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Methodology for evaluating the resilience of complex logistics systems under extreme infrastructure stress

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Abstract. *The purpose of the article is to develop and scientifically substantiate an integrated methodology for assessing the viability of complex logistics systems under extreme loads on the infrastructure, taking into account modern security, economic and technological challenges. The study aims to develop a comprehensive approach to analyzing the functioning of logistics networks that increases the validity of management decisions in crisis conditions.*

The methodological basis of the study is a system analysis, scenario approach and simulation modeling, supplemented by methods of statistical, comparative and multi-criteria analysis. Network models were used to determine structural dependencies between elements of logistics systems, scenario forecasting to assess sensitivity to external influences and quantitative indicators for an integrated assessment of functional stability, adaptability and recoverability. The methodology was tested through an analysis of the dynamics of transport indicators and changes in logistics flows under crisis conditions.

Modern theoretical and methodological approaches to assessing the viability of logistics systems are summarized, and key factors influencing extreme *infrastructure loads are identified, including overloading of transport nodes, capacity limitations, infrastructure destruction, information failures and changes in the structure of transport flows. An integrated assessment model has been developed that combines structural, functional and dynamic levels of analysis with an expanded system of quantitative indicators, allowing for a comprehensive assessment of the state of logistics systems, timely identification of critical risks and the formulation of adaptive management strategies. The proposed model can be used to improve mechanisms for managing logistics processes, optimizing resource and forming strategies for responding to crisis challenges in an environment of high uncertainty. Further research is required to adapt the model to industry-specific conditions, develop digital assessment tools and improve methods for forecasting the long-term performance of logistics systems.*

Keywords: *resilience, infrastructure constraints, multicriteria assessment, crisis conditions, logistics networks, transport flows, forecasting.*

Методологія оцінювання життєздатності складних логістичних систем при екстремальних навантаженнях на інфраструктуру

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Анотація. *Метою статті є розроблення та наукове обґрунтування інтегрованої методології оцінювання життєздатності складних логістичних систем в умовах екстремальних навантажень на інфраструктуру з урахуванням сучасних безпекових, економічних і технологічних викликів. Дослідження спрямоване на формування комплексного підходу до аналізу функціонування логістичних мереж, здатного забезпечити підвищення обґрунтованості управлінських рішень у кризових умовах.*

Методологічну основу дослідження становлять системний аналіз, сценарний підхід та імітаційне моделювання, доповнені методами статистичного, порівняльного та багатокритеріального аналізу. Використано мережеві моделі для визначення структурних залежностей між елементами логістичних систем, сценарне прогнозування для оцінювання чутливості до зовнішніх впливів і кількісні індикатори для інтегральної оцінки функціональної стійкості, адаптивності та відновлюваності. Апробація методології здійснювалась на основі аналізу динаміки транспортних показників і змін у логістичних потоках у кризових умовах.

Узагальнено сучасні теоретико-методологічні підходи до оцінювання життєздатності логістичних систем і визначено ключові чинники впливу екстремальних інфраструктурних навантажень, серед яких перевантаження транспортних вузлів, обмеження пропускної спроможності, руйнування інфраструктури, інформаційні збої та зміни структури транспортних потоків. Розроблено інтегровану модель оцінювання, що поєднує структурний, функціональний і динамічний рівні аналізу, та розширену систему кількісних індикаторів, яка дозволяє здійснювати комплексну оцінку стану логістичних систем, своєчасно ідентифікувати критичні ризики та формувати адаптивні управлінські стратегії. Запропонована модель може бути використана для вдосконалення механізмів управління логістичними процесами, оптимізації використання ресурсів та формування стратегій реагування на кризові виклики у середовищі високої невизначеності. Подальших досліджень потребує адаптація моделі до галузевих особливостей, розвиток цифрових інструментів оцінювання та удосконалення методів прогнозування функціонування логістичних систем у довгостроковій перспективі.

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Ключові слова: *адаптивність систем, інфраструктурні обмеження, багатокритеріальна оцінка, кризові умови, логістичні мережі, транспортні потоки, прогнозування.*

Problem statement. In the current conditions of transformation of logistics networks and the growth of military, technogenic and climatic risks, the problem of ensuring the viability of complex logistics systems under extreme loads on infrastructure becomes particularly relevant. Such systems function as multi-level networks that integrate transport, warehouse, information and management subsystems; therefore, exceeding critical loads or damage to infrastructure nodes can cause cascading failures, reduced efficiency and loss of controllability.

Despite the development of approaches to assessing the reliability and stability of logistics systems, existing methods remain fragmentary and do not sufficiently account for the nonlinear interactions among subsystems, load dynamics and the ability of systems to recover. This necessitates the formation of an integrated methodology for assessing viability, combining a systems approach, modeling and quantitative indicators.

Solving this problem is of great scientific and practical importance, as it will improve the management of logistics systems, increase the validity of management decisions, and ensure the continuity of logistics processes in conditions of high uncertainty.

Analysis of recent research and publications. A review of scientific sources shows an increase in attention to the problems of logistics system functioning in crisis conditions, particularly under the influence of military, economic and technological factors. N. Mykhaylik [1] examines the transformation of transport logistics under war conditions and emphasizes the role of adaptive solutions, yet pays insufficient attention to the quantitative assessment of system stability. V. Yuriev [2] substantiates the economic significance of the development of transport and logistics infrastructure, focusing on its impact on macroeconomic indicators, but considers the issue of the viability of logistics networks fragmentarily. O. Kostenko, V. Chernenko, A. Kulychkov [3] investigate the digital transformation of logistics, noting the role of digital platforms in ensuring the continuity of processes, while L. Gurch and V. Maistruk [4] emphasize the restoration of infrastructure and strategic directions of the industry's development. I. Zrybnieva [5] summarizes modern technological approaches in logistics but does not provide a comprehensive methodology for assessing system viability. O. Onyshchenko and V. Shyshkin [6] analyze international transportation under sanctions and conflicts, highlighting managerial aspects, while Y. Vorobiov [7] considers the adaptation of transport enterprises to crisis conditions. In the works of L. Kaptsov [8], M. Imanova et al. [9], and O. Korostin [10], the potential of digital technologies and artificial intelligence in logistics process management is examined, but these studies do not establish an applied connection and provide only a comprehensive assessment of the viability of the systems.

Identification of previously unresolved parts of the general problem. Despite a significant number of studies, the assessment of logistics system viability under extreme infrastructure loads remains underdeveloped. There is no single integrated methodological approach, and existing models generally do not account for the systemic interactions among subsystems, nonlinear effects and recovery dynamics.

Formulation of the article objectives (task statement). The purpose of the article is to develop and scientifically substantiate a comprehensive methodology for assessing the viability of complex logistics systems under extreme infrastructure loads based on a systems approach, quantitative modeling and integrated indicators of stability, adaptability and recoverability.

The objectives of the research are:

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1. To generalize theoretical and methodological approaches to assessing the viability of logistics systems and to identify key factors influencing extreme infrastructure loads.

2. To develop an integrated model for assessing the viability of complex logistics systems using systems analysis, scenario approach and simulation modeling methods.

3. To substantiate a methodological approach to assessing the viability of logistics systems based on the integration of modeling stages and a system of quantitative indicators.

Presentation of the main material of the study. With the onset of a full-scale war, Ukraine's transport and logistics system underwent significant transformations, including the forced restructuring of logistics routes, particularly in international transportation. The loss of access to seaports and the cessation of the grain corridor led to the reorientation of cargo flows to the west through the countries of the European Union, accompanied by the active introduction of multimodal transportation. At the same time, the increase in the load on the infrastructure of border crossings exceeded their limited capacity, leading to significant delays in the delivery of goods [1, p. 166].

The destruction of key transport hubs in the southern and eastern regions intensified these trends, causing the concentration of logistics flows in the west. As a result, border crossings, in particular Yagodyn, Krakivets and Rava-Ruska, have been transformed into critically important logistics hubs that ensure the redistribution of cargo to EU countries, but they also operate under conditions of excessive infrastructure load [3, p. 154].

In response to wartime challenges, Ukraine's transport infrastructure is being modernized, particularly railway and port infrastructure (including the Danube cluster), which has reduced delivery times by 15–20% and logistics costs by 8–12%. This contributes to the gradual restoration of export potential and increased efficiency of logistics operations, while maintaining the investment attractiveness of the industry [2, p. 154]. However, these positive changes do not eliminate the risks associated with uneven load on the infrastructure and a high level of external threats. Table 1 presents the dynamics of the number and volume of transported passengers and cargo by mode of transport in Ukraine for the period 2019–2024.

Table 1

Dynamics of the number and volume of transported passengers and cargo by modes of transport in Ukraine, 2019–2024

Mode of transport	2019	2020	2021	2022	2023	2024	Change rate, % 2024/2021
Number of transported passengers by modes of transport, million passengers:							
Road	1804.9	1083.9	1089.3	n/a	n/a	915.3	-15.9
Water	0.7	0.3	0.5	n/a	n/a	n/a	–
Aviation	13.7	4.8	9.3	n/a	n/a	n/a	–
Volume of transported cargo by modes of transport, million tons:							
Railway	312.9	305.5	314.3	n/a	n/a	174.9	-44.4
Road	244.2	191.4	224.0	n/a	n/a	128.8	-42.5
Water	6.1	5.6	5.3	n/a	n/a	2.2	-58.5
Aviation	112.7	97.5	77.6	n/a	n/a	n/a	–
Pipeline	0.1	0.1	0.1	n/a	n/a	n/a	–

Note: «n/a» – not available
Source: based on [12]

The significant reduction in passenger and freight traffic in the period under study is due to the impact of crisis factors, primarily a full-scale war. The largest decrease was recorded in freight traffic: in 2024, compared to 2021, rail traffic decreased by 44.4%, road traffic by 42.5%, and water traffic by 58.5%, indicating infrastructure losses and changes in logistics routes. Passenger traffic also decreased, particularly road traffic by 15.9%, reflecting a decrease in population mobility. At the same time, the limited statistical data on individual modes of transport for 2022–2024 complicates a comprehensive analysis of dynamics, although it confirms the

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high sensitivity of the transport system to external shocks and the need to increase the resilience of logistics networks.

In parallel with the transformation of physical infrastructure, the evolution of logistics' organizational and management models is underway. In particular, new levels of logistics operators are emerging, such as 6PL, 7PL, 8PL and 9PL, which are focused on integrating environmental approaches, comprehensive supply chain management, coordinating industry processes and personalizing "last mile" delivery [4, p. 309]. The implementation of such models increases the adaptability of logistics systems, but, at the same time, complicates their structure, requiring improved methods for assessing their viability.

The key factor in ensuring the efficiency of modern logistics systems is digitalization and automated information processing. The growth in data volumes on transportation parameters, the condition of cargo and vehicles, and the use of encrypted satellite information streams significantly complicates their manual processing. This increases the risk of errors in management decisions and underscores the need to implement intelligent data analysis systems [5, p. 5]. At the same time, information overload is a distinct type of infrastructure load that affects the stability of logistics systems.

At the corporate level, transport and logistics companies respond to the growing instability of the environment by implementing a set of anti-crisis measures, among which the key role is played by diversifying supply chains, developing multimodal transportation, digitalizing management processes and implementing risk management systems. These tools contribute to increasing the continuity of transport operations and reducing the vulnerability of logistics systems to external shocks [6, p. 196]. At the same time, the focus on «green» transformation stimulates the modernization of transport infrastructure and opens access to international financial resources, which further strengthens the institutional and investment capacity of the logistics sector [7, p. 686]. At the same time, in modern conditions

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of increased turbulence in the transport and logistics environment, with the intensification of cargo flows and the aggravation of infrastructure risks, the limitations of traditional approaches to assessing the effectiveness of logistics systems are becoming apparent. The complexity of their structure, the nonlinear nature of element interactions, the dynamics of change and the need to ensure adaptability and recoverability after failures necessitate the development of new methodological approaches to assess their viability.

Thus, the combination of these factors – destruction of infrastructure, concentration of cargo flows, limited throughput capacity, technological transformation and information overload – forms a complex environment for the functioning of logistics systems. This determines the need to generalize theoretical and methodological approaches to assess their viability and identify key influencing factors, which is an important scientific task in the context of ensuring the stability and adaptability of Ukraine's transport and logistics system (table 2).

Table 2

Theoretical and methodological approaches to assessing the viability of logistics systems

Approach	The essence of the approach	Main assessment indicators	Key factors of extreme loads
Systemic	Consideration of the logistics system as an integrated multi-level network	Bandwidth, flow balance, stability of operation	Node overload, infrastructure limitations
Risk-oriented	Assessment of the probability and consequences of malfunctions	Risk index, loss level, failure frequency	Military actions, corridor blockages and accidents
Process	Analysis of the effectiveness of logistics operations	Delivery time, level of delays, process continuity	Increase in transportation volumes, resource shortage
Functional	Assessment of the system's ability to adapt and recover	Reliability, flexibility, adaptability and recoverability	Destruction of infrastructure, digital disruptions

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Approach	The essence of the approach	Main assessment indicators	Key factors of extreme loads
Modeling and analytical	Using scenario analysis and modeling	Scenario indicators, recovery speed	Environmental uncertainty, complex risks

Source: author's development

Thus, the generalization of approaches shows that assessing the viability of logistics systems requires integrating a set of methods, in particular modeling and multi-criteria indicators.

The scientific literature substantiates that the most effective approach is an integrated approach that combines the tools of system analysis, scenario approach and simulation modeling, since it is this combination that allows taking into account the multidimensionality of influencing factors, the uncertainty of the external environment and possible scenarios, ensuring the formation of informed management decisions [8, p. 7].

System analysis within the framework of an integrated model involves decomposing the logistics system into interconnected subsystems (transport, warehouse, information and management) and determining the key parameters for their operation. This allows the formation of a structural and functional model in which the throughput capacity of nodes, the intensity of flows, the level of resource reservation, the degree of dependence between network elements and indicators of operational reliability are assessed. Within the framework of system analysis, it is important to use network models that allow for identifying critical nodes, determining the level of system vulnerability and assessing the impact of local disturbances on the overall stability of the logistics network [9, p. 240].

The scenario approach enables assessing the viability of logistics systems under different scenarios, including crisis and extreme situations. Within the framework of the integrated model, basic, pessimistic and adaptive scenarios are developed that account for changes in transportation volumes, infrastructure destruction, the blocking of transport corridors or information failures [10, p. 35].

This allows assessing the system's sensitivity to external influences and determining the load thresholds at which it loses functional stability.

Simulation modeling is a key tool for quantitatively assessing viability, as it allows for reproducing the behavior of a logistics system in a dynamic environment. The use of agent-oriented, discrete-event and network models enables analysis of delivery time parameters, levels of delay, resource efficiency and recovery speed after violations. The combination of simulation modeling results with multi-criteria evaluation methods enables the construction of an integrated index of the logistics system's viability [11, p. 33]. Thus, the proposed integrated model for assessing the viability of complex logistics systems is based on a combination of system analysis, a scenario approach and simulation modeling, which carefully considers the system's structural, functional and dynamic characteristics (table 3). Its application contributes to increasing the accuracy of predicting the behavior of logistics networks, the validity of management decisions and the effectiveness of responding to extreme infrastructure loads.

Table 3

Integrated model for assessing the viability of complex logistics systems

Modeling stage	Methodological tools	Key assessment indicators	Expected results
Structural analysis	System analysis, network models	Throughput, node load, reliability	Identification of critical system elements
Scenario formation	Scenario approach, expert assessments	Load variability, risk level	System sensitivity assessment
Simulation modeling	Discrete-event, agent models	Delivery time, delays, resource use	System behavior prediction
Integrated assessment	Multi-criteria analysis	Viability index, sustainability	Justification of management decisions

Source: author's development

The proposed model for assessing the viability of logistics systems is based on a consistent combination of complementary methodological approaches, each providing an analysis of a separate aspect of the system's functioning. System analysis identifies critical nodes and structural constraints; the scenario approach

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assesses the system's sensitivity to changes in the external environment; and simulation modeling reproduces its dynamic behavior under conditions of uncertainty. The final stage is an integrated assessment that summarizes the results in a single indicator of viability and serves as the basis for informed management decisions.

Thus, the advantages of the model include its complexity, the ability to account for both structural and dynamic parameters of logistics systems, and the ability to adapt to extreme infrastructure loads, making it an effective tool for strategic management and increasing the resilience of logistics networks.

In conditions of growing uncertainty, not only the technical and economic components of logistics system functioning, but also the regulatory and legal ones, become particularly important, as they underpin stability, adaptability, and recovery. The presence of conflicts between international standards and national practices of regulating transport in crisis conditions significantly affects the effectiveness of management decisions, increases transaction costs and creates additional risks for participants in logistics chains (table 4).

Table 4

Comparative characteristics of international and national norms in the field of international transport

Regulatory aspect	International norms (CMR, SOLAS, IMO)	National and EU practices	Identified problems	Management decisions
Carrier liability and force majeure	The CMR Convention defines the carrier's liability for loss or damage to cargo, the possibility of exemption from liability in the event of force majeure	In Ukraine and EU countries, military actions are recognized as force majeure, but the confirmation procedures differ; judicial practice is heterogeneous	Uncertainty in cases of blockades, sanctions or destruction of infrastructure	Unification of crisis clauses in contracts; harmonization of procedures for confirming force majeure

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Regulatory aspect	International norms (CMR, SOLAS, IMO)	National and EU practices	Identified problems	Management decisions
Safety of maritime transport	The SOLAS Convention and IMO standards regulate the safety of shipping, the protection of crew and cargo	National governments in conflict situations introduce additional restrictions (port closures, mining), which are not always consistent with international norms	Lack of coordination of actions in crisis zones; discrepancies between standards and local solutions	Formation of joint crisis centers, implementation of risk maps and agreed port protocols
Customs and sanctions procedures	International acts provide for freedom of transit and transparency of customs procedures, but do not directly regulate sanctions	The EU has enhanced sanctions compliance; Ukraine has introduced «green corridors» for humanitarian cargo	Conflicts between sanctions requirements and the right of transit; delays in processing	Introduction of electronic declarations, harmonization of sanction procedures, approval of exceptions for critical goods
Transport insurance in crisis conditions	International norms regulate insurance indirectly through the institution of carrier liability	National insurance systems take into account military risks in different ways; Ukraine has limited coverage programs	Lack of unified insurance standards, high insurance premiums	Development of special insurance products, state support for transportation insurance in crisis regions

Source: based on [12–16]

The presented data indicate that key problems arise in the areas of carrier liability, ensuring transportation safety, implementing customs and sanction procedures, and insuring risks in crisis conditions. The identified discrepancies between international standards (CMR, SOLAS, IMO) and the national practices of Ukraine and the EU led to legal uncertainty, transportation delays and a decrease in the overall efficiency of logistics systems, affecting their viability under increased infrastructure loads.

Thus, the inclusion of a regulatory component in the structure of logistics systems assessment is justified and necessary. The management decisions summarized in Table 5, in particular, the harmonization of procedures, digitalization of customs clearance, unification of insurance mechanisms and the creation of coordination centers, can be integrated into the developed model of viability assessment as external environmental factors. This allows for a more comprehensive analysis and increases the study's practical significance by enabling the formulation of effective strategies for managing logistics systems.

In the context of developing an integrated model for assessing the viability of logistics systems, an important stage is the development of a set of quantitative indicators that comprehensively reflect the state and dynamics of logistics network functioning under crisis conditions. Given the multidimensional nature of viability, such a system should cover both technical and infrastructure parameters, as well as operational, economic, risk and adaptive characteristics. A summary of the relevant indicators and methods for their assessment is given in Table 5.

Table 5

System of quantitative indicators for assessing the viability of logistics systems in crisis conditions

Group of indicators	Indicator	Content of the indicator	Evaluation method
Infrastructural	Level of infrastructure utilization	Ratio of actual load to throughput capacity	Load factor
	Reliability of nodes	Frequency of failures of infrastructure elements	Reliability index
Operational	Delivery time	Average duration of cargo transportation	Statistical analysis
	Delay level	Part of the untimely deliveries	KPI analysis
	Frequency of failures	Number of process violations for the period	Event monitoring
Economic	Logistics costs	Transportation and storage costs	Factor analysis
	Transportation profitability	Ratio of income and expenses	Economic analysis
Risk-oriented	Risk index	Combined assessment of external and internal risks	Multi-criteria analysis
	System sensitivity	System response to load changes	Scenario analysis

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Group of indicators	Indicator	Content of the indicator	Evaluation method
Adaptive	Recovery speed	Failure recovery time	Scenario analysis
	Resource reservation level	Availability of alternative routes and resources	Comparative analysis
Digital	Digitalization level	Share of automated processes	Digitalization index

Source: author's development

As shown in table 5, the proposed system of indicators is structured around key functional blocks, allowing assessment of the logistics system from the perspectives of throughput capacity, operational efficiency, economic performance, risk level, adaptability to change and degree of digitalization. The use of various assessment methods, in particular statistical, factor, scenario and multi-criteria analysis, enables a comprehensive analysis of both the current state of the system and its behavior under conditions of uncertainty.

Thus, the system of quantitative indicators provides a comprehensive assessment of the viability of logistics systems in crisis conditions, covering infrastructure, operational, economic, risk-oriented, adaptive and digital aspects of functioning. Its application within an integrated model enables timely identification of critical areas, enhancing the validity of management decisions and ensuring the stability and adaptability of logistics networks under conditions of high uncertainty and extreme infrastructure loads.

Conclusions. The generalization of the research results shows that in the conditions of a full-scale war, the transport and logistics system of Ukraine has undergone a significant transformation, manifested in changes in cargo flow directions, infrastructure overload and the development of multimodal transportation. It has been established that the viability of logistics systems is determined by a set of factors, in particular throughput capacity, operational efficiency, risk level, economic efficiency, adaptability and digitalization, which require integrated assessment approaches.

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The proposed methodological approach, which combines system analysis, scenario and simulation modeling with a system of quantitative indicators, provides a comprehensive assessment of the state of logistics systems and increases the validity of management decisions, identifies critical areas and predicts system behavior in crisis conditions.

Prospects for further research include assessing the effectiveness of artificial intelligence, digital monitoring platforms and the integration of big data and geographic information systems, as well as adapting the developed model to various modes of transport and international logistics corridors.

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