogFL solution makes it possible to train predictive risk models on distributed datasets from different companies without transferring primary datasets and without violating General Data Protection Regulation requirements and commercial secrecy regimes, thereby expanding the analytical base while preserving legal and competitive constraints [21]. The indicated effects form a foundation for the subsequent comparative evaluation of the performance of blockchain systems in cross-border logistics using unified metrics of operational reliability and transactional efficiency.

Table 4 will present a description of the features of assessing the effectiveness of the customs process.

Table 4. Comparative Assessment of Customs Process Effectiveness: Traditional (Electronic Data Interchange and Paper) versus Blockchain System (2024) (compiled by the author based on [20]).

Process parameter	Traditional system (paper-based/EDI)	Blockchain system (2024)	Improvement
Customs clearance time	4.0 hours (average 2020)	1.5 hours (average 2024)	-62%
Documentation errors	12% – 15%	< 1%	-93%
Operating cost per ton	$50 – $70	$30 – $40	-40%
Data update frequency	1 – 24 hours	5 seconds (IoT Real-time)	In real time

Despite the discontinuation of TradeLens in the preceding period, initiatives of 2025 demonstrate a reorientation from closed platform models toward architectures grounded in interoperability and open standards, which reduces the risk of technological lock-in within a single vendor and increases the long-term flexibility of the digital contours of cross-border logistics.

Digital Twins and the Internet of Things in Flow Monitoring

By 2025, the concept of the digital twin has shifted from the local reproduction of the characteristics of individual objects (a vessel, a terminal, a warehouse) toward the systemic modeling of integrated cross-border corridors. In this case, a corridor digital twin is interpreted as a highly detailed virtual representation of physical assets, operational processes, and freight flow dynamics, continuously updated by streams of telemetry and event data in a near real-time regime [23]. Such a model provides not only end-to-end observability of the movement chain, but also the capability for computational playback of alternative scenarios for managing throughput capacity, allocating resources, and reconfiguring routes when deviations arise.

The methodological architecture of a digital twin of an international transport corridor rests on three interconnected layers: a sensor layer, the Internet of Things, generating primary signals from vehicles, containers, and elements of infrastructure (including bridges, tracks, and access nodes); a data integration layer, aggregating information from Warehouse Management Systems, Transportation Management Systems, and Enterprise Resource Planning systems of different participants and ensuring the alignment of reference directories and statuses; and an analytical layer, where artificial intelligence algorithms perform forecasting and simulation modeling of system behavior under the impact of low-probability, high-amplitude events, black swans, including pandemics, armed conflicts, and climatic anomalies [24, 25]. Within this approach, the digital twin ceases to be a static map and becomes a computational environment for risk management and resilience, in which optimization decisions are tested on simulated trajectories of event development before their transfer into the operational contour.

Empirical results obtained on the basis of structural equation modeling indicate a statistically significant association between the characteristics of the deployed technology, above all the relative advantage and the compatibility of digital twins, and the resilience of logistics systems to external shocks [24]. This aligns with practical observations: under high compatibility with existing information technology landscapes and with the normative and procedural environment, a digital twin reaches scale effects more rapidly, reducing coordination transaction costs and accelerating the restoration of operability after disruptions. At the level of the technological foundation, it is expected that by 2025 approximately 60% of logistics companies will apply blockchain and the Internet of Things as an infrastructural basis for digital twins, anchoring trust in data and ensuring continuity of telemetry collection [20].

The practical feasibility of a corridor digital twin is to a significant extent determined by the maturity of interoperability and by data governance. At the cross-border level, unified semantic models are critical, including the unification of events, statuses, units of measurement, and identifiers, as well as data quality and data lineage regulations, and robust exchange mechanisms across organizational domains, including customs and port contours. Without formalizing a single source of truth for key entities (container, shipment, vehicle, route segment), an effect of misaligned digital representations emerges, which reduces forecast accuracy and limits the applicability of scenario modeling under conditions of high flow variability.

A separate layer of requirements is formed by issues of security and trust: a corridor digital twin aggregates critically important information about movements, capacities, and bottlenecks, therefore the role of access segmentation, cryptographic protection, anomaly monitoring, and provable integrity of event journals increases. In this logic, blockchain components are used not as a universal replacement for corporate databases, but as a means of fixing immutable traces of key operations and harmonizing trusted states among participants, which is especially important under distributed responsibility and heterogeneous levels of digital maturity across organizations.

CHAPTER3.STRATEGICMULTIMODALCORRIDORS AND GEOPOLITICAL RESILIENCE

In Chapter 3, Eurasia's strategic multimodal corridors were examined as instruments of geoeconomic flow reorientation and of strengthening the geopolitical resilience of supply chains. Using the International North–South Transport Corridor (INSTC) as an example, it was shown how, in 2024, the corridor is institutionally consolidated as a competitive alternative to maritime routes by shortening the haul and increasing transit predictability. In this configuration, the interfaces become critical, namely border crossings and multimodal nodes, where priority is given to measures of procedural and digital stitching, including unified event statuses, advance electronic pre-notification, end-to-end traceability, and tariff harmonization, alongside a shift toward corridor-level governance based on digital models and digital twins for scenario-based dispatching.

Next, the Middle Corridor (TITR) was analyzed as a fast-growing Trans-Caspian alternative between China and Europe, whose development within the 2025 logic hinges on synchronizing ferry and rail schedules, expanding node throughput, achieving interoperability with European Union norms, and digitalizing document circulation through CIM and SMGS consignment notes. In this context, the principal constraint is semantic alignment of data and unified tracking rules at interfaces [13, 22].

Finally, a methodological apparatus for risk management under conflicts and a VUCA environment was formed, in which resilience is interpreted through the distinction between engineering resilience, recovery, and ecological resilience, adaptation and transformation. The toolkit includes business impact analysis and recovery time objective metrics, diversification of routes and sources, artificial intelligence–supported scenario planning, dynamic risk dashboards with triggers and thresholds, and financial stress testing of total landed cost. This reframes resilience from an operational characteristic into a measurable parameter of competitiveness that depends on data maturity, decision speed, and the network's readiness for reconfiguration.

International North–South Transport Corridor (INSTC): A New Architecture of Eurasian Flows

In 2024, the International North–South Transport Corridor (INSTC) consolidated its position as a strategically significant alternative to traditional maritime routes, because it forms a stable linkage among India, Iran, and the states of the Caspian Basin across a distance of approximately 7,200 km [2]. The growth of operational activity is confirmed by freight-flow dynamics: by the end of 2024, total freight turnover reached 26.9 million tons, which is 19% higher than the 2023 figure [2]. In practical terms, this reflects not only a redistribution of a portion of foreign trade flows, but also the gradual institutional consolidation of the corridor as a route whose competitiveness is determined by the combination of delivery time, transit predictability, and risk controllability.

The internal structure of the INSTC is traditionally described through three complementary branches, each of which imposes its own requirements on infrastructure and on the organization of the transportation process. The western direction, running through Azerbaijan, focuses on creating a continuous rail leg, and the completion of the Rasht–Astara segment constitutes the key element here: the start of construction dates to March 2025 [2]. It is assumed that commissioning this line will produce a multiplicative effect on throughput capacity, bringing it to 15 million tons per year by 2028 [18]. The eastern branch, passing through Kazakhstan and Turkmenistan, is characterized by the most stable rail logic: in 2024, 1.9 thousand TEU were dispatched along this route, with coal, metals, and fertilizers serving as the dominant cargo categories [3, 18]. A comparison of the key parameters of the INSTC and the route via the Suez Canal is presented in Table 5.

From the standpoint of transport economics and supply chain management, corridor competitiveness is determined not only by geography and the length of the main leg, but also by the degree of procedural stitching at interfaces: schedule alignment, transshipment quality, the regularity of container services, and the maturity of customs and logistics administration. The most sensitive zones remain cross-border crossings and multimodal nodes, where total transit time is shaped by queues, regulatory heterogeneity, and infrastructure constraints. Under these conditions, measures that increase predictability become priorities: advance electronic pre-notification, the unification of event statuses, and digital traceability of the cargo unit along the entire route, which reduces coordination transaction costs among participants and increases service resilience to external disturbances.

The infrastructure agenda of the INSTC is logically complemented by a technological agenda: as freight flows grow, the value of integrated throughput planning and corridor-level risk management increases. A promising direction here is the development of corridor-level digital models, including digital twins, for scenario analysis of disruptions, optimization of transshipment windows, and the alignment of actions among carriers, terminals, and supervisory authorities. This approach shifts management from reactive consequence elimination to predictive dispatching, in which decisions on flow redistribution and the selection of alternative legs are made on the basis of verifiable data and a calculated assessment of implications for delivery time, cost, and reliability.

Table 5. Comparison of Route Logistics Efficiency: Suez versus the International North–South Transport Corridor, a Multimodal Corridor (compiled by the author based on [5, 26]).

Parameter	Route via Suez (maritime)	International Transport Corridor North — South (multimodal)	INSTC benefit
Distance	~16,000 km	~7,200 km	Reduction by 30-40%
Transportation cost	100% (baseline)	70% of baseline	Reduction in costs by 30%
Blockage risk	High (Suez; Bab-el-Mandeb)	Medium (local borders)	Increased reliability

A significant milestone was the agreement on unified tariff conditions among the participants of the eastern branch (Kazakhstan, Turkmenistan, Iran), because the unification of the tariff framework functions as a system-forming component of the methodology of seamless logistics: fragmentation of rates and transactional discontinuities at the junctions of jurisdictions are eliminated, the predictability of end-to-end pricing increases, and coordination costs in planning multimodal routes are reduced.

The Middle Corridor (TITR) and Integration with the One Belt One Road Project

In 2024, the Middle Corridor, the Trans-Caspian International Transport Route, became one of the most dynamically developing directions of Eurasian transit, strengthening its role as an alternative bridge between China and Europe that bypasses both the territory of Russia and vulnerable segments of maritime logistics associated with risks in the Red Sea area. The intensity of expansion is confirmed by statistics: the volume of cargo transported along the route in 2023 increased by 86%, and Kazakhstan railway volumes in 2024 grew by 63% [27]. Such a growth trajectory reflects not a single surge in demand but a structural reassessment of routes from the standpoint of schedule reliability and risk diversification, where decisive factors become the throughput capacity of multimodal nodes and the quality of coordination among supply chain participants.

Within the methodological framework of 2025, the development of the Middle Corridor concentrates on removing infrastructural and organizational constraints, increasing compatibility with European standards, and accelerating the transactional contour. A key element in increasing regularity on the Caspian segment is the synchronization of ferry fleet schedules and rail consists: the establishment of the joint venture Middle Corridor Multimodal Ltd in 2023 provided an institutional basis for coordinating timetables, allocating capacity, and smoothing transshipment windows [28]. In parallel, the line toward interoperability with the European Union is strengthening: the conclusion of service contracts in accordance with European Union norms, in particular the relevant agreements in Georgia in June 2024, builds trust among European cargo owners in service parameters and reduces barriers to integration into European Union supply chains [28]. A major accelerator is the digitalization of document management: the transition to CIM and SMGS consignment notes is associated with reducing border-crossing time by 4 days by decreasing paper content turnover, reducing the number of manual reconciliations, and accelerating status confirmation procedures [7]. Long-term estimates also support the trend: forecasts of the Eurasian Development Bank indicate an increase in freight flow along the three main corridors through Central Asia by a factor of 1.5, to 95 million tons by 2030 [7].

The expansion of the transit potential of the Middle Corridor depends to a substantial extent on coordinated management of interfaces and the standardization of data, because time losses and schedule variability are concentrated precisely at intermodal transfers. Unified rules for event tracking, arrival, handover, loading, release, become critical, along with the unification of reference directories and identifiers, as well as end-to-end visibility of the container and the cargo lot along the route with the distribution of access rights among participants. In the absence of a shared semantics, data remain fragmented, which limits the possibility of real-time dispatching and reduces the effectiveness of synchronizing ferry and rail schedules, especially under seasonal fluctuations in the Caspian Sea level and weather constraints.

The systemic effect of digitalization also manifests in lowering the transaction costs of compliance and risk insurance, because traceability and document verifiability accelerate claim settlement and increase the predictability of obligation performance. In this context, priority is given to technologies that ensure legally significant electronic exchange, document integrity control, and transparency of the event chain without disclosing commercially sensitive data beyond what is necessary. The set of these measures shifts corridor development from a regime of pointwise infrastructure expansion to a regime of governed growth in service reliability, in which competitiveness is determined not only by the tariff, but also by the stability of transit time, the quality of multimodal interfacing, and the maturity of the regulatory and digital environment.

Risk Management Under Conditions of Geopolitical Conflicts and a VUCA Environment

Cross-border transportation in 2024–2025 operates in a context of heightened uncertainty, in which the resilience of supply chains is determined not only by infrastructure reliability, but also by the ability of organizations to manage regulatory, geopolitical, and climatic shocks. The methodology of supply chain risk management (SCRM) during this period refined the conceptual framework of resilience by distinguishing engineering resilience, defined as the capacity of a system to return to an equilibrium state after a disruption, and ecological resilience, understood as the capacity to adapt and transform under the impact of external change [29]. This differentiation strengthens the applied character of SCRM: alongside post-incident recovery, the focal point becomes the reconfiguration of network topology, the contractual base, and logistics policies in accordance with an evolving risk environment.

When operating in conflict zones, including segments with an elevated probability of incidents, for example the Pakistan–Afghanistan border or the waters of the Red Sea, the methodology relies on a set of complementary procedures. Business impact analysis (BIA) is used to rank the criticality of assets and processes and to define the recovery time objective (RTO), thereby establishing measurable requirements for capacity redundancy and organizational operating procedures [30]. Diversification of routes and sources reduces dependence on single bottlenecks and increases transit controllability under abrupt constraints; empirically, this is confirmed by the reaction to the Red Sea crisis, when the rerouting of more than 2000 vessels was accompanied by route extensions of 10–14 days and an increase in fuel costs of approximately $1 million per voyage [12]. Additional reinforcement of SCRM is provided by artificial intelligence–enabled scenario planning, in which predictive analytics is used for early identification of likely disruptions through the integration of geopolitical indicators, telemetry, and meteorological data, making it possible to assess in advance the impact of risk on lead times, cost, and capacity availability [29].

The macroeconomic and regulatory background intensifies pressure on operational decisions. An analysis of tariff impacts conducted by McKinsey in 2025 shows that 82% of companies report exposure to new trade barriers; at the same time, 30% of respondents note a reduction in demand, while 39% report rising costs [31, 32]. Against this backdrop, the profile of managerial priorities changes: instead of predominantly long-term transformation, tactical response intensifies, expressed in inventory build-ups (45% of companies) and in a nearshoring strategy (33%), aimed at shortening supply chain length and reducing exposure to cross-border constraints [31].

A key methodological shift of recent years is associated with moving from risk registers to managing risk as a dynamic system, in which triggers and threshold values are formalized as observable metrics. For conflict-affected and high-risk directions, the construction of risk dashboards is practiced, integrating data on transit time, delay variability, infrastructure availability, insurance rates, incident frequency, and regulatory changes, with automated updates of threat levels according to predefined rules. This scheme makes it possible to link engineering resilience to operating procedures, including capacity buffers, alternative routes, and recovery plans, and to link ecological resilience to architectural decisions on restructuring the supply network and the contractual model.

An additional role is played by formalizing the financial contour of resilience: cost increases driven by tariffs and route deviations elevate the importance of total landed cost methodologies and stress testing of the cost base under shock scenarios. As a result, SCRM is integrated with inventory planning, customer service policies, and working capital management, ensuring a substantiated balance between the cost of reliability and the risk of supply disruption. In such a framing, resilience ceases to be perceived as an exclusively operational characteristic and becomes a measurable parameter of competitiveness, directly dependent on data maturity, decision-making speed, and the network's readiness for reconfiguration under conditions of a rapidly changing geoeconomic configuration.

CHAPTER 4. GREEN TRANSFORMATION AND SUSTAINABLE DEVELOPMENT OF CROSS-BORDER SYSTEMS

In Chapter 4, the green transformation of cross-border systems was articulated as an integrated linkage of technological, economic, and regulatory mechanisms of sustainable development. Within methodological block 4.1, the World Economic Forum approach with 15 levers for logistics decarbonization was systematized, including low-carbon fuels; green transport through electrification and alternative energy carriers; sustainable infrastructure up to and including net-zero warehouses; and digital optimization, including artificial intelligence–enabled reductions in empty runs. It was also shown that the transition from pilots to scaling requires institutionalized coordination among the state, business, and the financial sector on the basis of blended finance in order to increase the bankability of projects.

In 4.2, it was substantiated that the principal constraint on zero-emission transportation is not environmental desirability but the economics of ownership, total cost of ownership, with its sensitivity to energy prices, downtime driven by charging and hydrogen infrastructure availability, degradation dynamics, and residual value. At the same time, the regulatory trajectory, including carbon payments and low-emission zones, and commercial incentives from major shippers shift carbon intensity into a factor of market access and pricing; accordingly, planning is methodologically sound when structured as a portfolio of scenarios that also accounts for the monetization of green attributes.

Finally, in 4.3, green corridors were presented as a project of integrated governance in which the effect is achieved through standard harmonization and mutual recognition of certificates, including certificates of energy origin, the creation of regulatory sandboxes for autonomous electric transport and digital proofs, competency development, and a shift toward end-to-end emissions accounting linked to events of the transportation process. This reduces compliance uncertainty, increases the comparability of calculations, and makes decarbonization a measurable parameter of competitiveness that affects financing access, contract terms, and the risk profile of international operations.

Methodology for Implementing the 15 Levers of Green Logistics According to the World Economic Forum

The transport sector accounts for approximately 11% of global greenhouse gas emissions, as a result of which its decarbonization is treated as a priority direction of the climate agenda [12]. In 2025, the World Economic Forum proposed a comprehensive methodology of green transformation for developing markets, including 15 key levers grouped into four complementary blocks. The first block is associated with low-emission fuels and presupposes a transition to hydrogen, biofuels, and ammonia; the second emphasizes green transport through the electrification of vehicle fleets and the deployment of liquefied natural gas vessels; the third is oriented toward sustainable infrastructure, including the construction of warehousing facilities with a net-zero emissions balance [34]. The fourth block rests on digital optimization, where the use of artificial intelligence is aimed at reducing empty runs that reach 15–20% of total mileage, which simultaneously lowers the emissions burden and increases the operational efficiency of logistics [12]. Expert assessment for 2024–2025 makes it possible to construct a ranking of the impact of the specified green logistics levers (see Table 6).

Table 6. Matrix of Innovative Levers for Logistics Decarbonization: Emissions-Reduction Potential, ROI, and Implementation Barriers (compiled by the author based on [17, 34]).

Innovation lever	Emissions reduction potential	Economic payback (ROI)	Deployment barriers
Route optimization (AI)	15% – 20%	High (1-2 years)	Low data quality
Electrification of heavy-duty trucks (Heavy-duty EV)	40% – 60%	Low (high total cost of ownership (TCO))	Insufficient charging station availability
Green fuels (H2/LBG)	70% – 90%	Medium (subsidies)	Production cost
Energy-efficient warehouses	10% – 15%	Medium (5-7 years)	Initial capital expenditures

The transition from pilot deployments to the scaling of the specified solutions presupposes institutionalized coordination among public authorities, industry participants, and financial institutions on the basis of blended finance mechanisms. Within such a configuration, public resources and development instruments are used to reduce project risks and to establish predictable rules of the game, while private capital provides the necessary volume of investment and the discipline of efficiency. Combining grant components, concessional debt, guarantees, and market sources of capital makes it possible to increase the bankability of projects, accelerate their replication, and simultaneously sustain compliance with climate and technological requirements that are critical for the sustainable modernization of transport and logistics infrastructure.

Economic Aspects of the Transition to Zero-Emission Transportation

Despite the evident environmental motivation, the scaling of electric and hydrogen trucks in 2025 is constrained primarily by the parameters of total cost of ownership (TCO), which is composed not only of the purchase price, but also of expenditures on energy, maintenance, downtime, infrastructure, and residual value. As of March 2025, the TCO of zero-emission vehicles in most segments remains noticeably higher than that of diesel analogues, which keeps projects in the zone of selective deployments and pilot fleets oriented toward routes with predictable haul length and access to charging or hydrogen infrastructure [17]. An additional factor is payload limitation due to the mass of traction batteries or composite cylinders, as well as uncertainty regarding battery degradation and replacement costs, which directly affects service-life planning and residual value risk.

At the same time, the methodology of long-term planning in logistics requires accounting for indirect yet economically measurable effects that gradually change the underlying cost structure. Tax and regulatory pressure in the form of carbon charges and related mechanisms in the European Union and a number of other jurisdictions leads to higher costs for diesel mileage and increases the attractiveness of low-carbon technologies over a horizon of several years. In parallel, green transport is often deployed in conjunction with digital management contours and elements of automation: telematics, predictive maintenance, optimization of driving regimes, and, prospectively, autonomous functions are capable of reducing labor costs and increasing fleet utilization, which partially compensates for the high capital entry barrier. Market access also becomes significant: large retailers and marketplaces, including Amazon and Alibaba, establish a preference for logistics counterparties with a low carbon footprint, which transforms green indicators from image-related attributes into commercially consequential parameters of selection and pricing [35].

In practical sales and operations planning and in the investment contour, long-term planning is expediently structured as a portfolio of scenarios rather than as a linear replacement of the diesel fleet. The most methodologically sound TCO models incorporate sensitivity to electricity and hydrogen prices, to interconnection and capacity tariffs, to downtime rates caused by queues at charging hubs, as well as to battery degradation parameters, schedules for secondary utilization, and the potential monetization of green attributes, including contractual premiums, access to low-emission zones, and shippers' reporting requirements. As a result, the economic viability of zero-emission technologies is determined not by an abstract cost per kilometer, but by the combination of infrastructural readiness, the regulatory trajectory, and the operator's capacity to convert carbon-footprint reduction into a higher level of service and sustainable commercial demand.

Integrated Management of Green Corridors and the Regulatory Environment

The formation of green corridors in 2025 is interpreted as an institutional and technological project in which the decarbonization effect is achieved not so much through isolated innovations as through the alignment of regulatory regimes, control procedures, and digital trust contours across jurisdictions. Within this logic, the 2025 methodology envisages the creation of regulatory sandboxes for the controlled testing of cross-border movement of autonomous electric trucks and for piloting digital certificates of energy origin, which make it possible to verify the carbon intensity of transportation along the entire route. The key methodological emphasis shifts toward reducing compliance uncertainty: the legal validity of data, the reproducibility of emissions calculations, and the comparability of admission criteria become determinative for scaling solutions, especially when crossing multiple legal regimes.

The management of a green corridor relies on an interconnected set of elements, among which the synchronization of standards and recognition mechanisms is of primary importance. Mutual recognition of environmental certificates and the alignment of approaches to confirming energy origin, for example within the integration contours of the Regional Comprehensive Economic Partnership or the Eurasian Economic Union, are treated as instruments for lowering transaction costs and preventing double counting of environmental attributes [36]. The next level is represented by integrated policy: a shift from fragmented national strategies to sectoral road maps with harmonized standards, unified data requirements, and coordinated criteria for admitting transport into a green operating mode [33]. A substantial condition of practical feasibility remains anticipatory competency development: training specialists capable of ensuring the operation of hydrogen technologies, industrial safety, and simultaneous work with artificial intelligence analytics of emissions forms a personnel contour of resilience, without which technological investments yield limited returns [33].

A study by DHL Group (2024) records a shift in the corporate logic of decarbonization from the domain of voluntary initiatives to the sphere of governed performance indicators, characterizing it as a fourth bottom line of reporting alongside profit, people, and planet [37]. This observation reflects a change in the status of sustainable development: decarbonization begins to function as a measurable parameter of competitiveness that influences access to financing, contract terms, and the risk profile of international operations, rather than as a peripheral component of environmental, social, and governance rhetoric.

In addition, the methodological maturity of green corridors is determined by the capacity to link carbon reporting with operational planning. Practice is shifting toward end-to-end emissions accounting tied to events of the transportation process, loading, transfer of responsibility, border crossing, charging and fueling, which increases the verifiability of claims and makes it possible to differentiate tariffs by actual carbon intensity. As a result, a managerial contour is formed in which regulatory integration, digital proofs of energy origin, and standardized emissions analytics provide a reproducible foundation for cross-border business oriented toward long-term resilience and the reduction of aggregate risks.

CONCLUSION

The methodology of cross-border transportation in 2024–2025 is formed as a multilevel synthesis of engineering, economic, and digital solutions, reflecting the growing complexity of the logistics environment and the rising requirements for the reliability of international supply chains. The analysis conducted makes it possible to assert the dominance of the digital contour over exclusively physical capacity expansion: overcoming border constraints is ensured not only by infrastructural enlargement of the transport network, but also by the deployment of soft infrastructure, namely systems based on artificial intelligence, blockchain, and digital twins, which shift control, coordination, and compliance into a regime of data and algorithms, a shift associated with a 50–70% reduction in cargo processing time.

Particular attention is required for the reconfiguration of global routing, within which Eurasian corridors, the International North–South Transport Corridor and the Middle Corridor, have moved from the category of predominantly project concepts to the status of functioning logistics arteries with stable freight-flow dynamics. Their competitiveness is determined not only by geography and throughput capacity, but also by the degree of methodological alignment of tariffs and documents, because it is precisely the unification of procedures that reduces transaction losses and eliminates interface discontinuities between jurisdictions and modes of transport.

Resilience is being fixed as a normative standard of sectoral development: environmental neutrality and social responsibility cease to be optional elements of reputational management and become mandatory requirements for cross-border operators. Within this contour, the 15 green logistics levers proposed by the World Economic Forum form a structured decarbonization plan for the transport sector, setting priorities in fuel transformation, fleet renewal, sustainable infrastructure, and digital optimization.

Against the backdrop of high volatility, a key condition of effectiveness is adaptive risk management: the SCRM methodology becomes effective when it rests on principles of ecological resilience and on instruments of predictive analytics, ensuring not only recovery after disruptions, but also the accumulation of an organizational evolutionary capacity for reconfiguring processes, counterparty configurations, and routing decisions.

The application of the proposed methodology creates a foundation for market participants in cross-border transportation to maintain operational resilience under conditions of turbulence while simultaneously forming a resource for long-term development. The conclusions reached confirm that the prospective model of cross-border logistics is associated with intelligent, seamless, and environmentally neutral systems in which digital management, standardized coordination, and climate compatibility function as complementary components of a unified architecture.

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