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**INTELLECTUALIZATION OF LOGISTICS
AND SUPPLY CHAIN MANAGEMENT**

Electronic scientific and practical publication in economic sciences

The electronic scientific and practical journal is registered in international scientometric data bases, repositories and search engines. The main characteristic of the edition is the index of scientometric data bases, which reflects the importance and effectiveness of scientific publications using indicators such as quotation index, h-index and factor impact (the number of quotations within two years after publishing).

In 2020, the International Center for Periodicals (ISSN International Center, Paris) included the Electronic Scientific and Practical Edition "Intellectualization of logistics and Supply Chain Management" in the international register of periodicals and provided it with a numerical code of international identification: ISSN 2708-3195 (Online).

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Contents

INTRODUCTION

We are happy to invite you to get acquainted with the first issue of the new scientific and practical publication "Intellectualization of Logistics and Supply Chain Management".

We strongly believe that the launch of this magazine indicates the objective need to rethink a wide range of issues related to the development of theory and practice in logistics and supply chain management, awareness of the need to unite the scientific community and logistics practitioners, dissemination of modern knowledge and best practices for innovative development of the logistics services market.

The first issue of the magazine is published at a difficult time. The global coronavirus pandemic and the deep economic crisis have significantly worsened business activity in the world. Currently, global supply chains are collapsing, international trade is declining, and competition between global and regional logistics operators is intensifying. The most common thesis is that the world will never be the same again. Industry experts predict the emergence of new, more flexible and adaptive supply chain management strategies and approaches to logistics business process management. The trend towards collaborations, cooperation and unification of services is emerging, comprehensive proposals for clients are being developed. There is increasing talk about the need to build bimodal supply chains, which involves the development of different decision-making scenarios: the traditional approach - cost-effective efficiency, low risk, high predictability; a new approach "second mode" - rapid recognition of opportunities, adaptability, willingness to solve unexpected problems and look for new opportunities.

Radical transformations of the global and national markets for logistics services require appropriate scientific support. Logistics science has a special role to play in this process. Initiating the emergence of a new journal, we decided to focus on its coverage of problematic aspects of the formation and development of logistics systems at the micro, mezo and macro levels, supply chain management, digitization of logistics, methods and tools for optimizing processes in logistics and supply chains, sociopsychology relations and network interaction of enterprises using cloud technologies, artificial intelligence, e-learning, neural business process management systems, etc.

Therefore, we invite scientists, researchers and business representatives, as well as our colleagues from abroad, to cooperate and present the results of scientific research, to discus and debate on them, to work together to develop the scientific theory of logistics and promote mutual intellectual enrichment.

We hope that the new scientific publication will become a theoretical guide for young researchers and representatives of other fields.

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CONTEMPORARY CHALLENGES OF AVIATION LOGISTICS SAFETY

Dmytro Bugayko, Svitlana Smerichevska, Danylo Bugayko. "Contemporary challenges of aviation logistics safety". *Safety is an integral criterion for the development of aviation logistics. With the development of jet aviation, the first key problem was the failure of new aviation equipment. In these conditions of rapid development, Annex 13 to the Chicago Convention of 1944 was adopted, which included Standards and Recommended Practices in the field of methods for investigating disasters and serious incidents. Thanks to active work in the field of flight safety, the industry managed to overcome the criticality of technical failures. However, as always in aviation safety, a decrease in the criticality of one component leads to an increase in the criticality of another component. Thus, the weak link in the man-machine-environment triangle turned out to be a person. The organizational factor brought a conceptual shift in understanding the place of the human factor in safety. At the same time, the following problem emerged. Against the background of an active decrease in the probability of aviation accidents, unfortunately, the annual number of fatalities in aircraft crashes is relatively stable. Recognizing the problem, Annex 19 to the Chicago Convention of 1944 was developed, which*

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included generalizing approaches to the development of a comprehensive aviation safety system. The dramatic events of the last decade - numerous wars and conflicts, economic recessions and crises and, first of all, the COVID-19 pandemic - outlined modern challenges to the aviation logistics safety system.

Keywords: aviation logistics, safety, challenges, proactive risk management.

Дмитро Бугайко, Світлана Смерічевська, Данило Бугайко. «Сучасні виклики безпеки авіаційної логістики». Безпека є інтегральним критерієм розвитку авіаційної логістики. З розвитком реактивної авіації першою наріжною проблемою стала відмова нової авіаційної техніки. В цих умовах стрімкого розвитку отримав додаток 13 до Чиказької конвенції 1944 року, який включив в себе Стандарти та Рекомендовану Практику з напрямку методики розслідування катастроф та серйозних інцидентів. Завдяки активній роботі в сфері безпеки польотів галузі вдалося подолати критичність технічних відказів. Однак, як завжди у безпеці авіації, зниження критичності однієї складової призводить до збільшення критичності іншої складової. Отже слабким ланцюгом у трикутнику людина-машина-зовнішнє середовище виявилась людина. Організаційний фактор приніс концептуальний зсув у розумінні місця людського фактору у безпеці. При цьому виявилась наступна проблема. На фоні активного зменшення вірогідності авіаційних катастроф, на жаль, щорічна кількість загиблих авіа трощ має відносно стабільний характер. Усвідомлюючи проблему, було розроблено Додаток 19 до Чиказької конвенції 1944 року, який включив в себе узагальнюючі підходи щодо розвитку комплексної системи безпеки авіації. Драматичні події останнього десятиліття – чисельні війни та конфлікти, економічні спади та кризи та, в першу чергу, пандемія COVID-19 окреслили сучасні виклики системі безпеки авіаційної логістики.

Ключові слова: авіаційна логістика, безпека, виклики, проактивне управління ризиками

Introduction. Safety is an integral criterion for the development of aviation logistics. Over the years of development, the aviation safety management system has gone through a number of conceptual stages.

Technical era. With the development of jet aviation, the first key problem was the failure of new aviation equipment. The probability of a disaster in these conditions was 1 disaster per 1000 flights, which is an excessively high figure [1].

In these conditions of rapid development, Annex 13 to the Chicago Convention of 1944 was adopted, which included Standards and Recommended Practices in the field of accident and serious incident investigation methodology [2]. Thanks to active work in the field of flight safety, the industry managed to overcome the criticality of technical failures. They continued to occur, while, as a rule, not leading to catastrophic consequences. The probability of disasters gradually decreased to one disaster per 10,000 flights and continued to decrease [1].

The era of the human factor. However, as always in aviation safety, a decrease in the criticality of one component leads to an increase in the criticality of another component. Thus, the weak link in the triangle of man-machine-environment turned out to be a person. In 1970-2000, standards and Recommended Practices of the 18 Annexes to the Chicago Convention of 1944 were actively developed. Particular attention was paid to solving human factor problems, developing the principles of Crew Resource Management and Fatigue Risk Management Systems. The probability of disasters gradually decreased to one disaster per 100,000 flights and continued to decrease [1].

The era of the organizational factor. The organizational factor brought a conceptual shift in understanding the place of the human factor in safety. By organizational factor we mean the following maxim: "if a person makes

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a mistake during interaction in the triangle of man-machine-environment, not only the person is to blame, but also the system that allowed the person to make this mistake and did not provide him with additional means of protection after it was made.

At the same time, the following problem has emerged. Against the background of an active decrease in the probability of aviation accidents, unfortunately, the annual number of fatalities in aircraft accidents is relatively stable. This is due to the global trend of a doubling of the number of flights every 15 years. And although the probability of a disaster now reaches a record figure of one disaster per 10,000,000 flights [1], the situation is reminiscent of the conversation between Alice and the Queen from Lewis Carroll's book "Alice in Wonderland" - here you need to run very fast to stay in the same place [3]. Recognizing the problem, Annex 19 to the 1944 Chicago Convention was developed [4], which included general approaches to the development of a comprehensive aviation safety system, which creates the basis for the development of a global system-wide era of aviation safety.

The dramatic events of the last decade – numerous wars and conflicts, economic recessions and crises, and, above all, the COVID-19 pandemic – have outlined modern challenges to the aviation logistics safety system.

The purpose of the article: analysis of modern challenges to the aviation logistics safety system and development of a set of proactive measures to maintain a globally agreed level of safety in conditions of uncertainty.

Presentation of the main research material.

Global tendencies of aviation safety. The COVID-19 pandemic has had a devastating impact on the development of civil aviation. For the first time in history, the reduction in air traffic has become critical for the industry. This has led to conceptual changes in industry management strategies at the global, regional and national levels [5]. Fig. 1 shows Global traffic of passengers. Fig. 2 shows Global traffic of flight departures.
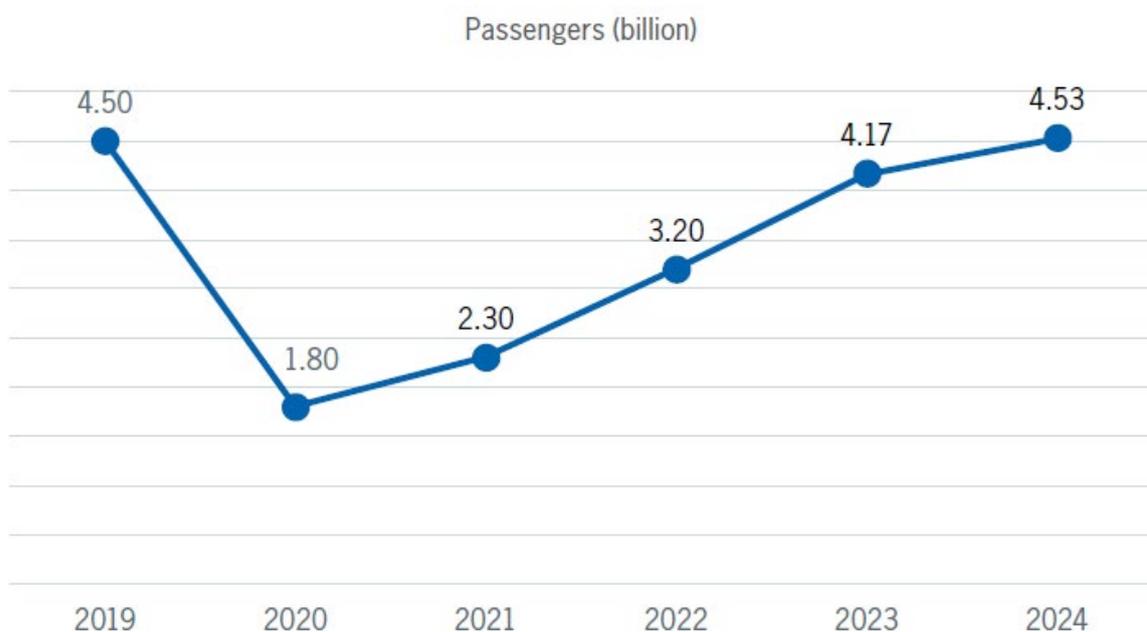
Figure 1 – Global traffic of passengers (billion)
Source: ICAO Safety Report 2025 Edition [6].

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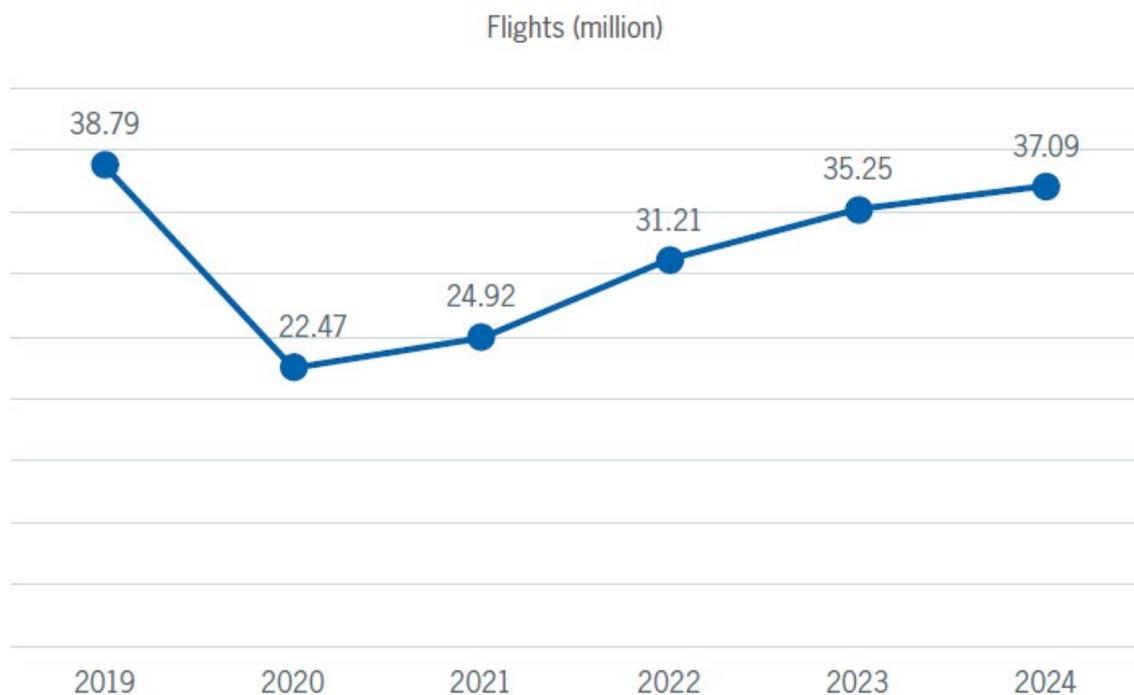
Figure 2 – Global traffic of flight departures (million)
Source: ICAO Safety Report 2025 Edition [6].

2020 became a crisis year for the entire industry as a whole. Thus, in 2020, the global volume of transportation decreased from 4.5 to 1.8 billion passengers (- 60%), and the number of flights from 38.79 to 22.47 (- 42%).

The main risks of the crisis were:

− unprofitability of passenger transportation,

− rapid burnout of financial assets of industry enterprises,

− reduction of the aircraft fleet,

− and, as a result of the implementation of a strict cost-saving program, a sharp reduction in experienced, certified aviation personnel.

To assist civil aviation authorities in managing aviation safety risks during the Coronavirus disease (COVID-19) pandemic, ICAO developed "ICAO Guidance for Civil Aviation Authorities on Aviation Safety Risk Management Issues Related to COVID-19" (Doc 10144) [5, 7].

Gradually, the civil aviation industry stabilized its work by implementing proactive risk management, diversifying activities towards the development of cargo and mail air transportation, introducing special quarantine measures and mandatory vaccination of the population. In the period from 2021 to 2024, we see a gradual increase in civil aviation production indicators. In 2026, we can state - aviation industry at the pre-pandemic level and support the trends of double growth in transportation volume every 15 years. The industry gradually coped with economic crisis phenomena, the aircraft fleet and infrastructure stabilized. The main residual vulnerability of the system is the provision of Critical Element 4 of the ICAO Safety Oversight System "Qualified technical personnel". During the years of the pandemic, many employees of the global civil aviation industry lost their certification, resigned and found new jobs. The rapid growth of air traffic volume is leading to a growing gap in personnel shortages and skills that cannot be quickly overcome. Figure 3 shows the 2024 Safety Review. Figure 4 shows Fatal accident records: 2019–2024 scheduled commercial operations.

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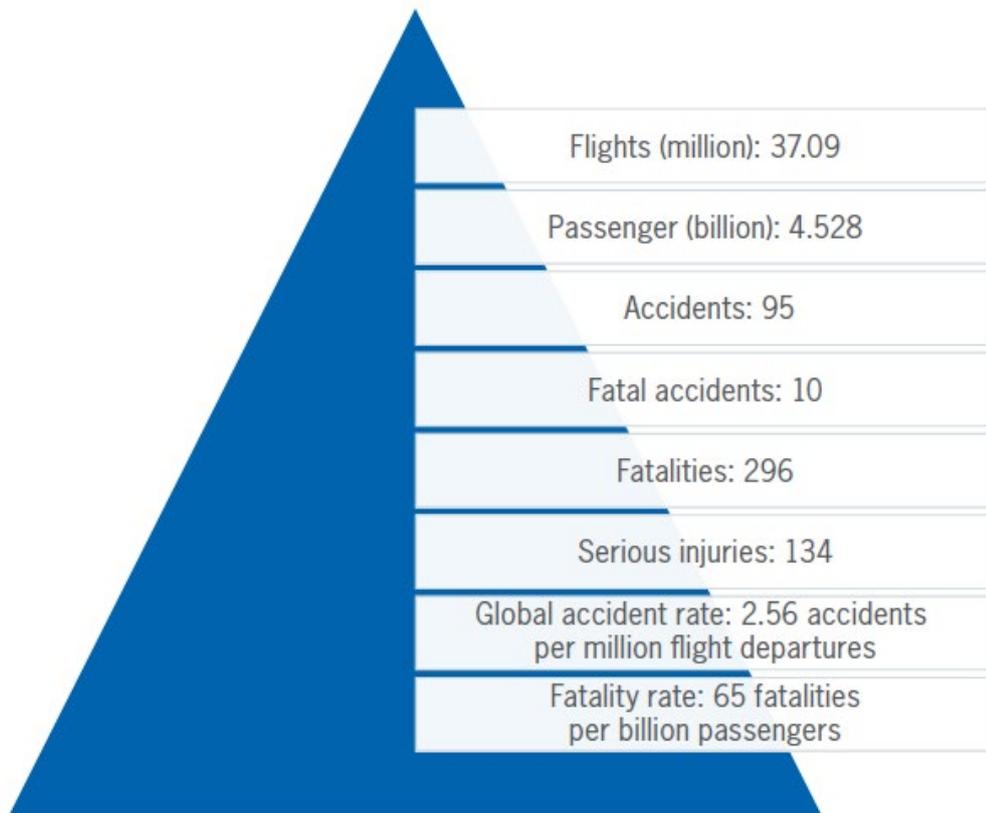
Figure 3 – Safety Overview 2024
Source: ICAO Safety Report 2025 Edition [6].
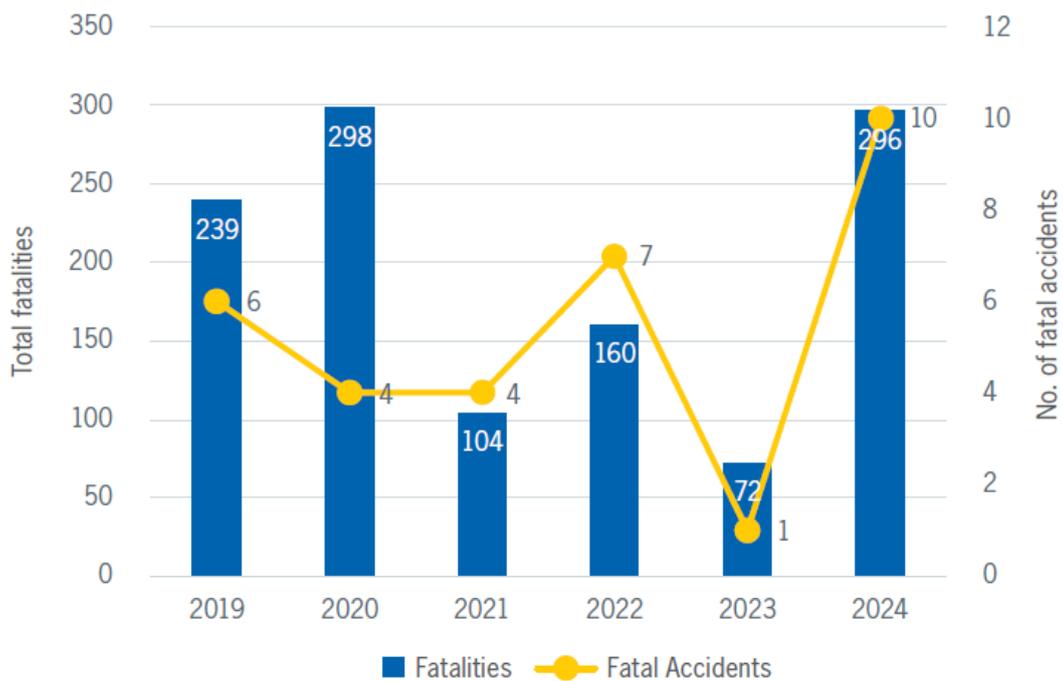
Figure 4 – Fatal accident records: 2019–2024 scheduled commercial operations
Source: ICAO Safety Report 2025 Edition [6].

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Thus, in 2024, after many years of decreasing fatal accidents and their victims, we are witnessing a quantum leap in the decline of the global level of aviation safety. In 2024, there was a tenfold increase in fatal accidents (10 compared to one in 2024) and a more than fourfold increase in the number of victims (296 compared to 72 in 2023). In addition, 134 serious injuries were registered. The global accidents rate was 2.56 accidents per million aircraft departures. The fatality rate was 65 victims per billion passengers [6].

Of course, civil aviation is an open system and is subject to thousands of different threats, but this trend cannot but worry experts. The green zone risk zone is sharply decreasing. This tendency requires the development of a number of rapid institutional measures.

Regional tendencies of aviation safety. Let's consider regional tendencies of aviation safety. Fig 5 shows number of fatal accidents by ICAO Region in 2024.

Figure 5. Number of fatal accidents by ICAO Region in 2024
Source: ICAO Safety Report 2025 Edition [6].

An analysis of the regional safety status in 2024 reveals that fatal accidents occurred in virtually all ICAO regions, with the exception of Western and Central Africa (WACAF), where passenger traffic is significantly lower than in other regions. Table 1 shows departures, accidents, and fatalities by ICAO Region based on State of Occurrence in 2024.

An analysis of regional statistics confirms the dependence of the number of accidents and casualties on the number of departures.

In 2024, the highest number of accidents occurred in the regions with the highest

aviation traffic: North America, Central America and Caribbean NACC (37), Asia and Pacific APAC (23), Europe and North Atlantic EUR/NAT (22) [6].

A similar number of fatal accidents (3 per region) occurred in Asia and Pacific APAC and Europe and North Atlantic (EUR/NAT) [6].

The highest number of casualties was recorded in Asia and Pacific APAC (185), South America SAM (62), Europe and North Atlantic EUR/NAT (40) [6].

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Table 1. Departures, accidents and fatalities by ICAO Region based on State of Occurrence in 2024

ICAO Region	Estimated departures (million)	Number of accidents	Accident rate (per million departures)	Number of fatal accidents	Number of fatalities	Serious injuries
Asia and Pacific APAC	12.37	23	1,86	3	185	78
Eastern and Southern Africa (ESAF)	0.78	3	3,85	1	2	1
Europe and North Atlantic (EUR/NAT)	9.23	22	2,38	3	40	23
Middle East (MID)	1.40	2	1,43	1	1	1
North America, Central America and Caribbean (NACC)	11.10	37	3,33	1	6	24
South America (SAM)	1.95	6	3,08	1	62	6
Western and Central Africa (WACAF)	0.26	2	7,62	-	-	1
World	37.09	95	2,56	10	296	134

Source: ICAO Safety Report 2025 Edition [6].

The highest number of serious injuries was recorded in Asia and Pacific APAC (78), North America, Central America and Caribbean NACC (24), Europe and North Atlantic EUR/NAT (23) [6].

Based on the above, unfortunately, even the most technologically advanced regions of the world are not 100% safe for civil aviation operations.

National tendencies of aviation safety of Ukraine. Despite the stereotype that during the war, Ukrainian civil aviation does not fully perform operational activities due to the closure of airspace, this is not the case. A number of Ukrainian airlines continue commercial operations from foreign bases, flight crew training is provided, and aviation work is performed [8].

In 2024, the total flight hours of certified airlines amounted to 90,988 flight hours, which is 12% more than the flight hours in 2023 (80,378 hours). This was due both to an increase in commercial transportation, as a result of which transport companies flew 86,655 hours (in 2023 - 76,999 hours), and to an increase in the flight hours when performing aviation work and scientific and technological research, where the flight hours amounted to 4,333 hours (in 2023, the flight hours were 3,379 hours) [9].

Among the main threats that accompany the operational activities of Ukrainian airlines during the war period, it is possible to highlight:

− The difficulties to perform regular flights from the territory of other countries.

− Economic problems associated with the increase in operating costs on the territory of other countries.

− Remoteness from repair and material and technical bases.

− Insufficient staffing with qualified aviation personnel, and as a number of aviation workers defend the Motherland, and

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many women with children are temporarily abroad.

An increase in the volume of transportation combined with the impact of objective threats in rare cases leads to

aviation incidents. The classification of aviation incidents in Ukraine in 2024 is presented in Figure 6.
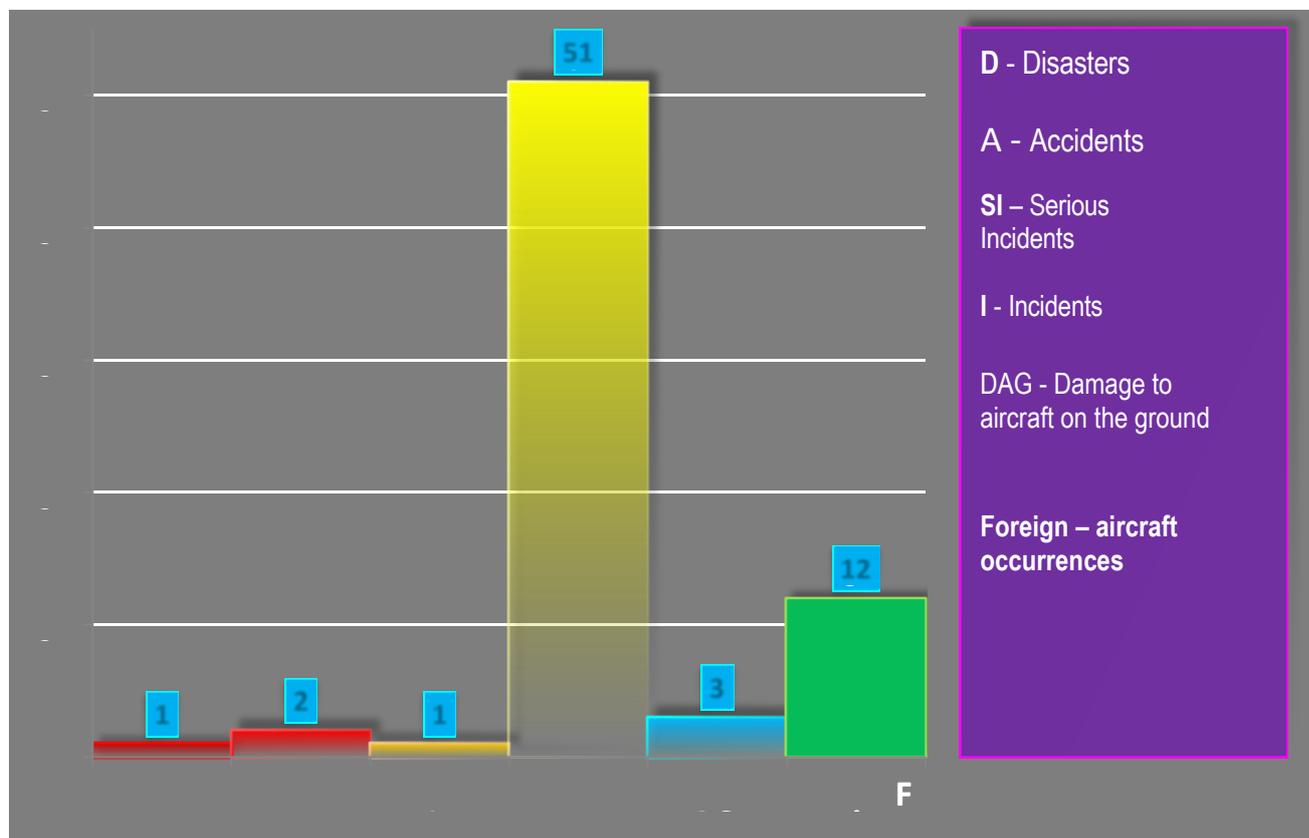
Figure 6 – Distribution of occurrences involving aircraft entered in the Civil Aircraft Register of Ukraine and aircraft of foreign registration that occurred in 2024 by class
Source: "Analysis of the state of aviation safety based on the results of the investigation of aviation accidence and incidents with civil aircraft of Ukraine and foreign-registered aircraft in 2024". National Bureau of Transport Investigations of Ukraine [9].

In 2024, during the operation of commercial civil aircraft of Ukraine during passenger and cargo transportation, aviation work, training flights and operation of general aviation aircraft, the following occurred: 1 disaster (during a training flight); 2 accidents (during training flights); 1 serious incident; 51 incidents; 3 aircraft damage on the ground; 2 extraordinary events [9].

During 2024, no flights of foreign civil aircraft were performed on the territory of Ukraine, however, during the analyzed period, 12 reports were received about incidents with aircraft manufactured or developed in Ukraine, or such incidents

during which citizens of Ukraine died, in particular: 8 incidents with amateur-built aircraft of the Ukrainian enterprise Aeroprakt LLC - a manufacturer of ultralight aircraft, namely 4 crashes, 3 accidents and 1 serious incident; 2 crashes with foreign-made aircraft during which 4 citizens of Ukraine died; 1 accident and 1 serious incident with aircraft developed by Ukraine [9].

Statistics of aviation incidents and incidents with civil aircraft of Ukraine in 2024 are presented in Table 2.

When performing passenger and cargo transportation on regular and irregular routes: in 2024 there were no disasters and accidents,

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as in 2023; 1 serious incident occurred, while in 2023 there were none; the number of incidents is 51, in 2023 there were 48; 3 damage to the airframe occurred, in 2023 there were 7; 2 emergency events occurred, and in 2023 there were 5 emergency events [9, 10].

Table 2. Aviation accidents and incidents with civil aviation of Ukraine in 2024

№	Occurrences classification	Number of occurrences				Number of victims			
		absolute quantity		for 100 thousand hours		died		injured	
		2024	2023	2024	2023	2024	2023	2024	2023
I	**Number of accidents and incidents during commercial transportation**								
1.1	Disasters								
1.2	Accidents		1	0	1,29				2
1.3	Serious incidents	1		1,15	0				
1.4	Incidents	51	48	58,8	62,3				
II	**Number of accidents and incidents during aviation operations, including training flights**								
2.1	Disasters	1		2,3	0	1			
2.2	Accidents	2		4,6	0			2	
2.3	Serious incidents								
2.4	Incidents								
III	**Total number of accidents and incidents with Ukrainian civil aviation**								
3.1	Disasters	1		1,1	0	1			
3.2	Accidents	2	1	2,2	1,24			2	2
3.3	Serious incidents	1		1,1	0				
3.4	Incidents	51	48	56	59,7				
3.5	Total	55	49	60,4	60,9	1		2	2

Source: "Analysis of the state of aviation safety based on the results of the investigation of aviation accidence and incidents with civil aircraft of Ukraine and foreign-registered aircraft in 2024". National Bureau of Transport Investigations of Ukraine [9].

When performing aviation work (including training flights): in 2024 there was 1 disaster, while in 2023 there were none; 2 accidents occurred, and in 2023 there were no accidents; There were no serious incidents, incidents, aircraft damages and emergencies, as in 2023 [9, 10].

In the operation of general aviation: information on disasters, accidents, serious incidents, incidents, aircraft damage on the ground, emergencies that occurred during 2024 was not received, as in 2023 [9, 10].

Thus, despite the extremely difficult conditions of operational activities in wartime, Ukrainian civil aviation managed not only to gradually increase its presence in the global and regional air transportation market, but also to maintain a consistent national level of safety through the development of safety management systems.

Managers and specialists of the National Bureau of Transport Investigations of Ukraine and Ukrainian airlines constantly improve their qualifications at the ICAO Institute of the National University "Kyiv Aviation Institute",

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which creates a platform for dialogue and proactive risk management, both at the state level and at the level of aviation organizations. Strategic management of national aviation security is based on synergy from the development of the interface between state regulatory authorities and the industry [11].

Conclusions. Unfortunately, despite the fact that aviation has been and remains one of the safest modes of transport, we can state that its safety status at the global, regional and national levels is not absolute. The industry faces a number of objective threats, one of the most urgent of which is the problem of experienced, certified and stable personnel. This problem is becoming even more urgent for Ukraine, which for the fourth year in a row has been counteracting military aggression unprecedented in the 21st century. At the same time, the role of training, retraining and upgrading of aviation personnel and strengthening the role of aviation educational institutions in this process is fundamentally increasing. A significant role in the national provision of Critical Element 4 of the ICAO Safety Oversight System "Qualified technical personnel" belongs to the National University "Kyiv Aviation Institute". The development of interaction between the teaching staff of aviation higher education institutions, scientists, experts from international organizations and the aviation community is the key to achieving a synergistic effect for increasing the acceptable level of safety at the global, regional and national levels.

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USE OF ARTIFICIAL INTELLIGENCE IN MODERN CONDITIONS OF DELIVERY BY UNMANNED AERIAL VEHICLES (INCLUDING IN THE COMBAT ZONE)

Danylo Grabovsky, Dmytro Bugayko. "Use of artificial intelligence in modern conditions of delivery by unmanned aerial vehicles (including in the combat zone)". With the popularization of unmanned aerial and ground vehicles as communication carriers, as well as a way to deliver goods and services, the demand for automation of a number of processes related to the technical component of these actions has increased. First of all, we are talking about the elimination of humans in making technical and machine decisions, namely control, guidance, resetting or even takeoff and landing of the device using automation using artificial intelligence. This is aimed at the fact that it is in the conditions of combat operations that the potential development and improvement of communication systems, information transmission and general use of unmanned vehicles takes place. In this article, we will consider the prerequisites for the emergence, the relevance of the study, its purpose and our own experience of using artificial intelligence systems in unmanned systems in real combat and civilian conditions.

Keywords: artificial intelligence, delivery, unmanned aerial vehicles, combat zone.

Данило Грабовський, Дмитро Бугайко. «Використання штучного інтелекту в сучасних умовах доставки безпілотними літальними апаратами (у тому числі, в зоні боєвих дій)». З популяризацією, безпілотних літальних та наземних апаратів, як носіїв зв'язку, а також, як способу доставки товарів та послуг, зріс попит на автоматизацію ряду процесів, що пов'язані з технічною

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складовою цих дій. Насамперед мова йде про усунення людини, у прийнятті технічних і машинних рішень, а саме керування, донаведення, скид або навіть зліт та посадка апарату за допомогою автоматизації за допомогою штучного інтелекту. Це спрямовано на те, що саме в умовах бойових дій іде потенційний розвиток і вдосконалення систем зв'язку, передачі інформації та загального застосування безпілотних апаратів. У цій статті ми розглянемо передумови виникнення, актуальність дослідження, його мету та власний досвід застосування систем штучного інтелекту в безпілотних системах в реальних бойових та цивільних умовах.

Ключові слова: штучний інтелект, доставка, безпілотні літальні апарати, зона бойових дій

Introduction. One of the prerequisites for the use of artificial intelligence in modern conditions of delivery by unmanned aerial vehicles was the agricultural sector, where it was necessary to reduce the cost of treating fields with fertilizers and pesticides and improve the process of supervising the cultivation process. The best suited for these tasks were copter-type drones, which were initially used for aerial reconnaissance. These drones were improved, added a spraying system and nutrient loading, as well as the power unit of the installation itself. Later, automated software was added to make it impossible for a person to make a mechanical error during the spraying process. So, with the beginning of the large-scale invasion into the territory of Ukraine, a request appeared for cheap, accurate and effective weapons against enemy equipment and enemy manpower.

Analysis of publications on the topic of the study. A number of publications by foreign and domestic scientists are devoted to the development of the application of artificial intelligence in the performance of tasks by unmanned aerial vehicles. The publications of Joshi, A., Spilbergs, A., & Miķelsone, E. identify aspects of the impact of the environment, technologies and availability of resources on autonomous navigation and decision-making processes by unmanned aerial vehicles based on artificial intelligence in the field of defence security [1].

Dash, B., Ansari, M. F., & Swayamsiddha, S. analyze the merger of artificial intelligence and 5G in determining future technologies of unmanned aerial vehicles [2].

In the publications of Sheygas O.K., Stepanko O.S., Dubovik G.V., Kashko V.G., Torchylov O.O., Dubnyuk A.V. [3] and Chepis, O. [4]. the use of artificial intelligence for the navigation of unmanned aerial vehicles was investigated.

In the publication of D. O. Borovyk, M. O. Zaretskyi, the use of drones and artificial intelligence in the military strategy of Ukraine was investigated [5].

The publication of Marko Radovanovic, Aleksandar Petrovski, Aner Behlic, Mohamed Zied Chaari, Elshan Giyas Hashimov, Radoslaw Fellner, Abayomi Agbeyangi [6] is devoted to the release of autonomous forces: the integration of unmanned aerial vehicles with artificial intelligence into modern military strategy.

In the publications of Grabovskiy D.Y., Bugayko D.O., automation is defined as one of the conceptual components of the future of logistics [7, 8].

The purpose of the study is to determine future directions for the use of AI in unmanned aerial vehicles (UAV).

Presentation of the main research material.

Table 1 provides an analysis of the main types of unmanned aerial vehicles in service with the Armed Forces of Ukraine, an assessment of their effectiveness, and the specifics of the use and potential of artificial intelligence using in their operations.

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Table 1. Use of artificial intelligence by unmanned aerial vehicles of the Armed Forces of Ukraine

Type of UAV	Main function	Examples of models	Efficiency	Use of AI	Limitations for AI	Potential with AI
Reconnaissance	Data collection, artillery adjustment	"Leleka-100", "Fury"	Range up to 50 km	None (manual analysis)	High speed, Electronic warfare	In-flight video analysis
Striking/Kamikaze	Destruction of equipment and manpower	«Switchblade», «Racoon»	Accuracy 80%	None (manual control)	Processing delays, resources	Autonomous target selection
Logistics	Cargo delivery	«Valkyrie»	Payload up to 20 kg	None (manual planning)	Simplicity of tasks	Route optimization
Electronic warfare drones	Suppression of enemy communications	«Bukovel», "Piranha"	Range up to 50 km	None (manual tuning)	Technical complexity	Adaptive response to electronic warfare
Reconnaissance (potential)	Autonomous analysis and return	Not in combat use	Theoretically high	Not implemented	Cost, Electronic warfare technologies	Autonomous in-flight data processing

Source: D. O. Borovyk, M. O. Zaretskyi (2025) [5]

From a systems engineering perspective, unmanned aerial vehicles equipped with artificial intelligence should be considered as cyber-physical systems operating under conditions of uncertainty, incomplete information, and external adversarial influence. The operational environment of such systems, especially in combat zones, is characterized by high levels of stochasticity, dynamic threats, electromagnetic interference, and limited computational and energy resources. Under these conditions, classical deterministic control models become ineffective, necessitating the application of adaptive, probabilistic, and learning-based approaches [1, 3, 6].

Artificial intelligence in UAV delivery systems performs not only a control function but also a cognitive one, enabling perception, interpretation, prediction, and autonomous action. The perception layer integrates multisensor data fusion, including inertial navigation systems, satellite positioning, optical and thermal imaging, and environmental sensors. AI-based data fusion algorithms increase robustness to sensor failure and signal degradation, which is critical in hostile operational environments [3, 4].

At the decision-making level, artificial intelligence enables the implementation of autonomous mission planning based on multi-criteria optimization. These criteria include flight safety, mission time, payload integrity, energy efficiency, and survivability under electronic warfare conditions. The use of reinforcement learning and heuristic optimization methods allows UAVs to iteratively improve their decision-making strategies based on accumulated operational experience, both in civilian and military contexts [2, 5].

A critical advantage of artificial intelligence in UAV logistics is its ability to ensure mission continuity under communication denial conditions. By utilizing pre-trained models, onboard data processing, and decentralized control logic, UAVs can maintain operational effectiveness even in complete radio silence. This characteristic fundamentally changes the paradigm of unmanned delivery, shifting from remote-controlled platforms to self-sufficient autonomous systems [1, 6].

Furthermore, the integration of AI into UAV delivery systems enables predictive logistics. Using historical mission data, environmental parameters, and system

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performance metrics, AI algorithms can forecast maintenance needs, battery degradation, payload limitations, and mission success probabilities. This predictive capability enhances the sustainability and reliability of UAV-based logistics networks, particularly in prolonged conflict scenarios [7, 8].

The convergence of military and civilian UAV applications demonstrates the dual-use nature of artificial intelligence technologies. Innovations originating in civilian sectors such as agriculture and infrastructure monitoring are rapidly adapted to military logistics and vice versa, reinforcing their strategic importance [4, 6].

Let's focus on our own practical examples of using artificial intelligence in modern conditions of delivery by unmanned aerial vehicles.

Example 1 – With the advancement of the technology of using drones, there was a request for additional guidance to the target, because in parallel with the development of radio communication, control and countermeasures to it were also developing. To bypass the radio blockade, it was clear that programming was needed that could independently make a decision to switch to another communication channel or independently guide the device to the target using advanced algorithms based on the existing conditions.

Example 2 – we have a modified argodrone that we use to deliver combat equipment and provisions to positions. At the same time, we cannot use the manual operator mode due to the density of the enemy's electronic warfare equipment. Therefore, we program the drone as follows - we have the coordinates of the takeoff position - we have the coordinates of the drop position and return to the takeoff point. Enemy electronic warfare equipment will not be able to intercept it, because it is already flying along a given route "offline", and not in manual control mode.

Example 3 – civil use - we have a field for sowing wheat - the agrodrone has coordinates for fertilizer cultivation - it has a starting point, the area of the field, as well as a calculation of fertilizer use, a refuelling point. Having these coordinates, we start working using programming. The only thing that will be needed is for a person at the refuelling point to change the batteries on the drone.

The above examples determine the relevance of the research and the direction of its application.

Therefore, we can say that one of the most important and ambitious areas of use of artificial intelligence in unmanned aerial vehicle control systems is logistics: delivery, sorting, warehousing, as well as multifunctional technical actions associated with these processes.

First of all, we can determine that AI helps to replace a person in hard-to-reach places or in places close to the conduct of hostilities. My personal experience involved the use of AI precisely in the delivery of provisions to extremely difficult routes to fighters, even in conditions of semi-encirclement, when conventional logistics gives 50% delivery to the target, and this in turn is a risk to people and equipment. The drones used for this were domestically produced - Baba Yaga, Vampire. Food per load - 20 kg. Range up to 10 km.

Let's consider another example - a more complex and systematized structure of interaction of various fire and reconnaissance means: we have two separate systems and two different control stations, the first is a reconnaissance drone, the second is an artillery system "partisan"

The reconnaissance drone transmits the coordinates of the enemy's equipment to the calculator in the artillery system, the calculator in turn analyzes the data and enters them into its launch table, gives out data to which the system automatically adjusts the sight, after the data on the sight is set and the system has checked the weather and weight balance of the projectile, the launch occurs.

The reconnaissance drone at this time monitors the enemy's defeat, if the impact occurred, it returns to the starting position, if

the impact did not occur, then a correction is made and a new launch procedure begins.

Conclusions. From the above it follows that almost all unmanned systems have a dual purpose.

In addition, recently in the Donetsk direction, the 3rd Army Corps stormed and captured enemy positions without the use of human force - the entire assault was carried out by unmanned complexes.

So, based on the above, we can come to a unanimous conclusion: the use of artificial intelligence of unmanned systems significantly increases their accuracy, reliability in conditions of uncertainty, and in conditions of military operations it can save the lives of personnel.

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ARTIFICIAL INTELLIGENCE AS THE BASIS FOR THE FORMATION OF SUSTAINABLE INTEGRATED AIR TRANSPORT SYSTEMS IN CONDITIONS OF UNCERTAINTY

Olena Harazha, Dmytro Shevchuk. "Artificial intelligence as the basis for the formation of sustainable integrated air transport systems in conditions of uncertainty". The article reveals the application of artificial intelligence in the organization of air transportation of cargo and passengers in the modern period of development, which is characterized by the rapid introduction of high-tech tools into all areas of the aviation industry.

Rapid transformations concern not only the management sphere of society, but also the acceleration of logistics activities in the organization of cargo and passengers in the context of deepening globalization and integration through the use of complex routes with an increase in air transportation volumes in the international market of trade, tourism and business activity. Thanks to artificial intelligence, it is possible to automate the planning and adjustment of cargo transportation routes by multimodal transport, form additional passenger flights during vacations, carry out total reductions in fuel costs, operating costs and maintenance, which is becoming an important factor in the context of growing competition in the aviation industry. It is well known that artificial intelligence systems have broad capabilities for fast and thorough processing of large data sets in real time. The main problem is the complexity of integrating artificial intelligence into modern aviation process management systems for ground and air support. It is obvious that outdated equipment and software of airports and airlines require modern updating and the latest design solutions that will meet modern norms and standards. It is well known that in different countries and regions there is a need to harmonize the regulatory framework in accordance with the standards of the global community, which slows

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down the rapid implementation of innovations. By the way, one of the acute problems is the cybersecurity of data regarding the transportation of cargo and passengers by air fleet. Therefore, to guarantee the safety of flights and personal data of passengers, thorough protection against cyberattacks and hacking is necessary.

The purpose of our work is to study the theoretical and methodological basis for the implementation of artificial intelligence in the formation of sustainable integrated air transport systems under conditions of uncertainty.

The methodological basis for the study of artificial intelligence in the organization of air transportation is a systems approach, which is based on the analysis of the structure of air transportation as a single whole and all the relationships between its components. The main methods of the systems approach in the organization of air transportation are: an analysis method, which considers all components of air transportation as a holistic structure based on the relationships between its main elements (aircraft, airports, crews, dispatch services, passengers); a modeling and simulation method, which allows testing various scenarios for predicting changes in the structure of the system; The system integration method allows you to combine various subsystems of air transportation and create a unique information system for managing the movement of the air fleet and other components by creating a continuous flow of information between individual elements of the air transportation structure for the purpose of coordination and management. The process optimization method involves improving the efficiency of air transportation, taking into account the optimization of flight schedules and resource potential management. The system monitoring and control method allows you to observe the functioning of all elements of the air transportation chain based on the collection and processing of data in real time in order to eliminate challenges and solve them.

Based on the results of the study, the following stages of the development of artificial intelligence in the organization of air transportation were identified: 1. initial automation; 2. data analysis stage; 3. passenger experience improvement stage; 4. intelligent pilot support systems; 5. autonomous flights. It was found that powerful artificial intelligence resources direct efforts to implement innovations: first, artificial intelligence affects the development and production of aircraft; second, artificial intelligence will ensure aviation safety; third, artificial intelligence will solve the problem of staffing flights from pilots and flight crew; fourth, increasing fuel use and reducing environmental impact; fifth, artificial intelligence allows you to order and book tickets in advance using online services; sixth, new approaches to baggage handling; seventh, ethics and personnel replacement. It is proven that the development of artificial intelligence in the organization of air transportation, highlighting the main key points: route optimization, technical maintenance, passenger flow management, autopilot and pilot assistance systems.

Key prospects for the further development of the use of artificial intelligence for the organization of air transportation: 1. Further development of artificial intelligence will provide a breakthrough in the aviation industry by creating aircraft on which the flight will take place without human intervention, including takeoff, cruise phase, landing and control. 2. Individual approach to passengers. 3. Forecasting and optimization of aircraft maintenance. 4. Increasing flight safety. Intelligent systems using artificial intelligence detect potential threats and quickly respond to them. 5. Optimization of airline operations

Keywords: artificial intelligence, air transportation, passengers, cargo, autopilot, route, safety, ethics.

Олена Гаража, Дмитро Шевчук. «Штучний інтелект як основа формування стійких інтегрованих систем повітряного транспорту в умовах невизначеності». *Стаття розкриває застосування штучного інтелекту в організації авіаційних перевезень вантажів та пасажирів в сучасний період розвитку, який характеризується стрімким впровадженням високотехнологічних інструментів у всі сфери авіаційної галузі.*

Швидкісні перетворення стосуються не тільки управлінської сфери життя суспільства, але й пришвидшення логістичної діяльності в організації вантажів та пасажирів в умовах поглиблення

глобалізації та інтеграції шляхом застосування складних маршрутів із збільшенням обсягів авіаперевезень на міжнародному ринку торгівлі, туризму та бізнес-активності. Завдяки штучному інтелекту можливо автоматизувати планування і коригування маршрутів перевезень вантажів мультимодальним транспортом, формувати додаткові рейси пасажирських перевезень під час відпочинку, проводити тотальні скорочення витрат на паливо, експлуатаційні витрати та технічне обслуговування, що стає важливим чинником в умовах зростаючої конкуренції в авіаційній індустрії. Загальновідомо, системи штучного інтелекту мають широкі можливості для швидкої та ґрунтовної обробки великих масивів даних у реальному часі. Головною проблемою є складність інтеграції штучного інтелекту в сучасні системи управління авіаційними процесами наземного та повітряного забезпечення. Очевидно, що застаріле обладнання та програмне забезпечення аеропортів та авіакомпаній потребують сучасного оновлення та новітніх проектних рішень, які відповідатимуть сучасних нормам та стандартам. Загальновідомо, що в різних країнах та регіонах існує потреба у узгодженні нормативно-правової бази відповідно до стандартів світової спільноти, що гальмує швидке впровадження інновацій. Доречи, однією з гострих проблем стає кібербезпека даних стосовно перевезень вантажів та пасажирів повітряним флотом. Відтак, для гарантування безпеки польотів та особистих даних пасажирів необхідний ретельний захист від кібератак та хакерського злому.

Метою нашої роботи є вивчення теоретико-методологічного базису впровадження штучного інтелекту у формування стійких інтегрованих систем повітряного транспорту в умовах невизначеності.

Методологічною основою дослідження штучного інтелекту в організації авіаційних перевезень є системний підхід, який базується на аналізі структури авіаційних перевезень як єдиного цілого та всіх зв'язків між її компонентами. Основними методами системного підходу в організації авіаційних перевезень є: метод аналізу, який розглядає всі складові авіаційних перевезень як цілісну структуру на основі взаємозв'язків між основними її елементами (літаки, аеропорти, екіпажі, диспетчерські служби, пасажири); метод моделювання та симуляції, який дозволяє тестувати різні сценарії щодо прогнозування змін у структурі системи; метод інтеграції систем дозволяє поєднувати різні підсистеми авіаційних перевезень і складати унікальну інформаційну систему управління рухом повітряного флоту та інших компонентів шляхом створення безперервного потоку інформації між окремими елементами структури авіаційних перевезень з метою координації та управління, метод оптимізації процесів передбачає поліпшення ефективності функціонування авіаційних перевезень, враховуючи оптимізацію розкладів польотів та управління ресурсним потенціалом, метод системного моніторингу та контролю дозволяє спостерігати за функціонуванням всіх елементів ланцюга авіаційних перевезень на основі збирання та обробки даних у реальному часі з метою усунення викликів та їх вирішення.

Виділено за результатами дослідження основі етапами розвитку штучного інтелекту в організації авіаційних перевезень стали: 1. початкова автоматизація; 2. етап аналізу даних; 3. етап вдосконалення пасажирського досвіду; 4. інтелектуальні системи підтримки пілотів; 5. автономні польоти. Виявлено, що потужні ресурси штучного інтелекту спрямовують зусилля на впровадження інновацій: по-перше, штучний інтелект впливає на розробку та виробництво літаків; по-друге, штучний інтелект забезпечить авіаційну безпеку; по-третє, штучний інтелект вирішить проблему кадрового забезпечення польотів від пілотів та льотного складу; по-четверте, підвищення використання палива та зменшення впливу на навколишнє середовище; по-п'яте, штучний інтелект надає змогу завчасно замовляти та бронювати квитки, використовуючи онлайн-сервіси; по-шосте, новітні підходи до обробки багажу; по-сьоме, етика та заміна персоналу. Доведено, що розвитку штучного інтелекту в організації авіаційних перевезень, виділивши основні

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ключові моменти: оптимізація маршрутів, технічне обслуговування, управління пасажирськими потоками, автопілот та системи допомоги пілотам.

Ключовими перспективами подальшого розвитку використання штучного інтелекту для організації авіаційних перевезень: 1.Подальший розвиток штучного інтелекту забезпечить прорив у авіаційній галузі шляхом створення літаків, на яких політ відбуватиметься без втручання людини, включаючи зліт, крейсерську фазу, посадку та керування. 2.Індивідуальний підхід до пасажирів. 3.Прогнозування і оптимізація обслуговування повітряних суден. 4.Підвищення безпеки польотів. Інтелектуальні системи з використанням штучного інтелекту виявляють потенційні загрози та швидко реагують на них. 5.Оптимізація діяльності авіакомпаній.

Ключові слова: штучний інтелект, авіаційні перевезення, пасажири, вантаж, автопілот, маршрут, безпека, етика

Introduction. At the present stage of development of society, the latest technologies are being introduced into various branches of the national economy, which, under the influence of globalization processes, is leading to significant transformations and changes in the organization of air and cargo transportation around the world. With the development and spread of artificial intelligence as a branch of computer science, it has been possible to replace human thinking in performing various tasks: language recognition, visual perception, types of speech, recognition of things, making optimal decisions. Rapid transformations concern not only the management sphere of society, but also the acceleration of logistics activities in the organization of cargo and passengers in the context of deepening globalization and integration through the use of complex routes with an increase in air transportation volumes in the international market of trade, tourism and business activity. Thanks to artificial intelligence, it is possible to automate the planning and adjustment of multimodal cargo transportation routes, form additional passenger flights during vacations, carry out total reductions in fuel costs, operating costs and maintenance, which is becoming an important factor in the conditions of growing competition in the aviation industry. It is well known that artificial intelligence systems have broad capabilities for fast and thorough processing of large data sets in real time. Obviously, this allows you to fully detect potential terrorist attacks and anomalies, which contributes to an increase in the level of flight safety and prevents disasters. Thus, artificial intelligence provides the ability to provide passenger service on a personal basis, among which the most significant are automated support, providing individual recommendations, processing requests for services and services, and baggage delivery, which has a positive effect on the image of the company and customers. At the same time, artificial intelligence systems can predict malfunctions and aircraft destruction during flight and maintenance, relying on a set of data on the technical parameters of the aircraft and the functioning of its individual parts, which helps to find all breakdowns and creates a continuous process of aircraft operation. Indeed, artificial intelligence makes it possible to timely identify breakdowns of parts and prevent the destruction of an entire mechanism or its part, which reduces the airline's operating costs. At the same time, there is a reduction in costs for fuel and lubricants, aircraft maintenance, personnel management, which in general creates competitiveness in the aviation services market. Of course, artificial intelligence is developing new directions in technologies such as unmanned aerial vehicles that perform transportation tasks without human intervention. Indeed, this significantly reduces flight crew costs and prevents errors that arise based on the human factor. Thus, the introduction of automatic

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control provides high accuracy and safety of aircraft flights, which makes it possible to deliver cargo to remote areas and difficult terrain. At the same time, artificial intelligence allows for constant data exchange between aircraft, ground surveillance systems and dispatch services. Obviously, this allows for real-time receipt of a set of information about the technical condition of the aircraft in the air, observation of the flight during its flight along its route, diagnostics and monitoring of its technical condition. Thus, artificial intelligence becomes a new way and an indispensable tool for the transformation of air transportation, contributing to the increase in the efficiency and quality of passenger and cargo service based on improved air traffic. At the same time, the issues of development and future prospects for the use of artificial intelligence in the organization of air cargo and passenger transportation in the field of ethics and privacy, safety and reliability, regulation and standardization, impact on jobs and environmental efficiency remain quite relevant, and artificial intelligence is becoming the main critical element in managing organizational processes of transport activities in the aviation industry. To solve it, it is necessary to take into account a set of economic, technological, environmental, political instruments with a rethinking of the participation of logistics as the main instrument of global stability in the conditions of uncertainty of the modern global economy. The latest technologies are being densely implemented in various areas of organizing air cargo and passenger transportation to gradually increase the efficiency of service provision, flight safety and quality of service. At the same time, there are a number of unresolved problems and challenges that require a specific management solution. The main problem is the complexity of integrating artificial intelligence into modern systems for managing aviation processes of ground and air support. It is obvious that outdated equipment and software of airports and

airlines require modern updating and the latest design solutions that will meet modern norms and standards. It is well known that in different countries and regions there is a need to harmonize the regulatory framework in accordance with the standards of the global community, which slows down the rapid implementation of innovations. By the way, one of the acute problems is cybersecurity of data regarding the transportation of cargo and passengers by air fleet. Therefore, to guarantee the safety of flights and personal data of passengers, thorough protection against cyberattacks and hacking is necessary. It is obvious that the creation of a reliable protection system is a critical problem in the modern realities of the existence and functioning of information systems and technologies. At the same time, special attention should be paid to the issues of ethics and legal aspects of the use of artificial intelligence in the transportation of cargo and passengers by aircraft. First of all, it is necessary to pay attention to the fact that artificial intelligence leads to the replacement of human labor and a reduction in jobs at aviation enterprises. Along with this, the question of liability for errors or malfunctions in the functioning of the system arises. To successfully solve this problem, there is a need to conduct a more in-depth study of the use of artificial intelligence in the field of organizing air cargo and passenger transportation.

Analysis of recent research and publications. Garazha O., Shevchuk D. identified five elements of the organization of air transportation at the global level: the largest share of passenger transportation in the structure of aviation activity; the aviation industry is promising, which is gradually expanding the boundaries of its niche in the global transport market; the COVID-19 pandemic has negatively affected the aviation industry, changing the centers of economic gravity; active activities of global aviation organizations and associations, which cover most countries in the world; development of a world-class regulatory

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framework and global standardization of aviation activities and characterized the challenges of the aviation industry that arise at the global level [1].

Stenyakin I., Shevchuk D., Garazha O. developed a two-stage multi-class classification method for airport type recognition, which involves sequential binary clustering that optimizes the order of class comparison to improve the resulting classification performance, therefore, to achieve significant results, seven classifiers were used, among which the method iteratively performs binary classification to determine the most effective sequence for class distinction. They performed binary classification to distinguish international airports from non-international airports, and then another binary classification was performed to distinguish regional airports from airfields. At the same time, they conducted numerical experiments and calculated the F1 score to evaluate the effectiveness. The minimum representative volume for the training dataset was determined and feature extraction was completed. The developed optimization method was verified and all metrics were cross-validated. The method was applied to recognize and classify international airports, regional airports, and airfields [2].

Shevchuk D., Yakushenko O., Pomytkina L., Medinsky D., Shevchenko Y. determined the initial information for training the model as the carrier's data on the expected average task completion time and the date of the trip. Using the Monte Carlo method, the initial data were obtained, on which the neural network was trained. The results obtained were analyzed. The results show that using the developed neural network model to predict the time of the transport task allows to significantly reduce the forecast error compared to the average estimate of this parameter. In the work on training a neural network to predict the time required to complete a transport task, the network has three levels. When changing the parameter values, we used the Levenberg-Marquardt algorithm and as a result obtained the mean square error of the task completion time estimate for the training and control samples [3].

Korobiychuk I., Shevchuk D., Prokhorenko I., Tymoshenko N., Smityukh Yu. and Boyko R. developed a model that can be expanded by creating a multi-level model of aviation security, which requires further research (in particular, from the point of view of the principle of Occam's razor) and a significant sample of statistics. The results confirmed the authors' assumptions about the dependence of acts of unlawful interference and crime in the territory in which the airport is located: there is a significant positive correlation; with the increase in crime, there is a +0.017 increase in acts of unlawful interference. From a practical point of view, the developed aviation security model allows you to manage and predict the level of danger in order to ensure the safety of the airport operation [4].

Korobiychuk I., Smityukh Yu., Kyshenko V., Ladanyuk A., Shevchuk D., Ivashchuk V., Boyko R., Elperin I. considered an approach that allows automating the process of obtaining a neurofuzzy model and identifying the main dependencies between input and output variables. The considered approaches can be used to develop simulation models of heat and mass transfer processes. The obtained models can be used in control systems that are formed on the basis of optimal, robust and scenario methods [5].

Boldyreva M., Ivannikova V., Konovalyuk V. conducted research and allowed to identify new ways to eliminate the catastrophic impact of air transport. According to the results of the study, a positive direction of environmental changes in the aviation industry was identified - an updated assessment method in the form of a mathematical model of the use of the aircraft fleet, which will help reduce emissions from old aircraft. A mathematical model of aircraft replacement in the most optimal period of time was developed, which allows achieving environmentally safer and more economically efficient transportation [6].

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Ovsak O., Sadlovska I., Liskovich N. identified the activation of aviation companies in the performance of charter flights, while foreign airlines began to dominate in the performance of regular flights with the active participation of leading European airlines. Analysis of the market share of airlines with the largest volumes of passenger air transportation in the Ukrainian air market showed that over the past three years there has been a rapid decline in the market shares of leading network airlines, both domestic and foreign. There has been a rapid growth in the market shares of foreign airlines - low-cost carriers [7].

Ovsak, OP, Liskovych, NY, & Nazarenko, OP identified strategic groups of Ukrainian airlines based on the results comprising cluster analysis of profile indicators of airlines available from open sources, clusters. Construction of a competitive map of the air transportation market of Ukraine, identification of clusters of domestic airlines provide an opportunity to use a differentiated approach to the tools of strategic positioning and crisis management of airlines of Ukraine [8].

Liskovych, N. investigated the features of strategic positioning of air transport enterprises, which are due to the specifics of air transport services themselves, as well as the peculiarities of their organizational, legal and economic support. The strategic position of the air transport company is by its nature synthesizing, combining the positions of its product, brand and aviation business. The methodological toolkit of definition of a strategic position of the air enterprise on the basis of calculation of indices of its competitive advantages on the list of the defined competencies based on branch and functional features of activity of air transport enterprises is offered [9].

Sokolova, O., Ivannikova, V., & Cherednichenko, K. revealed the environmental impact of supply chains, revealing the unique characteristics of their operation within the framework of sustainable development. It has been demonstrated that current supply chains are unsustainable and often contribute to environmental degradation, adversely affecting both human health and the natural environment. Research has shown that a 'green' supply chain operates in harmony with environmental, economic, and social factors within a defined transport-logistics space, and can be modeled as a directed graph. New methodological approaches have been introduced for designing sustainable supply chains, facilitating the creation of an optimal model that incorporates air transport. An economic and mathematical model has been developed to optimize the interaction between surface and air transportation modes, which is a key component of sustainable supply chains. Additionally, a multicomponent mathematical model of the transport and logistics space has been developed, enabling medium- and long-term forecasting of sustainable supply chains. Future research could further explore optimal strategies for establishing a sustainable functioning of the air transport system through the development of a resource-efficient logistics infrastructure at airports [10].

However, the creation of sustainable integrated air transport systems in conditions of uncertainty requires research with an in-depth study of scientific developments of scientists from different countries of the world, which determines the relevance of the topic under study. The main directions of the formation of sustainable integrated air transport systems are: development of infrastructure, digitalization and greening of aviation, integration with other modes of transport, as well as increasing the level of security and international cooperation.

Purpose of the article consists in studying the theoretical and methodological basis for the implementation of artificial intelligence in the formation of sustainable integrated air transport systems under conditions of uncertainty.

Presentation of the main research material.

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Artificial intelligence has the properties of human thinking processes and imitates the cognitive functions of the brain by copying the architecture in order to achieve specific results. Artificial intelligence is capable of intelligent decision-making and is a system that processes large amounts of data and makes connections with the knowledge embedded in it and provides its own understanding of the object of study. It is obvious that artificial intelligence can think at a weak level with the help of a person after some training, and at a strong level - learn independently, think without a person, accumulate its own experience and use it to make decisions.

According to the capabilities inherent in artificial intelligence, it can perform a variety of tasks, it is classified as: weak, strong, superintelligence, theory of mind, self-awareness. Weak artificial intelligence has a narrow profile of tasks, which include speech recognition, automation in car production, so it cannot perform tasks outside the limits of its built-in. General artificial intelligence is able to perform any intellectual task independently, like a person. It can learn, has flexibility and makes decisions independently. Superintelligence has higher intellectual knowledge and capabilities than a person, including social habits, problem solving and creativity. Artificial intelligence based on the theory of mind is capable of perceiving and emotionally understanding the thoughts and intentions of other people, so it can communicate with people at high levels. Artificial intelligence with self-awareness, which is equipped with its own consciousness and the idea of the existence of its personality in the world, has its own motivations and goals with the highest level of development.

By type of training and provision of resources, artificial intelligence can be divided into: artificial intelligence with limited access to resources, artificial intelligence with high computational capabilities, reinforcement learning, deep learning, hybrid artificial intelligence systems. Artificial intelligence with limited access to resources has limited computational and energy sources to perform the tasks set. Artificial intelligence with high computational capabilities is designed to process large data sets and perform complex calculations and is used for scientific experiments, weather forecasting. Artificial intelligence with reinforcement learning has the ability to learn when in contact with the ecosystem and receive a positive or negative response for further adaptation to existing conditions. Deep learning artificial intelligence uses multilayer neural networks and can recognize complex patterns in existing information flows, namely, sound, text, images. Hybrid artificial intelligence systems have a set of approaches and methods based on logic, heuristics, and machine learning to obtain the best effects.

By type of tasks, artificial intelligence is divided into analytical, cognitive, reactive. Analytical artificial intelligence is used to analyze data with subsequent decision-making. Cognitive artificial intelligence repeats a person's conscious representations, such as memory, thinking, learning. Reactive artificial intelligence has an answer to questions from the external environment, but cannot learn or remember past experience.

By field of application in the national economy and society, artificial intelligence is divided into medical, aviation, financial, etc. Medical artificial intelligence is able to diagnose, create new drugs, monitor the patient's health. Aviation artificial intelligence is used for air traffic control, weather forecasting, aircraft maintenance, etc. Financial artificial intelligence is used to analyze the financial condition of markets, predict risks, automate banking processes.

The main stages of the development of artificial intelligence in the organization of air transportation were:

Initial automation. The first and simplest tasks of using artificial intelligence are the autopilot system, which is aimed at maintaining the course and altitude of aircraft.

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Data analysis stage. Improving the capabilities of artificial intelligence provides opportunities for analyzing large volumes of data. This allows for the prediction of technical equipment and technological maintenance, optimization of aircraft flight routes, and increased efficiency of resource provision and resource management.

Passenger experience improvement stage. The use of artificial intelligence allows airlines and airports to improve quality indicators and create comfortable conditions for passenger service, covering a wide range of service processes from the provision of personalized services for in-flight entertainment to automated check-in systems.

Intelligent pilot support systems: The use of artificial intelligence to facilitate the work of pilots based on the analysis of weather conditions, flight mode, fuel availability in real time and developing a recommendation system to increase the level of flight safety.

Autonomous flights. A promising direction is the design of completely autonomous aircraft that can be operated without human control, based on a system of up-to-date and modern algorithms and sensors.

Thus, there has been a transition from the initial base to a system intellectual complex that covers various aspects of the organization of air transportation.

In modern conditions, artificial intelligence is rapidly transforming the world economy and its industries, and the aviation sector is experiencing special transformational processes. It is obvious that the powerful resources of artificial intelligence are directing efforts to introduce innovations into the sphere of activity of aviation enterprises, which covers the design of aircraft and improves the comfort of passengers.

First, artificial intelligence affects the development and production of aircraft. Thanks to artificial intelligence, optimal aerodynamic models are developed based on artificial intelligence analysis of large data sets in order to optimize fuel use, increase speed, and establish overall stability. Artificial intelligence helps designers choose parts and materials from which they are made, which leads to reduced waste and increased aircraft performance. At the same time, in subsequent maintenance, artificial intelligence helps technical personnel find existing breakdowns and eliminate them, as well as predict possible malfunctions in the future based on the analysis of previous data. Thus, artificial intelligence will allow to avoid transport downtime, cargo delays due to technical malfunctions, reduce costs for expensive repairs, equipment, and timely diagnostics will allow to identify possible malfunctions of equipment.

Secondly, artificial intelligence will ensure aviation safety. It is well known that artificial intelligence has the ability to analyze and predict potentially dangerous situations based on the analysis of flight data, weather conditions, data from aircraft sensors in real time. This makes it possible to avoid areas with high turbulence or provide timely support and recommendations to mitigate its impact. At the same time, artificial intelligence allows the use of biometric systems for facial recognition, passenger identification, reducing waiting times, increasing security on board by avoiding fraudulent actions, terrorist acts, and other possible threats.

Thirdly, artificial intelligence will solve the problem of staffing flights from pilots and flight crew. Modern capabilities of intelligent systems guarantee the selection of specialists for a specific flight, taking into account qualifications, health care, and safety. Along with this, artificial intelligence will draw up an optimal schedule for the employment of all crew members, which will positively affect the effectiveness of its work, reducing flight crew fatigue and reducing operating costs.

Fourth, increasing fuel efficiency and reducing environmental impact. Thus, artificial intelligence allows you to create economical flight routes based on the analysis of data sets on wind patterns and directions, passenger numbers, and weather

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data in real time. At the same time, intelligent systems can provide recommendations for minimizing flight times and routes that avoid large footprints, which becomes a protection against warming. It is obvious that artificial intelligence helps in the development of sustainable aviation fuel, which is more environmentally friendly than traditional fuels.

Fifth, artificial intelligence allows you to order and book tickets in advance using online services. Thus, information systems based on artificial intelligence store the travel history of each client, provide the status of a regular client, offer tickets according to the budget, indicate the most convenient routes, and allow you to avoid complex routes. At the same time, they prevent fraudulent actions, check financial transactions in the event of suspicious activity, which guarantees the security of advance ticket booking activities for traveling customers of a particular airline in real time.

Sixth, the latest approaches to baggage handling. It is obvious that the use of automated passenger check-in systems based on artificial intelligence has simplified and accelerated the boarding of passengers on the plane. At the same time, similar systems have improved and accelerated the delivery of cargo and tracking its transportation to destinations in real time. Therefore, even in the event of a flight delay, intelligent systems ensure uninterrupted operation. In addition, intelligent systems are able to replace traditional paper baggage tags with a new method of photo recognition, which provides the ability to track cargo by a set of unique markings or marks (design, stickers, abrasions). Along with this, passengers have the opportunity to track their own luggage in real time using special software and be calm about their luggage.

Seventh, ethics and personnel replacement. The reduction of jobs and their replacement by robots and other gadgets is a concern. Therefore, ethical issues and security measures are concentrated in the center of attention of many scientists, practitioners and customers. Challenges of liability in the event of a failure in the operation of intelligent systems and errors in their work and who should be punished for this.

Given the constant development of intelligent technologies, artificial intelligence is being actively introduced into the aviation industry, therefore, rules, regulations, and precautions are being developed that contribute to the comprehensive implementation of safety measures, flight route experience, and optimization of the performance of professional duties by personnel (Fig. 1).
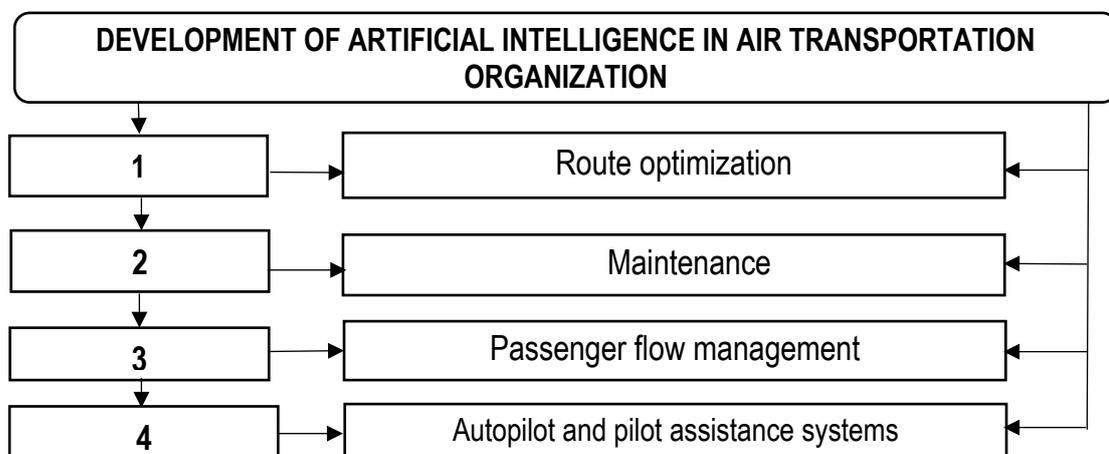
Figure 1 – Modern trends in the development of artificial intelligence

Therefore, we come to a generalization of the development of artificial intelligence in the organization of air transportation, highlighting the main key points:

1. Route optimization. It involves taking into account weather forecast indicators, air traffic analysis, and fuel economy to design the most optimal routes that help reduce flight time.

2. Maintenance. Predicting technical malfunctions of an aircraft based on artificial intelligence helps prevent the destruction of individual parts and mechanisms, conduct diagnostics and their replacement in advance, which will strengthen safety measures.

3. Passenger flow management. Artificial intelligence algorithms prevent queues and better allocate resources, enable personal service for each client, automate the scanning and document verification processes, which makes it possible to clearly and harmoniously manage passenger flows at airports, reducing waiting times and providing a positive experience for passengers.

4. Autopilot and pilot assistance systems. Modern autopilot systems help pilots control aircraft, including landing and takeoff, by performing routine tasks and providing recommendations in emergency situations when detecting equipment damage and bad weather conditions.

Thus, thanks to artificial intelligence, convenient, safe and efficient flights are ensured, which positively affects the experience of companies and customers.

Along with this, there are a number of unresolved problems in the use of artificial intelligence, including: data security, which has a large amount of data used to train artificial intelligence models, requiring protection from cyberattacks. In the event of data corruption, there will be a serious impact on flight safety; ethical issues related to the distribution of responsibility for errors or emergencies between people and automated systems, which causes many difficulties; system reliability, which on the one hand increases efficiency, but on the other hand there is a set of risks that undermine the basis

of reliability. For example, there may be errors in algorithms that lead to disruptions in the functioning of the system that ensures flight safety; dependence on technology, which reduces the experience of pilots in manual control of the aircraft and causes the need for recommendations and automated actions of the intelligent system, although in emergency situations the skills and readiness of pilots to manually control the aircraft will be required; integration with existing systems, which requires interoperability and compatibility with other automated existing aviation systems, which may cause certain difficulties and costs of resource material and time. Therefore, the existing range of problematic challenges requires a gradual solution that will ensure the safe and effective use of artificial intelligence in the aviation sector.

It is necessary to determine the main prospects for the further development of the use of artificial intelligence for the organization of air transportation:

1. The further development of artificial intelligence will provide a breakthrough in the aviation industry by creating aircraft on which the flight will take place without human intervention, including takeoff, cruise phase, landing and control. The key advantages are the reduction of human errors, the efficiency of the flight trajectory while reducing human errors. Ensuring uninterrupted and stable operation of the aircraft in extreme conditions. Optimization of the flight trajectory to reduce fuel costs and flight time in the air.

2. An individual approach to passengers. Artificial intelligence can learn about the preferences of passengers and provide its own suggestions regarding existing drinks and food, entertainment programs during the entire flight. At the same time, provide personalized settings for seats and the atmosphere in the aircraft cabin to create an optimally convenient and comfortable environment. Providing quick feedback on passenger requests, improving service quality.

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3. Forecasting and optimizing aircraft maintenance. Thanks to the capabilities of artificial intelligence to process large amounts of data on the technical condition of the aircraft to predict the needs for further maintenance, technical personnel will be able to carry out repair work before problems and downtime arise. Thus, the costs of vehicle maintenance and repair will be reduced, and flight safety will increase due to timely elimination and detection of problems.

4. Improving flight safety. Intelligent systems using artificial intelligence detect potential threats and quickly respond to them. Thus, artificial intelligence is able to detect unusual flight parameters and warn the crew and ground services about deviations from regulatory standards. At the same time, there is a rapid automatic response to dangerous situations. Obviously, the detection of anomalies and rapid response to flight safety leads to a decrease in the number of emergencies and incidents due to preventive measures.

5. Optimization of airline operations. Artificial intelligence is able to increase various operational processes related to flight planning and resource management. Potential benefits include optimization of aircraft flight routes and reduction of fuel costs, formation of optimal flight schedules and effective management of the air fleet. Thus, there is a constant reduction in management costs and making the right decisions by automating the management of airlines and airlines within airports.

The logistics chain of air transportation using artificial intelligence includes several main stages that use the latest technologies to increase efficiency and safety. First, the use of artificial intelligence to optimize the route of cargo collection from the sender and plan the needs and types of transportation based on the volume and type of cargo. Second, the processing of cargo shipments at airports using artificial intelligence includes customs control, security checks, and cargo packaging. Third, the optimization of flight routes based on artificial intelligence allows you to predict weather conditions, airspace congestion, develop optimal flight routes, as well as avoid delays and reduce fuel costs. Fourth, artificial intelligence makes it possible to monitor the condition of the aircraft, use autopilot. Fifth, artificial intelligence allows you to very quickly carry out shipments, pass customs control, sort cargo, and also predict arrival times for resource allocation at the airport. Sixth, optimizing the route of cargo delivery and using machine learning to analyze traffic and plan the shortest effective flights.

The scheme of organizing the logistics chain includes: sender, cargo collection, departure airport, cargo handling, route optimization, air transportation, destination airport, cargo handling, delivery to the recipient, recipient.

In the organization of air transportation, artificial intelligence plays a key role in increasing the efficiency, safety and comfortable movement of passengers and crew. Therefore, the classification of artificial intelligence is carried out according to the main categories. It is obvious that automated air traffic control systems and autopilot are implemented in flight control systems, helping to monitor and control the movement of aircraft in space, providing flight safety and efficiency. Artificial intelligence is able to monitor the technical condition of the aircraft in real time and eliminate deficiencies. Personalized passenger service during the flight ensures high-quality resolution of passenger issues at a high level, quickly and efficiently. Indeed, artificial intelligence protection systems detect threats and protect aviation systems from potential cyberattacks, ensuring flight safety for all participants in air transportation (Fig. 2).

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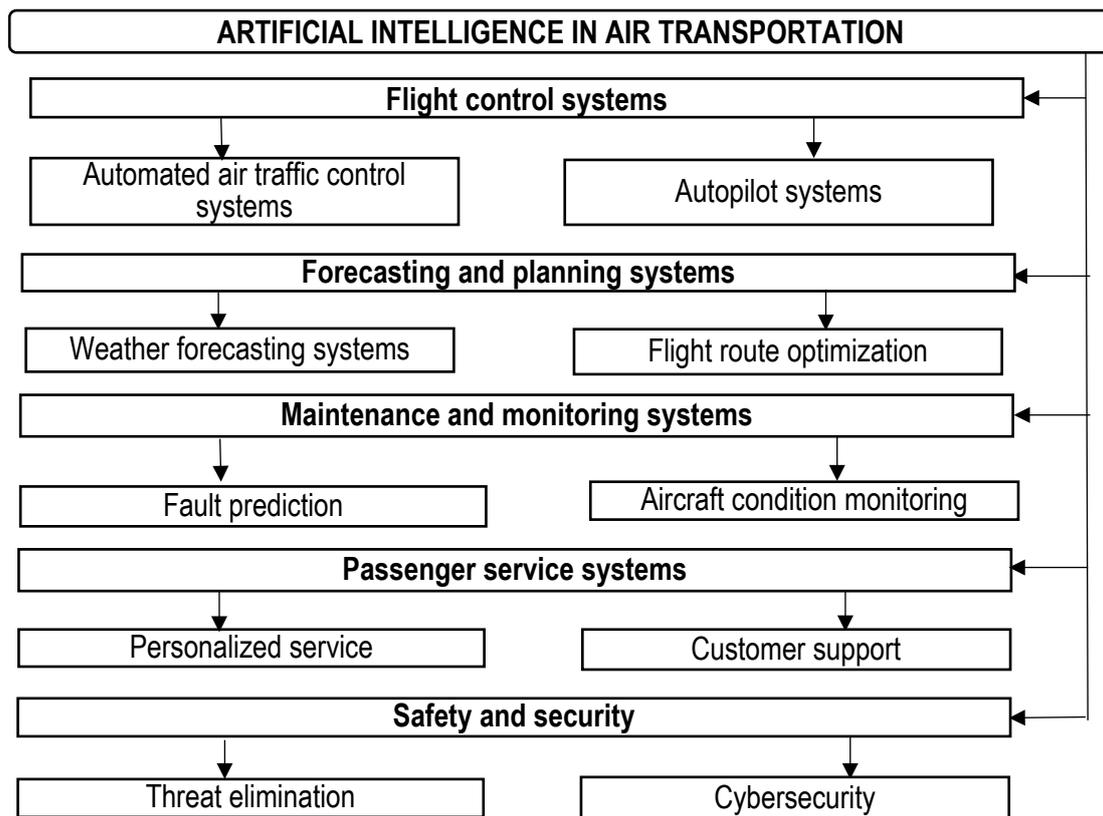
Figure 2 – Structural and logical model of the use of artificial intelligence in the organization of air transportation

Let us consider a general model for optimizing the air flight schedule to reduce delays and increase the efficiency of resource use (aircraft, crew, etc.). Let us highlight the main stages for the air transportation optimization model. First, data collection, which includes data on past flights (delays and their causes, arrival and departure times), weather conditions, flight load (number of passengers and cargo), availability of aircraft and crews. Second, data analysis, which includes data cleaning, data normalization, and converting text data into numeric data using coding (coding of reasons for delays). Third, machine learning, which consists of regression models to eliminate or predict flight delay times, clustering to identify groups of flights with similar properties (flights with a high probability of delays), optimization algorithms to develop an optimal schedule that reduces delays and provides maximum use of resource potential. Fourth, model validation and model control evaluation, which consists of dividing into training and text samples, assessing the accuracy of predictions on the text sample, comparing results with the exact schedule, and analyzing economic benefits.

The presented model shows a perfect forecast for determining the delay of air flights, optimizing the flight schedule, which leads to a reduction in costs and an increase in the comfort and needs of passengers.

Using this model will significantly improve the organization of air transportation using artificial intelligence.

Data collection consists of:

$X_1, X_2, ..., X_n$ – independent factors that have a significant impact on flight delays. For example, weather, aircraft load, time of day, etc.

Y – independent variable (target indicator), flight delay time.

To predict time, we use a regression model:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + ... + \beta_n X_n + \varepsilon,$$

where β_0, β_1, β_2, ..., β_n – regression coefficients, ε – random error.

We are reprocessing data:

$$X_{norm}=(X-\mu)/\sigma,$$

where μ – average value, σ – standardized deviation.

Next, we use Gradient Boosting algorithms to accurately predict delays. Then, we train the model on training data and validate it on test data.

Conclusions. The modern aviation industry requires a wider implementation of artificial intelligence in various areas, creating new opportunities for effective management and ensuring flight safety. Unmanned aerial vehicles and autonomous aircraft without pilots create new and promising areas of development of modern aviation, which make it possible to provide all stages of the flight with minimal risks to the human factor and minimizing fuel costs and time in the air, which will allow to control the vehicle in extreme weather and abnormal conditions. A personal approach to each passenger will allow airlines to implement individual high-level service using artificial intelligence based on the analysis of large data sets, and to implement an individual approach to the tastes of each passenger regarding food and drinks, entertainment programs and comfortable seat settings in the aircraft cabin. The reaction to passenger feedback will be taken into account and will allow to continuously improve the level of passenger service. Artificial intelligence will significantly increase the level of forecasting and optimization of technical repairs and maintenance of the air fleet. Thus, repair work can be carried out before serious problems arise, which will reduce the downtime of the vehicle and reduce costs for repair work. Analysis of flight data will significantly increase flight safety by identifying dangerous situations and unusual flight parameters. Thus, the risks of accidents will be reduced and incidents will be avoided. Optimization of airline operations based on modeling using artificial intelligence will provide optimal solutions with low costs and rational use of resource potential. Obviously, there will be savings in fuel and lubricants, effective placement of airline flights, management of the aircraft fleet, which will have a positive impact on administrative costs and financial and economic activities of the aviation enterprise. Further research in these areas will open up new opportunities for aviation companies and their customers, ensuring the achievement of new heights in air transportation.

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SUSTAINABILITY OF UKRAINE'S EXPORT SUPPLY CHAINS THROUGH THE PRISM OF MULTIMODAL TRANSFORMATION AND ROUTES COMPETITION IN 2022–2026

Yana Korniiko, Sergiy Karpeliuk. "Sustainability of Ukraine's export supply chains through the prism of multimodal transformation and routes competition in 2022–2026". *The article examines the transformation of Ukraine's export cargo flows in 2022–2026 amid wartime shocks and structural changes in the transport and logistics system. It synthesizes theoretical and practical aspects of three key logistics subsystems: the seaports of the Odesa region, the Danube cluster, and land border crossings. The study highlights patterns of flow reorientation during shock periods, institutional turbulence, and the emergence of a new multimodal balance. It analyzes the dynamics of maritime freight rates as well as rail and road freight rates and assesses their impact on the structure of transport and logistics costs. The article further elaborates the mechanism through which changes in logistics costs are transmitted into export price formation under Incoterms (DAP, CPT, FOB, and CIF). It also examines how institutional decisions, inspection restrictions, infrastructure congestion, and security risks reshape route configurations. Competitive advantages of alternative export channels are evaluated under capacity constraints and heightened uncertainty. A multi-criteria route assessment framework is proposed, incorporating cost, logistics cycle time, reliability, security, and environmental parameters. Finally, key directions for strengthening export logistics resilience are identified based on a multimodal export logistics architecture, and recommendations are offered for transport and technological solutions and infrastructure development under prolonged instability.*

Keywords: export cargo flows, logistics, multimodal transport, transport and logistics system, transport corridors, seaports, maritime freight rates, rail freight rates, road freight rates, logistics costs, risks.

Яна Корнійко, Сергій Карпелюк. «Стійкість експортних ланцюгів постачання України через призму мультимодальної трансформації та конкуренції маршрутів у 2022–2026 рр».

Стаття присвячена дослідженню трансформації експортних вантажопотоків України у 2022–2026 рр. в умовах воєнних шоків та структурних змін транспортно-логістичної системи. У статті викладено теоретичні та практичні аспекти функціонування трьох ключових логістичних підсистем - морських портів Одеського регіону, Дунайського кластеру та сухопутних прикордонних переходів. Висвітлено особливості переорієнтації потоків у періоди шоку, інституційної турбулентності та формування нового мультимодального балансу. Проаналізовано динаміку ставок морського фрахту, залізничних і автомобільних тарифів та їх вплив на структуру транспортно-логістичних витрат. Надано розширене пояснення механізму трансляції змін логістичної складової у формування експортної ціни за базисами DAP, CPT, FOB, CIF. Розглянуто роль подієвих факторів (інституційні рішення, інспекційні обмеження, інфраструктурні затори, безпекові ризики) у зміні конфігурації маршрутів. Проведено аналіз конкурентних переваг різних каналів експорту в умовах обмеженої пропускної спроможності та підвищеної невизначеності. Запропоновано багатокритеріальний підхід до оцінки маршруту, що враховує вартість, час логістичного циклу, надійність, безпекові та екологічні параметри. Визначено ключові напрями підвищення стійкості експортної логістики на основі мультимодальної архітектури перевезень. Надано рекомендації щодо формування транспортно-технологічних рішень та розвитку інфраструктури в умовах довготривалої нестабільності.

Ключові слова: експортні вантажопотоки, логістика, мультимодальні перевезення, транспортно-логістична система, транспортні коридори, морські порти, морський фрахт, залізничні тарифи, автомобільні перевезення, залізничні перевезення, логістичні витрати, ризики

Introduction. Before 2022, Ukraine's export logistics for agricultural cargo operated within a relatively predictable configuration: inland rail and road transport to the seaports of the Odesa region, accumulation and shipment of large lots at the ports followed by maritime transport, and the use of Danube ports as a supplementary channel [7]. The full-scale invasion changed not only the geography of flows but also the "rules of the game" in cost formation: risks, access to infrastructure, queues, and inspections became as important as the tariff or freight rate.

Under wartime conditions, route "efficiency" is no longer purely economic. Logistics costs may be lower, yet the route may not function reliably due to capacity constraints or the risk of operational disruption. In this sense, the Ukrainian case is illustrative for transport-system resilience theory: the system survives not because of a single optimal path, but because of the ability

to rapidly redistribute volumes across different freight-flow channels.

Developing transport-technological solutions requires combining quantitative indicators with "field" understanding of how the market responds to unpredictable events: where cargo is reallocated, which rates become the new benchmarks, where shortages of tonnage or railcars emerge, and how this is reflected in domestic price bases [21].

Analysis of recent research and publications. The sustainability of export supply chains viewed through multimodal transformation and route competition, has been examined in studies by M. Osadchyi [19], B. Burkynskyi, O. Laiko, N. Khumarova [20], S. Ilchenko, V. and I. Hryshchenko, M. Christopher and H. Peck, Y. Sheffi, M. Stopford, T. Notteboom, J.-P. Rodrigue, T. Saaty, and others. However, integrated analyses that jointly compare Ukraine's key export channels in 2022–2026 - the Odesa seaports, the Danube cluster, and land border crossings - in

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terms of resilience and competitive performance under capacity constraints and heightened uncertainty remain limited. In the context of Ukraine's 2022–2026 export logistics transformation-covering the Odesa seaports, the Danube cluster, and land border crossings - the empirical background is also provided by analytical and statistical publications of the European Commission, UNCTAD, the World Bank, and Ukrainian sectoral and operational statistics.

Identification of previously unresolved parts of the overall problem. Despite the substantial number of academic publications devoted to the functioning of Ukraine's transport and logistics system, the transformation of export cargo flows in 2022–2026 has not yet received a comprehensive, system-level treatment. Most studies focus either on individual modes of transport (maritime, rail, or road) or on the institutional aspects of the Black Sea Grain Initiative [1] and the "Solidarity Lanes" [5], without integrating them into a unified multimodal export architecture. The mechanism through which changes in maritime freight rates and domestic tariffs are transmitted into the structure of the export price under different delivery terms (DAP, CPT, FOB, CIF) also remains insufficiently developed. In addition, the academic discourse offers limited coverage of a multi-criteria approach to route selection under wartime risks, where - alongside cost - logistics cycle time, execution reliability, and security factors are taken into account. The absence of an integrated model for evaluating multimodal routes during structural shocks underscores the need for further research in this direction.

The institutional context and the role of "events" in logistics shape how export routes operate during wartime turbulence and create a new decision-making logic for transport-technological solutions. In 2022–2023, the Black Sea Grain Initiative [2], [3] became the key external institution affecting the maritime component: it established a limited but real export channel through the Black Sea while also introducing control procedures (inspections) that emerged as a new bottleneck in the system. When an institution opens a route, it does not automatically remove constraints - rather, infrastructure, human resources, tonnage, the insurance market, and port schedules all require adaptation.

In parallel, the EU and neighboring countries developed the "Solidarity Lanes" and border infrastructure in 2022–2024, yet in practice the border often operated in waves: capacity would increase at times, but congestion would re-emerge due to regulatory changes or protests. This is why, for wartime logistics, the concept of an "event" becomes an analytical tool no less informative than classical time-series approaches.

In this study, events are interpreted as moments when the rules change: restrictions or openings of the "maritime leg," changes in border-crossing conditions, railcar accumulation at ports, as well as threats or attacks on infrastructure. Such events affect the route attractiveness index not only through cost (C), but also through cycle time (T), reliability (R), and security (S). As a result, trading decisions are often made according to the principle "second-best in price, but first-best in execution."

The purpose of this article is to provide a comprehensive analysis of the transformation of Ukraine's export cargo flows in 2022–2026 under structural changes in the transport and logistics system and external constraints, with a focus on the operation of three key logistics subsystems: the seaports of the Odesa region, the Danube cluster, and land border crossings. The study aims to assess the dynamics and redistribution of cargo flows among these subsystems, determine the impact of changes in maritime freight rates and rail and road tariffs on the structure of transport and logistics costs, and examine the mechanism through which these changes are transmitted into export price formation under the delivery terms DAP, CPT, FOB, and CIF.

The scientific novelty of this study lies in substantiating the transformation of

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Ukraine's export cargo flows as a process of changing the system's transport-technological architecture, rather than merely a quantitative redistribution of volumes across directions. A multi-criteria approach to evaluating export routes under risk is proposed, integrating transportation cost, logistics cycle duration, execution reliability, and security parameters, and enabling the tracing of the mechanism through which changes in maritime freight rates and rail and road tariffs are transmitted into the price-formation structure under the delivery terms DAP/CPT/FOB/CIF. This approach extends the classical economic interpretation of transport efficiency and explains the variability of export-channel choices under "structural shocks" and an unstable external environment.

Data and Methodology. The data are drawn from the author's dataset of market reviews and operational indicators for 2022–2026, which includes: prices for agricultural crops and processed products under the DAP/CPT/FOB/CIF bases; rail and road freight rates for key routes; Danube barge rates and sea freight rates for typical vessel sizes and trading lanes (the Mediterranean, Spain, Italy, China); and operational indicators of JSC "Ukrzaliznytsia" on the volume and structure of export transportation and the status of port-side logistics [12], [21].

The methods include descriptive statistics and period-to-period comparisons, as well as event-based structuring:

- 2022 is treated as a period of shock and forced reorientation;

- 2023 – as a period of partial normalization of the maritime channel with high sensitivity to inspection delays;

- 2024–2025 as a period of a new balance formation and route competition;

- early 2026 as a period of rail-export stabilization and a shift in the role of road transport.

Summary of the main research material. The period 2022–2026 is characterized in today's world as an evolution of the multimodal logistics system, which can be divided into several stages:

1. 2022 - shock, "logistics premium," and forced multimodality.

March 2022 marked the moment when logistics effectively "rewrote" the export economy. As of 25 March 2022, the cost of cargo logistics to the port of Constanța increased from approximately USD 80 to USD 120 per tonne. At the same time, corn price indications on the CPT Constanța route declined from EUR 323.6 to EUR 320 per tonne, while DAP Izov/Hrubieszów decreased from USD 265 to USD 260 per tonne. The average transit time for railcars to the Izov–Hrubieszów border crossing was also estimated at about 5 days [21].

The essence of these indicators is that the logistics component became the dominant price driver. When costs increase by dozens of dollars per tonne, any fluctuations in the underlying base price are no longer sufficient to protect margins. Exporters and traders are therefore forced to focus on the physical availability of a route: whether railcars are available, whether the border is operating, whether transshipment capacity exists, and whether a cargo lot can be consolidated. This is how, in 2022, the "border–Danube–Constanța" triangle emerged, partially offsetting the constraints of Black Sea ports.

From a transport-technological perspective, 2022 marked the launch of forced multimodality. Cargo moved in smaller lots, the number of transshipment operations increased, the role of temporary storage expanded, and wagon/truck turnaround became critical. In this phase, the ports of the Odesa region partially lost their role as the dominant hub but did not disappear from the system: functions were redistributed and the system began adapting in anticipation of subsequent institutional changes.

2. 2023 - the grain corridor, inspections, and "parallel" routes. In 2023, maritime logistics received an institutional "window" through the grain corridor [4]; however, in practice this window was uneven. Inspection procedures turned part of the supply chain

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into a queue-based system. In June 2023, market briefs noted that 6 vessels were inspected in one day, while 39 vessels were waiting for inspection. This imbalance implies direct time losses and additional idle-time costs. After the grain initiative was terminated in the summer of 2023 [6], temporary corridors for merchant vessels to/from Ukrainian ports were announced [8], [9].

Price indications in March 2023 highlight that demand in Europe was weak and the market was oversupplied. Demand for corn at the border was assessed at USD 215–225 DAP (Poland), while for off-spec lots in Ukrainian ports a decline below USD 200 was expected. For the transport system, this meant intensified route competition: each additional day in a queue or an extra transshipment reduces supply competitiveness (fig. 1).
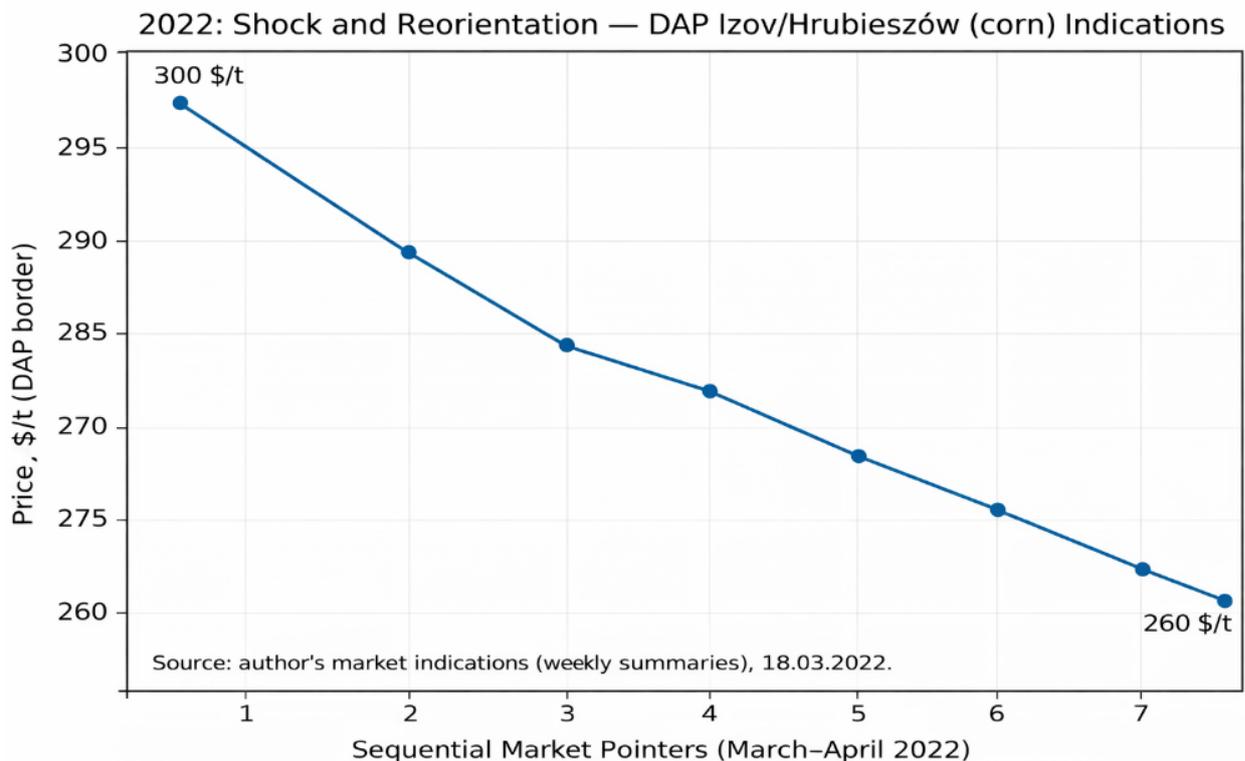
Figure 1 – 2022: DAP (Poland) indications and the manifestation of the "logistics premium" after the reorientation of flows
Source: author's calculations based on market indicators

The market's response in 2023 involved the development of "parallel" routes. The Danube cluster became an insurance buffer, while land border crossings served as a channel for regular lots and processed products. At the same time, Danube-region logistics [14], [15] faced limitations in lot size and required additional transshipment operations, which kept costs at a high level (fig. 2).

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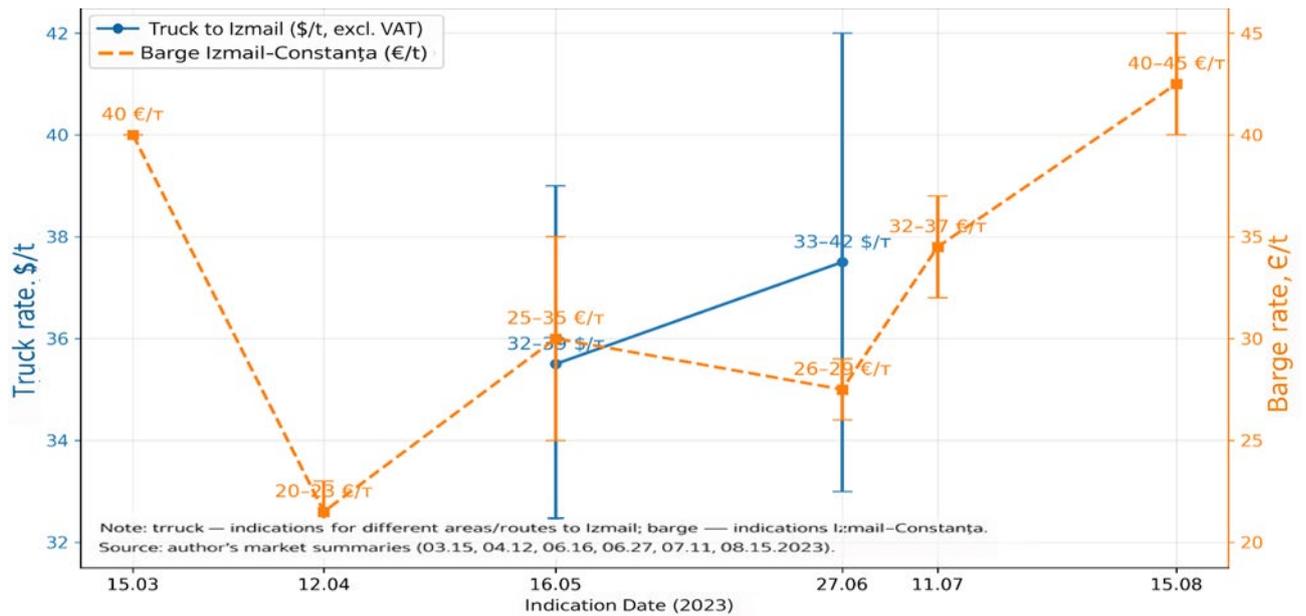
Figure 2 – 2023: the ratio of road logistics rates to Danube barge rates as an indicator of route competition

Source: author's calculations based on market quotations

3. 2024 - balance systematization and the renewed role of the Odesa ports. In 2024, signs of systematization emerged. Operational data from JSC "Ukrzaliznytsia" for January 2024 report 14.13 million tonnes of total freight transportation and 7.50 million tonnes in export traffic. Grain accounted for 3.37 million tonnes and was the largest export cargo (44.9% of the export structure) [11], [13]. This indicates that rail transport regained the capacity to provide stable export volumes (fig. 3).
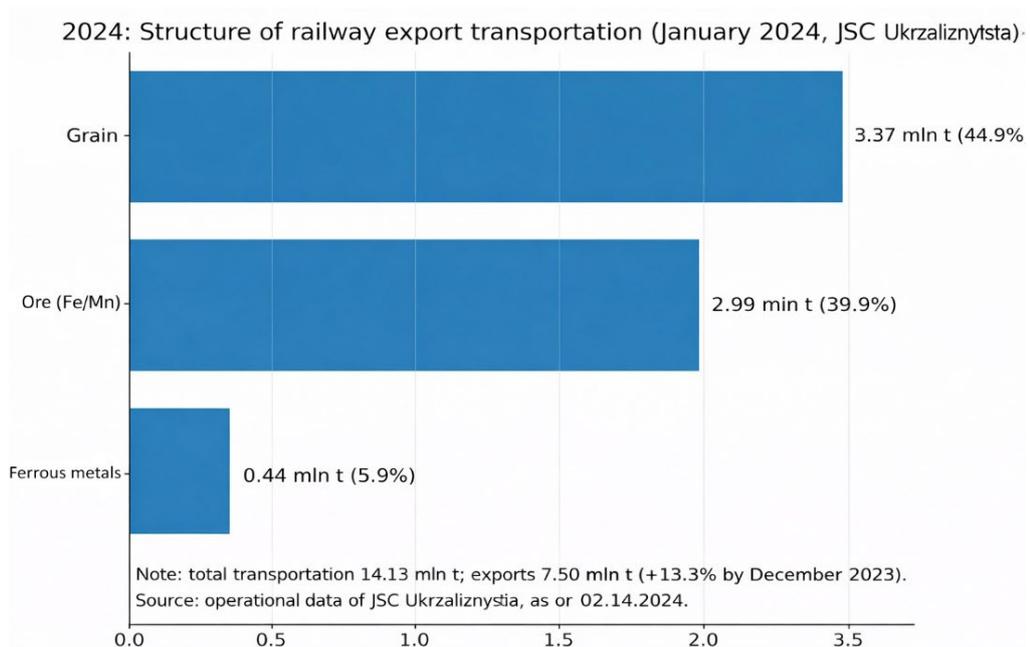
Figure 3. 2024: structure of rail export shipments (January 2024), million tonnes
Source: operational data of JSC "Ukrzaliznytsia" summary as of 14 February 2024 [12]

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In 2024, the market simultaneously recorded a decrease in rail transportation rates by USD 3–7 per tonne and, at the same time, periodic border restrictions due to protests and infrastructure slowdowns. This "cheaper but slower" combination once again highlights that cost without time and reliability does not adequately capture efficiency.

For maritime logistics, 2024 provides benchmark freight rates that make it possible to compare the economics of different lines: freight to the Mediterranean appears manageable, while long-haul destinations have a much higher freight component. For the Danube cluster, the short "water leg" to the port of Constanța is often cheaper on the water segment itself, but it requires additional operations and is constrained by lot size. It was in 2024 that the Odesa region ports began to reassert their role as the base hub for bulk lots when the "maritime leg" is available; as a result, total cargo transshipment in Ukrainian ports increased by 57% by the end of 2024 [16].

4. 2025 - route competition and port "waves." In 2025, the market demonstrates "normalization through competition." Logistics indications for inland water transport place Izmail–Constanța barge rates at EUR 13–14 per tonne, while sea freight from Chornomorsk to Eastern Italy is estimated at around USD 16–17 per tonne, to Spain at USD 18–20 per tonne, and to Southern China at USD 47–49 per tonne. This range implies that for long-haul legs, freight remains the dominant cost component.

At the same time, the impact of infrastructure "waves" becomes more pronounced. As of 25 December 2025, 11,656 railcars had accumulated in the port-adjacent hub, while average unloading was estimated at 953 railcars per day. When the system enters such peaks, the logistics cycle lengthens, railcar turnaround declines, and even with low transport rates the total delivered cost may increase. This makes capacity management no less important than contracting the rate (fig. 4).
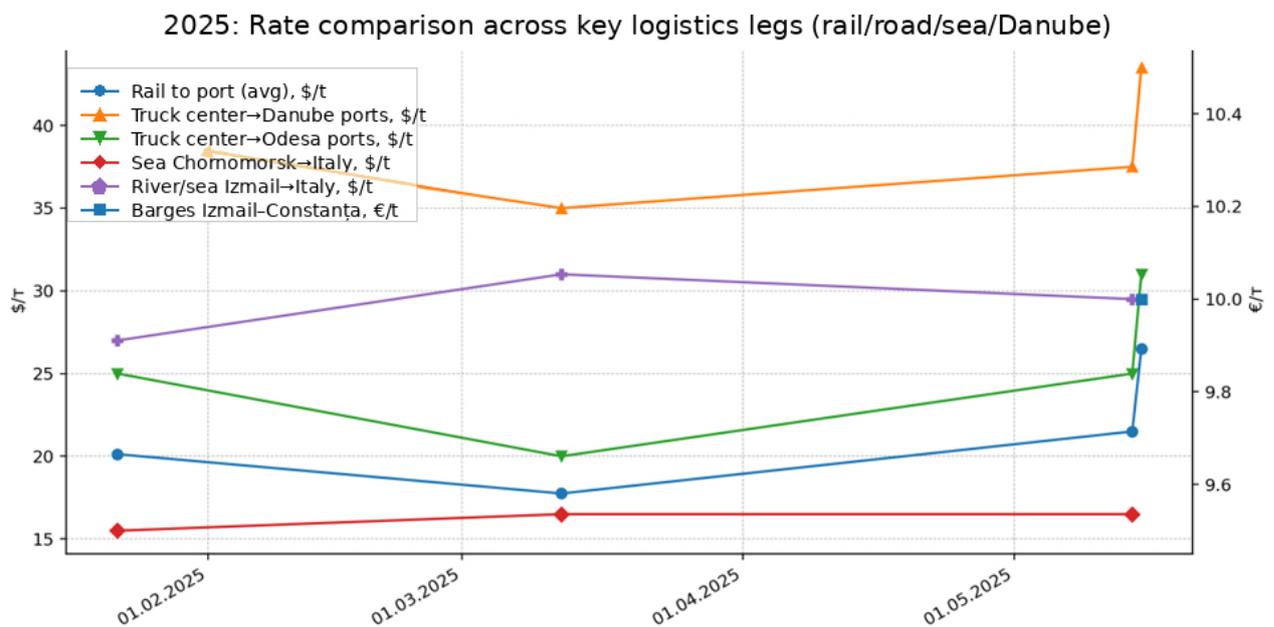
Figure 4 – 2025: dynamics of multimodal transport rates and the manifestation of infrastructure "waves"
Source: author's calculations [21]

In 2025, a technological segmentation across cargo types also becomes evident: bulk grain tends to move via maritime transport, whereas shipments of processed products are

reoriented toward land corridors due to higher regularity and smaller lot sizes.

5. 2026 - rail stabilization, road-haul stagnation, and the attack factor. Operational data for early 2026 indicate a regime of controlled stabilization, especially on the "rail leg." In January 2026, total grain transportation amounted to 2.64 million

tonnes (10% more than in December, but 20% less than in January 2025), while 2.37 million tonnes were shipped in the export direction. This suggests that the rail export system is operating more predictably, albeit against the backdrop of a constrained export supply base (fig. 5).
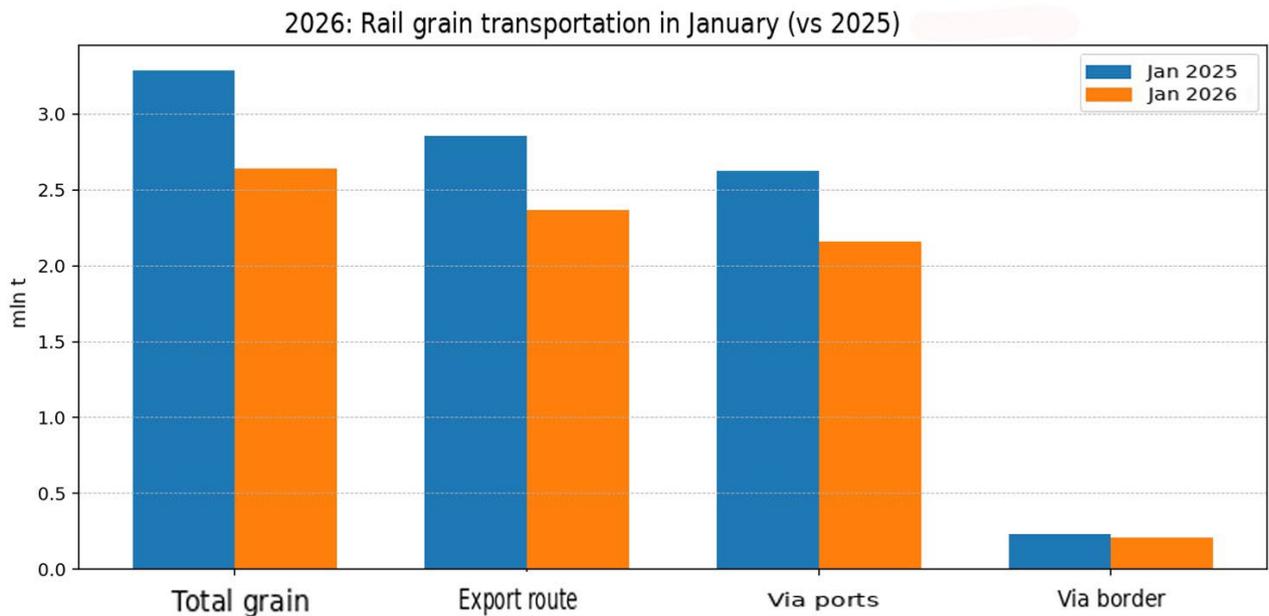
Figure 5 – 2026: indicator of rail grain transportation in January (y/y)
Source: author's calculations based on operational data

Road transport in this period consolidates as a tool for niche logistics. Statistical indicators show that January shipments of agricultural products by road were the lowest since January 2024, while the share of processed products in road flows reached 85–90%. This is logical: road logistics wins on speed and flexibility but loses economies of scale for bulk grain transportation.

For port logistics, the security factor remains critical. Reports of strikes on port infrastructure near Odesa in February 2026 indicate that even under relatively stable freight rates, the weight of the security component increases, reinforcing the need for multichannel routing as a risk-management instrument.

In our view, periodic attacks [17] on port and energy infrastructure affect logistics through two channels:

- the first channel is direct: damage to warehouses, berths, conveyor systems, or rail approaches immediately reduces throughput capacity and creates a wave of railcar/truck accumulation;

- the second channel is indirect: even when physical damage is limited, uncertainty increases - along with it, insurance premiums, shipowners' caution, and the demand for more flexible contract terms.

From a rate-setting perspective, this means that when risk rises, the market does not always show a "linear" increase in freight. Some vessels leave the region, but some remain, and then the price may reflect bargaining power, seasonal cargo supply, and the availability of alternatives. For exporters, this implies that the contracting strategy should include not only the rate but also execution terms: deadlines, penalties, risk

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allocation, and the option to reroute via the Danube River or land borders.

At the level of multimodal architecture, the latest attacks [18] confirm that the Greater Odesa ports remain the core hub for economies of scale, but functionally they must be integrated with alternative channels so that the system can "switch" without collapse. In other words, resilience is not only about protection, but also about having a prepared logistics switching capability.

Overall, the 2022–2026 period confirms that an effective logistics solution for Ukraine cannot be built around a single dominant channel. The best strategy is a multichannel portfolio in which the Greater Odesa ports provide economies of scale, the Danube cluster offers flexibility, rail creates baseline resilience and the "green" potential of the inland leg, and road transport covers niche and time-critical flows.

Key practical thesis: a difference of just a few dollars per tonne in a transport rate can be entirely "absorbed" by idle time, queues, or changes in infrastructure availability. Therefore, route selection should be multi-criteria: cost, time, reliability, security, and environmental impact must be assessed jointly. For investment planning, the highest returns come from solutions at the interfaces between transport modes, where time losses and additional operations concentrate. From a practical standpoint, exporters and operators should strengthen digital flow management (slot planning, congestion forecasting, coordination of time windows at

ports and on access routes) and expand "buffer" capacities where they reduce the risk of contract failure. For public policy, priority should be given to projects that improve the sustainability of the key multimodal interfaces: port–rail, river–sea, and rail–border.

Conclusions. Ukraine's export logistics in 2022–2026 evolved from the forced reorientation of flows and a sharp increase in total logistics costs in 2022 to a partial normalization of the maritime channel in 2023, under conditions of high sensitivity to inspection delays. In 2024–2025, a new multimodal balance emerged: the Greater Odesa ports regained their role as the core hub for bulk lots [10], the Danube consolidated as an insurance buffer, and rail served as the stabilizer of exports. In early 2026, a regime of controlled stabilization in rail grain transportation and a structural stagnation of the road channel for bulk grain movements were observed, while security risks to port and rail infrastructure persisted. The results confirm that effective transport-technological solutions should be developed through a multimodal export architecture that enables flow reallocation during shocks without destructive increases in cost and time. This logic aligns with sustainable development approaches, where not only price matters, but also resilience and the environmental efficiency of logistics processes.

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PERMANENT INSTABILITY IN GLOBAL CONTAINER LOGISTICS: EVOLUTION FROM SUPPLY CHAINS TO DIGITAL ECOSYSTEMS

***Mariia Hryhorak, Kateryna Molchanova, Marharyta Sinaiko, Kateryna Cherneha.** «Permanent instability in global container logistics: evolution from supply chains to digital ecosystems». Global container logistics operates under conditions of permanent systemic instability manifested in extreme freight rate volatility, chronic port congestion, geopolitical disruptions, and nonlinear demand fluctuations. The aim of*

this paper is to develop a conceptual and methodological framework for assessing the resilience of container transportation under exogenous turbulence based on an ecosystem approach and multi-criteria route optimization.

The study clarifies the basic concepts of «permanent instability», «container transport stability triangle» (cost – time/reliability – CO₂ emissions), «delay risk», and «digital route transparency index». A generalized model of multi-criteria optimization of container transport route selection is proposed, taking into account stochastic tariff volatility, port infrastructure reliability, and environmental constraints. A three-level analytical architecture of a digital ecosystem for container flow management (Data Layer – Analytics Layer – Decision Layer) has been developed, which integrates heterogeneous data sources and supports the construction of Pareto-efficient alternatives for management decision-making.

The scientific novelty lies in the operationalization of the concept of container transport sustainability through a formalized multi-criteria approach at the level of an individual container as an autonomous optimization unit and in the justification of the role of digital transparency as a key resource of the logistics ecosystem. The practical significance of the results lies in the possibility of using the proposed model as a basis for developing digital platforms to support the decisions of carriers, cargo owners, and port operators in conditions of permanent market instability.

Keywords: container logistics, permanent instability, logistics ecosystem, multi-criteria optimization, transport resilience, freight rate volatility, digital transparency, decision support systems, maritime supply chains.

Марія Григорак, Катерина Молчанова, Маргарита Сінайко, Катерина Чернега. «Перманентна нестабільність у глобальній контейнерній логістиці: еволюція від ланцюгів постачання до цифрових екосистем». *Глобальна контейнерна логістика функціонує в умовах перманентної системної нестабільності, що проявляється у високій волатильності фрахтових ставок, хронічних портових заторах, геополітичних ризиках та нелінійних коливаннях попиту. Метою статті є формування концептуально-методологічної рамки аналізу стійкості контейнерних перевезень в умовах екзогенної турбулентності на основі екосистемного підходу та багатокритеріальної оптимізації маршрутів.*

У дослідженні уточнено базові поняття «перманентна нестабільність», «трикутник стійкості контейнерних перевезень» (вартість – час/надійність – викиди CO₂), «ризик затримки» та «індекс цифрової прозорості маршруту». Запропоновано узагальнену модель багатокритеріальної оптимізації вибору маршрутів контейнерних перевезень з урахуванням стохастичної волатильності тарифів, надійності портової інфраструктури та екологічних обмежень. Розроблено трирівневу аналітичну архітектуру цифрової екосистеми управління контейнерними потоками (Data Layer – Analytics Layer – Decision Layer), що інтегрує гетерогенні джерела даних і підтримує побудову Парето-ефективних альтернатив для прийняття управлінських рішень.

Наукова новизна полягає в операціоналізації поняття стійкості контейнерних перевезень через формалізований багатокритеріальний підхід на рівні окремого контейнера як автономної одиниці оптимізації та в обґрунтуванні ролі цифрової прозорості як ключового ресурсу логістичної екосистеми. Практична значущість результатів полягає у можливості використання запропонованої моделі як основи для розробки цифрових платформ підтримки рішень перевізників, вантажовласників і портових операторів в умовах перманентної ринкової нестабільності.

Ключові слова: контейнерна логістика, перманентна нестабільність, логістична екосистема, багатокритеріальна оптимізація, транспортна стійкість, волатильність фрахтових ставок, цифрова прозорість, системи підтримки прийняття рішень, морські ланцюги постачання

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Introduction. The modern global container shipping system operates in conditions of permanent systemic instability, manifested in hypervolatility of freight rates, chronic port congestion, geopolitical shocks, climatic restrictions on shipping, and growing regulatory environmental pressure. Unlike classic cyclical crises, the current instability is nonlinear, cumulative, and prolonged, creating an environment of constant turbulence in which traditional approaches to route planning and supply chain management lose their predictive power.

Most of the existing scientific research in the field of maritime logistics and SCM focuses either on cost optimization under deterministic conditions or on isolated analysis of individual risks (port delays, rate volatility, environmental restrictions). Such a fragmented approach does not reflect the systemic interaction of financial, physical, and information flows in container logistics and does not allow for adequate consideration of the effects of cascading failures characteristic of modern digitalized transportation networks.

At the same time, there is an evolutionary transition from linear supply chains to networked logistics ecosystems, within which shipping lines, ports, terminal operators, freight forwarders, digital platforms, and regulators interact. In such an ecosystem configuration, data and digital route transparency become critical resources, ensuring coordination of decisions, rapid reconfiguration of flows, and prevention.

Analysis of recent studies and publications. Research on global container logistics shows that modern supply chains are highly vulnerable to external and internal shocks. Significant attention is paid to this problem by authors analyzing economic volatility and structural asymmetries in global transport systems (T. Notteboom, A. Pallis, J. Rodrigue, 2021; C. Ducruet, E. Cocuzza, M. Ignaccolo, 2020) [1-3]. In particular, emphasis is placed on the role of key ports and state-owned companies that control strategic hubs,

creating monopolistic positions and increasing the risk of systemic disruptions in global supply (UNCTAD, 2022) [4].

The COVID-19 pandemic was a turning point for research on container logistics. Port congestion, lockdowns, and supply chain disruptions have exposed the weaknesses of just-in-time models and highlighted the need for new approaches to risk management (K. F. Yuen, 2019; W. Shih, 2020; Pan et al., 2021; D. Russell, 2021) [5-8]. Research shows that traditional methods of cost optimization and route planning do not provide sufficient flexibility to respond to systemic failures, and information lags between chain participants exacerbate the effects of crises (Liu et al., 2022; C. A. Ouedraogo, 2022) [9-10].

Contemporary scientific discourse in the field of maritime logistics and supply chain management increasingly focuses on the transition from a paradigm of relative equilibrium to one of permanent instability in global container flows. Works devoted to the post-pandemic transformation of logistics networks are dominated by the conclusion that models focused on minimizing costs through a high concentration of production and transit hubs and strict synchronization of flows within the just-in-time concept are structurally vulnerable -time concept (M. Christopher, H. Matthias, 2017, J.-S. Kim et al., 2023) [11-12]. In response to this, the literature actively discusses the need to move from linear supply chains to network configurations and digital logistics ecosystems capable of providing adaptability, multiple route options, and risk sharing among participants. Network models allow risks to be distributed among several nodes and alternative routes to be used, but they are still limited in their ability to adapt predictively due to limited data visibility. Digital ecosystems that integrate chain participants through a standardized digital infrastructure are becoming a new focus of research in maritime and container logistics (A. Wang et al., 2022; M.-L. Tseng et al., 2021; H. Sun et al., 2025). The use of IoT, Big Data,

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and artificial intelligence technologies enables real-time monitoring, forecasting, and adaptive management of multimodal routes, which significantly increases the stability of the system. Some researchers note that digital technologies not only improve the operational efficiency of container logistics, but also contribute to sustainable development and reduce harmful environmental impacts (J. Lyu et al., 2023) [16]. At the same time, most scientific works focus on the technical aspects of digitalization and do not integrate multi-criteria approaches to sustainability assessment that simultaneously take into account the financial, time, and environmental parameters of container transportation.

An important area of research is multi-criteria modeling of risks and resilience in global supply chains. Developments related to freight indices, such as the Drewry World Container Index (WCI) and the Freightos Baltic Index (FBX), allow for the assessment of market volatility and its impact on shipping costs. However, the integration of this data into digital platforms and the creation of models that evaluate each container as a separate object of optimization remains under-researched.

Identification of previously unresolved parts of the overall problem. Contemporary scientific discourse emphasizes the permanent instability of global container chains and the need to transform management models from classic linear supply chains to dynamic digital ecosystems. At the same time, existing studies remain fragmented in terms of methodology. On the one hand, a developed theoretical body of work is being formed on the issue of resilience in container supply chains, in which resilience is interpreted through the system's ability to recover from shocks, diversify routes, and reduce dependence on critical nodes. However, these approaches mostly remain at the conceptual level or are limited to aggregated resilience indicators without direct integration into operational route planning algorithms. On the other hand, in

the field of transport optimization and operations research, real-time container and multimodal transport routing models are actively being developed using heuristics, stochastic models, and machine learning methods. However, these algorithms typically optimize individual criteria (minimizing cost or delivery time) and treat risks and environmental constraints as external or auxiliary parameters that are not integrated into a unified sustainability concept.

Thus, there is a methodological gap in contemporary literature between theoretical models of sustainability and ecosystem development in container logistics, as well as between applied routing algorithms used in digital transportation management platforms. It is this gap that is filled by the concept of multi-criteria management of container logistics sustainability proposed in the article. This study not only conceptually supports the ecosystem paradigm of container logistics development, but also offers operationalized tools suitable for implementation in digital transportation management platforms, which is its main scientific and applied contribution.

Formulation of the article's objectives. The aim of the study is to develop and test the concept of multi-criteria management of container logistics sustainability in conditions of permanent systemic instability, integrating financial, time, and environmental indicators into a digital ecosystem for managing container transport routes.

The research methodology is based on a combination of systemic, ecosystemic, and multi-criteria approaches to the analysis of global container logistics in conditions of permanent instability. The research is interdisciplinary in nature and combines the tools of logistics, transport economics, network theory, risk analysis, and digital transformation. The first stage involved conceptualizing the phenomenon of permanent instability in global container logistics by synthesizing the provisions of system instability theory, supply chain resilience concepts, the ecosystem approach,

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and exogenous turbulence theory. This made it possible to form an analytical framework for the study, within which container logistics is interpreted as an open socio-technical system functioning in conditions of constant external shocks (geopolitical, market, regulatory, security, and climatic). The empirical basis of the study is formed on the basis of secondary data from leading industry sources (Clarksons Research, Drewry, Freightos, UNCTAD), public statistics from port administrations and shipping lines, as well as analytical reports from consulting companies. To illustrate market instability, we used freight rate dynamics (WCI and FBX indices), TEU-mile indicators, data on port congestion, and service reliability. Descriptive statistics, comparative analysis, and trend analysis methods were used to identify nonlinear changes in market dynamics. Within the framework of the study, a generalized formalized model of multi-criteria assessment of container delivery routes based on the "stability triangle" (cost – time/reliability – carbon intensity) was developed. The object of modeling was defined as a single container as an autonomous optimization unit. Additionally, the risk of delay is formalized as the probability of exceeding the acceptable transit time, taking into account port congestion and geopolitical restrictions; the digital transparency index of the route is formalized as an integral indicator of the availability, relevance, and detail of data in real time.

Presentation of the main results. Given the interdisciplinary nature of global container logistics and the ambiguity of interpretations of key categories in scientific literature, the initial stage of the study involved a targeted clarification of the basic concepts that form the conceptual framework of the work. This approach ensures the methodological integrity of the analysis, reduces the risk of terminological discrepancies, and increases the reproducibility of the results obtained.

Permanent instability in the context of this study is interpreted not as a temporary crisis or a phase of cyclical market fluctuations, but as a structural characteristic of modern global container logistics, reflecting the persistent presence of exogenous shocks, nonlinear dynamics of freight rates, transit times, and spatial configuration of flows. Permanent instability is formed under the influence of the cumulative effect of geopolitical conflicts, military actions, regulatory changes, climate risks, and trade restrictions, which makes it impossible for the system to return to a stable equilibrium in the medium term. The resilience of container logistics is defined as the ability of the logistics system to maintain an acceptable level of functioning and restore operational capacity after external shocks through adaptive route restructuring, flow redistribution, and flexible transformation of contractual terms, rather than simply by accumulating excess capacity reserves.

The digital ecosystem of container logistics is defined as an integrated environment for interaction between carriers, ports, freight forwarders, cargo owners, financial institutions, and government agencies, within which physical, financial, and information flows are coordinated through digital platforms, API interfaces, and algorithmic data analysis tools. Unlike linear supply chains, the digital ecosystem functions as a network of co-evolution of actors and technologies, enabling dynamic restructuring of routes and contract strategies in response to exogenous shocks.

The clarification of basic concepts provides the necessary conceptual and methodological framework for further analysis of the specifics of global container logistics in conditions of permanent instability. On this conceptual basis, further consideration focuses on three interrelated areas:

1) identification of the key features of container logistics in an environment of permanent instability, dominated by nonlinear effects, cascading failures, and degradation of effective network throughput;

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2) analyzing the evolution of linear supply chains towards digital container transport ecosystems as an organizational form capable of ensuring coordination between actors and reducing information asymmetry;

3) formalization of the route selection task as multi-criteria optimization, reflecting the inevitable trade-offs between cost, time/reliability, environmental constraints, and delay risks.

1. Features of container logistics in conditions of permanent instability.

The modern container supply chain functions as a multi-level multimodal network of interaction between five key types of participants, integrated into a single logistics circuit based on joint management or a unified transport document. The core of the system is the mainline maritime transport subsystem, represented by liner shipping operators that connect global hubs — seaports. Ports operate a container transshipment and handling subsystem, represented by container terminals, which play a system-forming role for the efficiency of the entire supply chain. The port infrastructure is integrated with the hinterland transport subsystem, which includes rail and road transport and provides the «first» and «last mile» connections. The system is complemented by a warehouse subsystem, which covers internal warehouses and port cargo stations, performing a buffer function and optimizing container loading. The coordination of all elements is ensured by logistics providers and freight forwarders, who synchronize material, information, and financial flows within the container supply chain.

However, even a high level of integration and coordination among supply chain participants does not eliminate the systemic vulnerability of container logistics to exogenous shocks. Figure 1 shows the growth dynamics of global container trade volumes, which is shaped by stable consumer demand on the main intercontinental routes: East Asia – North America, East Asia – Northern Europe, and the Mediterranean. The container throughput indicator, adjusted for transport distance (TEU-miles), grew faster than the physical volume of container traffic in 2024. This indicates a structural change in the geography of routes, not just an increase in demand. The sharp increase in TEU-miles was due to a prolonged deviation of shipping routes from the traditional passage through the Red Sea, primarily on the East Asia-Europe route. The detour around the Cape of Good Hope extended the average voyage time by approximately 30%, which, according to Clarksons Research estimates, accounted for about 11% of the increase in total demand for container TEU-miles in 2024 [17]. This trend perfectly reinforces the key thesis of permanent instability and demonstrates an important methodological difference between the growth of physical transport volumes (TEU) and the growth of transport performance (TEU-miles).

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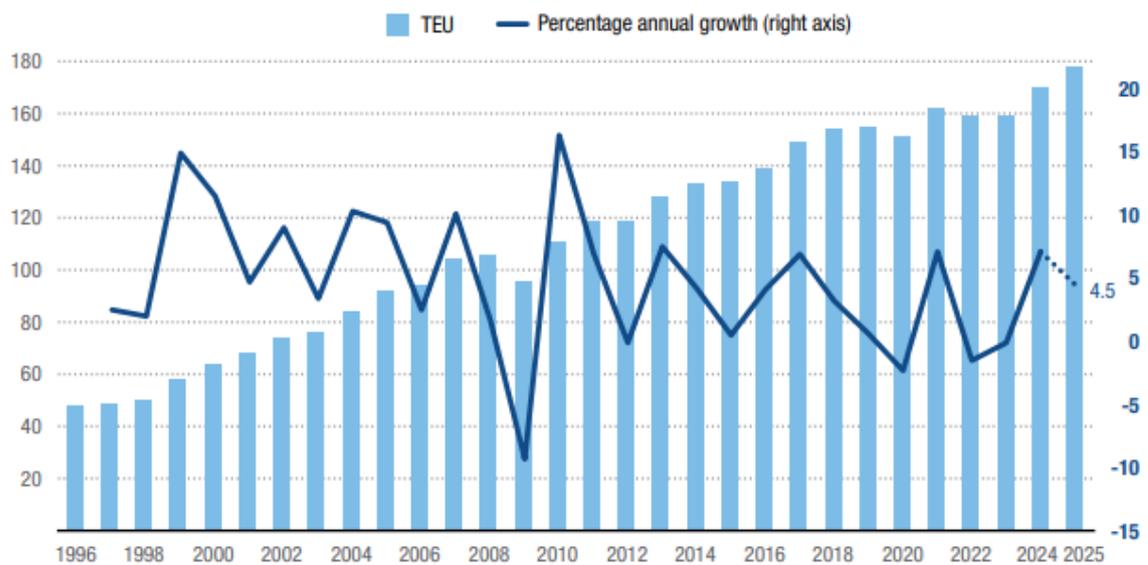
Figure 1 – Dynamics of global container trade volumes
(millions of TEU and percentage annual change)
Source: MDS Transmodal [17]

Market instability in maritime logistics also manifests itself in the form of extreme volatility in freight rates, which is a macroeconomic symptom of deeper operational and structural imbalances in the global container system. Industry indicators, in particular the Drewry World Container Index (WCI), show sharply non-linear price dynamics, as reflected in Figure 2.

Throughout 2025, rates for the transportation of a 40-foot container showed weekly fluctuations of 8–10%, with price dynamics being markedly asymmetrical across transport routes. In particular, the decline in tariffs on Asia-Europe routes could have occurred in parallel with an increase in rates on trans-Pacific services during the same period [18].
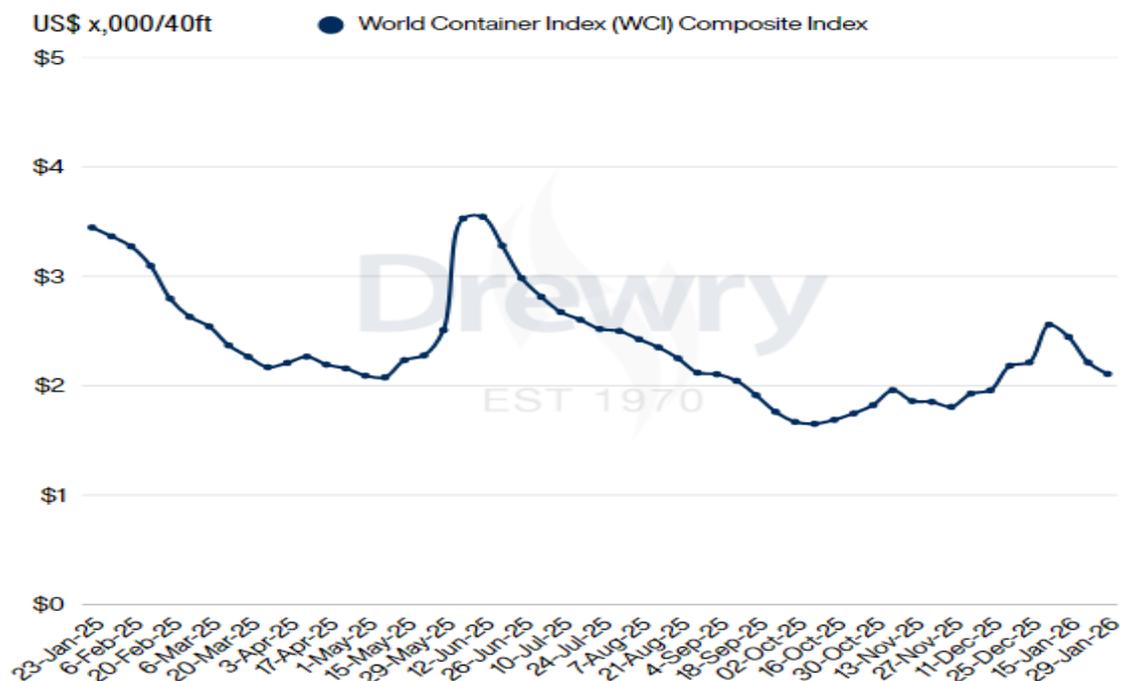
Figure 2 - Drewry World Container Index 2025 (US$/40ft)
Source: [18]

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It should be noted that the volatility of freight rates in 2024–2025 is structural rather than cyclical in nature. It is caused by the simultaneous action of several factors:

- asymmetric logistics shocks (the crisis in the Red Sea affects the Asia–Europe and Asia–North America routes differently);

- uneven redistribution of the fleet between trades (carriers are quickly shifting ships to more marginal routes);

- a rigid oligopolistic structure of the liner shipping market (alliances coordinate capacity, which amplifies price fluctuations);

- the growing role of the spot market amid the erosion of long-term contracts.

Figure 3 shows the dynamics of freight rates for the transportation of a 40-foot container along key export routes from Shanghai to major ports in Europe and North America. The graph shows high amplitude and asynchrony of price fluctuations between transport directions, indicating fragmentation of the global container market and the growing role of regional imbalances in supply and demand. Periods of sharp rate increases are followed by phases of rapid correction, but prices do not return to pre-crisis levels, forming a new «raised base» for freight rates. The divergence in dynamics between the Shanghai–Northern Europe and Shanghai–US West Coast routes is particularly pronounced, reflecting the different sensitivity of transcontinental routes to exogenous shocks (geopolitical risks in the Red Sea, port congestion, seasonal peaks in US imports).
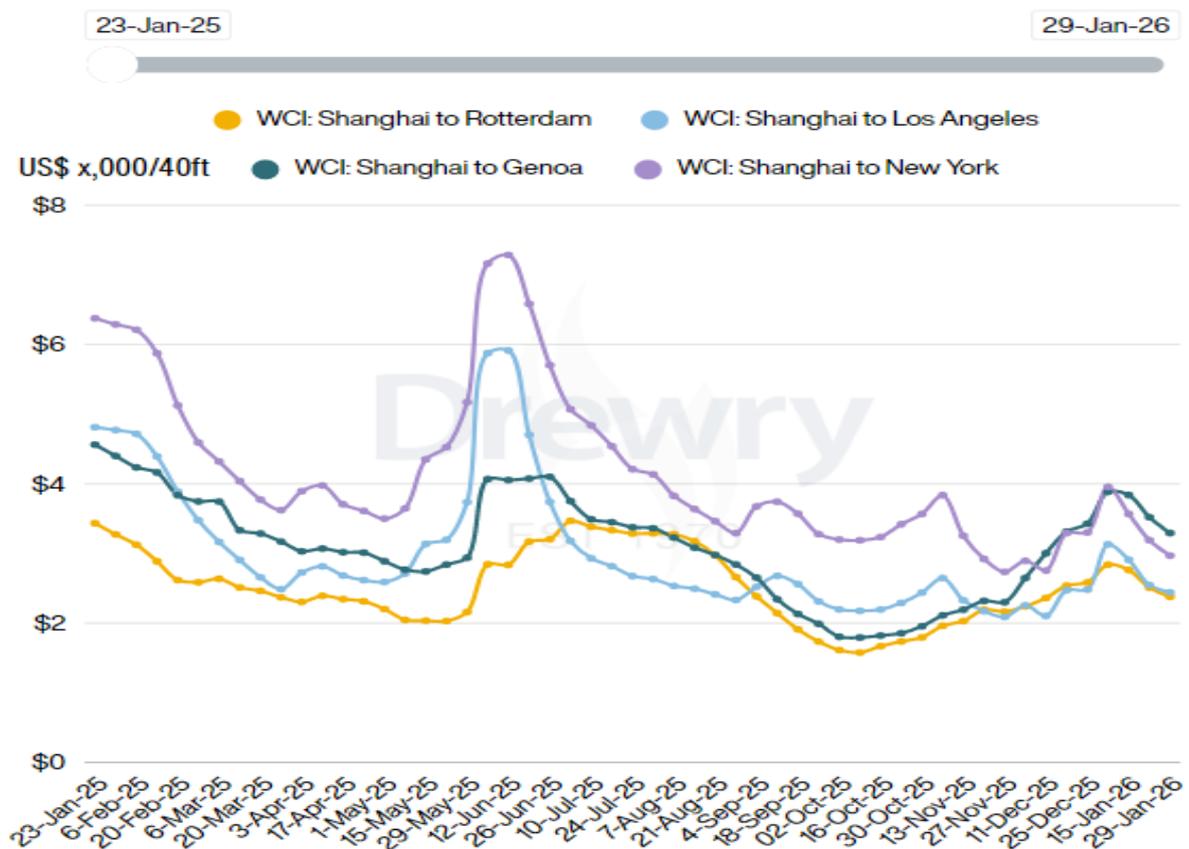
Figure 3 - WCI Trade Routes from Shanghai (US$/40ft)
Source: [18]

The nonlinearity and asymmetry of freight rate dynamics recorded in the graph confirm the transition of container logistics to a state of permanent instability, within which price signals are increasingly less effective in performing a stabilizing function, and short-

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term imbalances are quickly translated into macro-level fluctuations in the transportation market. As a result, freight rates no longer reflect the «average market equilibrium» and become an indicator of local bottlenecks and capacity imbalances. The volatility of freight rates ceases to be just market noise and transforms into a systemic risk factor that directly affects the stability of container supply chains and requires a transition from single-factor price optimization to multi-criteria decision-making models within digital ecosystems.

Thus, permanent instability in global container logistics manifests itself not only in the growing volatility of freight rates, but also in changes in the spatial -temporal configuration of container flows, which objectively reduces the effective throughput capacity of the global logistics system and reinforces the need to transition to digital ecosystems of adaptive management. The origins of the current systemic crisis are cumulative in nature and are caused by the overlap of several interrelated shocks that have successively destroyed the relative equilibrium of global supply chains. The COVID-19 pandemic was the primary catalyst, exposing the structural fragility of just-in-time models through lockdowns, disruptions in production links, and unprecedented port congestion at key hubs in the US and China. Further escalation of instability was caused by the Red Sea shipping security crisis since late 2023, which effectively blocked the traditional route through the Suez Canal and forced carriers to massively reroute traffic around the Cape of Good Hope. As shown in Figure 1, this led to a sharp increase in TEU-miles, i.e., the volume of transport work, with relatively moderate dynamics in physical container traffic volumes. The extension of voyages by 10–14 days led to a reduction in the effective capacity of the fleet, an increase in fuel and insurance costs, and a secondary price shock in the freight market, which is empirically confirmed by the increased volatility of the WCI index (Fig. 2) and the

asynchronous dynamics of rates on major intercontinental routes (Fig. 3).

The war in Ukraine has radically transformed the logistics geography of the Black Sea region, limiting access to traditional port hubs and increasing overall geopolitical uncertainty for global carriers and cargo owners. An additional long-term structural factor is the concentration of control over port infrastructure and logistics data: Chinese state-owned companies exert operational or investment influence over a significant number of strategic ports in various regions of the world and are developing their own digital flow management platforms, which creates asymmetry in access to information and sets the stage for potential non-market influence on industry dynamics [3,4,11].

A synthesis of theoretical approaches and practical cases allows us to conclude that global container logistics is transitioning from a regime of predominantly cyclical fluctuations to a paradigm of permanent systemic instability. This instability is cumulative in nature and is shaped by the interaction of short-term market volatility with long-term structural challenges, including geopolitical fragmentation, escalating armed conflicts, climate risks, and trade wars. Geopolitical shocks and military actions, particularly in Ukraine, demonstrate the ability to rapidly and radically change the configuration of global supply chains through the blocking of sea corridors, the destruction of transport infrastructure, and the destabilization of critical resource flows. Current dynamics have revealed the fundamental vulnerability of global supply chains as a direct consequence of the dominance of management paradigms focused on minimizing costs and maximizing efficiency through high concentration of production and transit hubs. The implementation of just-in-time models has led to the formation of highly complex, tightly interconnected systems without built-in reserves of resilience and adaptability, resulting in a low capacity to quickly reroute

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in the event of loss of access to key maritime corridors.

In conditions of hypervolatility and cascading failures, traditional approaches to container logistics management demonstrate systemic inadequacy due to a number of fundamental limitations. First, the problem of information lags and data fragmentation persists: traditional communication channels create information asymmetry between carriers, ports, customs authorities, and freight forwarders, leading to decisions based on outdated data in the event of sudden disruptions (e.g., port blockages) [5]. Second, classical approaches rely on static route planning using historical data, which quickly becomes irrelevant in conditions of hypervolatility. Third, the computational complexity of multimodal alternatives exceeds the operational capabilities of non-digital management systems, making it impossible to quickly reorganize supply chains. Fourth, traditional risk management methodologies are based on the assumption of event recurrence, while modern crises are structural breaks with no historical analogues, making such models unsuitable for use in conditions of high uncertainty and systemic shocks.

2. The evolutionary transition from linear models to digital ecosystems in container shipping.

The development of logistics systems in the field of container transportation is evolutionary rather than discrete in nature and reflects the gradual transformation of the ways in which material, financial, and information flows are organized in response to the increasing complexity of the global environment. Traditionally, container logistics has functioned within the linear model of the supply chain, which is interpreted in modern science as a sequence of organizations linked primarily by hierarchical and contractually fixed relationships. Within this model, the material flow passes through clearly defined stages from the source to the end consumer, and the interaction between participants is linear and sequential, with each link functionally dependent on the results of the previous one [6].

A rigid linear configuration generates high systemic risks based on the «domino effect» principle: a failure at any stage (e.g., a delay in a ship's arrival at port or a break in the production chain) is cascaded to all subsequent links. In conditions of relative market stability, this model ensured a reduction in total costs through just-in-time strategies and a high level of process standardization. However, in an environment of permanent instability, linear supply chains demonstrate fundamental vulnerability due to the low flexibility of contractual relationships, the inertia of change approval procedures, and the high transaction costs associated with the operational replacement of routes or partners.

The next stage of evolution was the Supply Network model, in which the logistics system is interpreted as a nonlinear configuration of interconnected nodes with many alternative routes and channels of interaction. This architecture allows for partial diversification of risks among several operators, increasing the structural reliability of the system by enabling the redistribution of flows without radically changing the overall network configuration. At the same time, even the network model often remains limited in terms of proactive management, since information flows in it mainly perform the function of post-factum monitoring rather than a tool for preventive optimization of decisions in real time.

The highest form of organization of logistics systems in container transportation is the Digital Ecosystem, which can be defined as an integrated information and economic environment that brings together heterogeneous participants (shipping lines, ports, terminals, freight forwarders, IT platforms, financial institutions, and government agencies) around a common digital infrastructure for shared access to data and services. The technological foundation of

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such an ecosystem is digital platforms that provide standardized application programming interfaces (APIs), electronic booking, electronic document management, and data exchange in near real time [7].

For a comparative analysis of these stages in the evolution of logistics models, it is advisable to use the system of criteria summarized in Table 1.

Table 1. Comparative characteristics of evolutionary models of logistics in integrated logistics structures

Comparison criterion	Supply chain	Supply network	Digital ecosystem
Essence and structure	Linear sequence, static configuration	Nonlinear configuration of interconnected nodes	Integrated environment around shared digital infrastructure
Degree of interdependence	Sequential dependence on the previous link (high risk of cascading failures)	Cross-dependence and partial risk sharing	Technological compatibility while maintaining decision-making autonomy
The role of data	Discrete exchange with time lags, local storage	Data is used for synchronization and partial visibility of processes	Data as a key production resource, available in real time
Flexibility and adaptability	Low, focus on cost minimization	Medium, adaptation through redistribution of flows	High dynamism and capacity for preventive adaptation

Source: Developed by the authors

The key difference of the digital ecosystem is the transformation of data into a strategic asset, which creates the conditions for the application of predictive analytics, machine learning algorithms, and artificial intelligence tools to automate decision-making processes. Within the ecosystem, there is a "structural alignment" of interdependencies between participants, which increases the resilience of container transport to external shocks by increasing transparency, consistency of decisions, and reducing information asymmetry.

The transformation from linear models to digital ecosystems is driven by the need to overcome the «computational incapacity» of traditional approaches to logistics management [8]. While within a linear chain, a manager-operator can only operate with a limited set of variables and scenarios, a digital ecosystem, thanks to the integration of IoT, Big Data, and AI technologies, provides the ability to quickly analyze thousands of alternative multimodal combinations of routes, tariffs, and risks. This forms the basis for a transition to a co-evolutionary logic of development, in which participants not only respond to market changes but also jointly adapt their business models and services to conditions of permanent instability.

Therefore, the evolutionary transition to digital ecosystems in container logistics is not a technological fashion, but a systemic response to the growing complexity and turbulence of the global environment. Current analytical reviews of the digital transformation of the maritime industry emphasize that the introduction of digital technologies in ports and shipping (data sharing platforms, artificial intelligence, digital twins, 5G connectivity) is aimed at improving the operational efficiency and sustainability of supply chains. Studies of digital logistics platforms in maritime logistics show that their basic functions are data integration, analytical optimization of flows, increased visibility and transparency of processes, and automation of operations planning. In the author's concept, these functions are focused on minimizing market instability for individual container shipments through rapid analysis of market conditions and adaptation to external shocks.

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The key hypothesis is that as the digital ecosystem matures – that is, with the expansion of the circle of integrated participants, improvement in data quality and completeness, and development of analytical and AI modules – the variability of key indicators such as cost, time, and emissions decreases, and the supply chain's ability to bypass high-risk areas increases. By «circumvention» we mean not only the physical reorientation of routes (avoiding war zones or congested hubs), but also institutional and contractual adaptation: the transition from fixed tariffs to indexed contracts (for example, linked to the Freightos Baltic Index), the redistribution of flows between carriers based on their reliability, and the dynamic selection of ports of departure and destination depending on the level of congestion and risks of disruption.

Thus, the author's proposed concept of a digital ecosystem for container logistics forms a logical framework for the further algorithmization of management decisions: at the input stage – integrated data on the market, operational parameters, environmental restrictions, and customer requirements; in the analytical core – an AI module for multi-criteria route optimization; at the output – formalized recommendations for choosing a route, carrier, and pricing strategy for a specific container shipment in conditions of permanent instability.

3. Methodology for multi-criteria assessment of container logistics stability in conditions of permanent systemic instability.

The current paradigm of container logistics operation objectively requires a review of traditional approaches to assessing its effectiveness. In the context of the market transition from predominantly cyclical fluctuations to a regime of permanent systemic instability, focusing exclusively on minimizing transportation costs is methodologically insufficient and practically risky. Single-factor models ignore critical delays, increasing regulatory and environmental pressure, and the increased vulnerability of supply chains to exogenous shocks.

The methodology proposed within the author's concept is based on a transition to a multi-criteria assessment, where the object of analysis is a single transport unit – a container. The management goal is formulated not as choosing the «cheapest» route, but as minimizing the cumulative effects of market instability for each shipment, while balancing costs, time/reliability, and environmental impact.

The methodology is based on the concept of a «stability triangle» that encompasses three basic vectors of indicators: cost – time/reliability – carbon emissions (CO_2).

1. Financial criterion (cost level and variation).

In conditions of hypervolatility, the cost of container transportation ceases to be a quasi-static value and is formed as a combination of the base freight rate and a set of surcharges (fuel, war, port charges, insurance premiums, demurrage and detention penalties). The methodological novelty lies in taking into account not only the mathematical expectation of the cost, but also its dispersion as an indicator of the financial instability of the route. Increased variation in costs due to port delays or sharp fluctuations in the Drewry World Container Index (WCI) and Freightos Baltic Index (FBX) is interpreted as a marker of increased risk for the cargo owner.

2. Time criterion (service duration and reliability).

For cargo owners, not only the average transit time (lead time) is critical, but also the stability of its compliance, i.e., the reliability of ETA/ETD fulfillment. In the context of systemic failures and the formation of bottlenecks in global maritime corridors (the Suez and Panama Canals, overloaded hubs), service reliability becomes a priority. The methodology involves assessing the probability and scale of deviations from planned parameters. Ship speed is considered a control parameter with an inter-criterion

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effect: reducing it decreases fuel consumption and emissions, while increasing delivery time and inventory maintenance costs in the supply chain.

3. Environmental criterion (carbon intensity of transportation, CO_2/TEU).

In the context of the "green transition," the environmental dimension is integrated into the transportation economy as a mandatory component of management decision-making. The criterion is formalized through the amount of CO_2 emissions per TEU for a specific route and type of vessel. The choice of route, transshipment scheme, and speed regime directly shapes the environmental profile of a container, which in the long run translates into direct financial costs through carbon regulation and tax burden mechanisms (in particular, CBAM).

In addition to the basic «stability triangle», the proposed methodology integrates additional dimensions that are not independent optimization criteria but act as moderators of the effectiveness of management decisions in conditions of permanent instability.

First, the risk of delay is interpreted as the probability of exceeding the specified delivery time threshold due to port congestion, transit hub overload, sea corridor blockages, or geopolitical restrictions. Unlike average transit time, the risk of delay reflects the asymmetric nature of uncertainty in container logistics, where isolated but high-intensity events (blockage of the Suez Canal, attacks in the Red Sea, sudden port closures) generate disproportionately high losses for the cargo owner. In this sense, delay risk is an indicator of the structural vulnerability of a route, not just its operational efficiency, and is a key parameter in assessing the resilience of a supply chain to exogenous turbulence.

The integral route delay risk index can be calculated using the following formula:

$$DRI_i = \lambda_1 \cdot P(T_i > T^*) + \lambda_2 \cdot \frac{E[\Delta T_i | T_i > T^*]}{T_i^{plan}} \qquad (1)$$

where, T_i - actual transit time of route i (random variable),

T_i^{plan} - scheduled (nominal) transit time,

T^* - maximum permissible delivery time (SLA, contractual threshold),

$\Delta T_i = T_i - T_i^{plan}$ - deviation from the plan,

P — probability,

E — mathematical expectation;

λ_1, λ_2 - weight (for example, 0.5 / 0.5).

The risk of route delays is formalized as the probability of exceeding the specified delivery time threshold $P(T_i > T^*)$ with additional consideration of the depth of the delay due to the conditional mathematical expectation of exceedances. This approach allows for the asymmetric nature of uncertainty in the context of geopolitical and infrastructure shocks to be taken into account.

Second, digital transparency is conceptualized as a systemic characteristic of the logistics network that determines the level of availability, relevance, and integration of information about the location of the container, flight status, ETA/ETD changes, and tariff parameters in near real time. Digital transparency is not an independent target variable for optimization, but it directly affects the quality of management decisions, as it reduces information lags, data asymmetry between supply chain participants, and cognitive limitations of managers in situations of rapid environmental change. In conditions of permanent instability, it is the lack of relevant information that transforms market shocks into systemic crises; accordingly, a high level of digital transparency is an institutional prerequisite

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for the implementation of multi-criteria optimization and adaptive route replanning.

Digital route transparency is operationalized through the aggregated DTI index, which integrates five dimensions: node coverage with data, update frequency, level of actor integration, depth of event visibility, and degree of automation of management decisions (Table 2).

Table 2. Components of the digital route transparency index

Component	Formalization	Interpretation
Data coverage	Number of nodes with API / Total number of nodes on the route	Percentage of ports/terminals connected to the platform
Update frequency	1/ average update interval, (hours)	Speed of data retrieval
Integrity	Binary or 0-1 scale	Integration with ports, customs, lines, terminals
Status visibility	Number of available events / Maximum list of events	ETA
Automation of decisions	0-1 scale	Availability of AI recommendations, ETA forecasts, risk alerts

Source: Developed by the authors

The proposed digital transparency index of the route $DTI \in [0;1]$ has a threshold interpretation: low values (up to 0.3) correspond to reactive management models with high information lags; medium values (0.3–0.6) reflect partial adaptability due to fragmentary digital integration; high values (above 0.6) characterize the transition to proactive management of container flows within digital ecosystems using predictive analytics and artificial intelligence. The DTI index reflects the institutional capacity of a digital ecosystem to reduce information lags and transform permanent instability from an exogenous shock into a controllable decision-making parameter.

Thus, delay risk and digital transparency form a meta-contour of stability that determines not only the parameters of a single route, but also the ability of the logistics system as a whole to respond in a timely manner to exogenous shocks. In combination with the basic «stability triangle» these measurements allow us to move from a static assessment of route efficiency to a dynamic model of container flow management in a state of constant turbulence.

The choice of a container transport route is formalized as a multi-criteria optimization problem on a directed graph of a logistics network $G=(V,E)$, where the nodes correspond to ports and terminals, and the edges correspond to individual transport sections. For each admissible route $r \in R$, a vector of criteria is formed as follows:

$$F(r)=(C(r),\ T(r),\ E(r),\ R(r),\ -DTI(r)) \rightarrow min, \qquad (2)$$

where $C(r)$ – integral cost of transportation, taking into account the volatility of freight rates and surcharges,

$T(r)$ – expected transit time adjusted for service reliability,

$E(r)$ – carbon intensity of transportation (CO_2/TEU),

$R(r)$ – risk of delay, interpreted as the probability of exceeding the acceptable lead time,

$DTI(r)$ – digital route transparency index.

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Optimal solutions are defined as a set of Pareto-efficient routes, between which a choice is made using scalarization (weighted sum or ε-constraint method) in accordance with the strategic priorities of the cargo owner (cost minimization, reliability improvement, decarbonization, risk reduction). The parameters of the network edges are considered dynamic, which provides the possibility of adaptive route restructuring in real time in conditions of market and geopolitical instability.

The proposed three-dimensional analytical model provides a systematic implementation of a multi-criteria assessment of the stability of container transportation in conditions of permanent market instability. Its structure corresponds to the three key tasks of modern logistics management: data collection and structuring, analytical forecasting, and support for informed decision-making.

The Data Layer is the foundation of the system, as it provides aggregation and cleansing of information from various sources – from industry indices (WCI, FBX) and shipping line schedules to operational data from IoT container sensors and port congestion indicators. This layer is critical for overcoming the problems of information fragmentation that are characteristic of traditional management models, where decisions are often based on outdated or incomplete data.

The Analytics Layer implements the process of modeling alternative routes and evaluating their multi-criteria indicators using machine learning and optimization methods. At this level, indicator vectors are formed that take into account not only the expected cost and its variation, but also delivery time, reliability, carbon intensity of transportation, and integral risk. This approach allows not only to predict the consequences of external shocks, but also to evaluate the trade-offs between economic efficiency, operational efficiency, and environmental requirements.

The Decision Layer transforms analytical results into understandable, user-friendly decisions. By constructing a set of Pareto-efficient routes, the user receives transparent information about the trade-offs between criteria: for example, a more expensive route may provide high reliability and a lower carbon footprint. This ensures the adaptability of the logistics system to market and geopolitical instability, allowing decisions to be made that minimize risks and increase the sustainability of each shipment.

The proposed three-dimensional analytical model fully corresponds to the ecosystem approach in container logistics, as it integrates the three main dimensions of the modern digital ecosystem: physical, financial, and information flows.

1. Flow integration. The data level provides information gathering from various sources (port systems, IoT sensors, WCI/FBX indices), allowing for a complete picture of physical and financial flows to be constructed. The analytical level creates interconnected vectors of indicators that simultaneously assess costs, time, reliability, and environmental footprint, integrating various aspects of chain operations. The decision-making level visualizes trade-offs between indicators, allowing the user to adaptively manage routes and resources in line with the principles of ecosystem coordination.

2. Adaptability and dynamism The ecosystem approach assumes that each element of the system (port, ship, container, carrier) is an integrated part of the whole and responds to changes in the environment. The model achieves this through: real-time monitoring (Data Layer) and rapid updating of analytical forecasts (Analytics Layer), the ability to select the optimal route from a set of Pareto-efficient alternatives (Decision Layer), which ensures adaptation to market, geopolitical, and environmental shocks.

3. Synergy of ecosystem components. The model allows coordinating physical transportation, financial flows, and information interactions between

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participants in the logistics network. This creates conditions for flexible resource management and risk reduction in global container logistics.

Thus, the proposed three- dimensional structure implements the key principles of a digital logistics ecosystem: data and flow integration, adaptive decision-making, and synergistic interaction between participants, making it an effective tool for managing the sustainability and flexibility of container chains in conditions of permanent instability.

Conclusions. Modern global container logistics is in a state of permanent systemic instability, manifested by high volatility of freight rates, port congestion, geopolitical risks, and fluctuations in demand. Traditional linear supply chains demonstrate low flexibility and limited adaptability, making them vulnerable to external shocks. The transition from linear models to network structures and digital ecosystems increases the resilience of container transport. Networked models allow risks to be distributed among multiple participants and alternative routes to be used, while digital ecosystems integrate physical, financial, and information flows in real time, enabling adaptive and preventive flow management. The key resource of a digital ecosystem is data, which enables forecasting and adaptive route planning. The integration of IoT, Big Data, and artificial intelligence technologies

allows for the evaluation of thousands of combinations of multimodal routes, helping to minimize risks, optimize costs, reduce delivery times, and lessen the environmental impact of transportation.

The proposed multi-criteria methodology based on the «stability triangle» (cost – time/reliability – emissions) demonstrates effectiveness in forecasting and minimizing the effects of external shocks. Modeling a single unit of transport – a container – as an autonomous optimization object allows logistics management to be transformed from reactive to adaptive, providing flexibility in route selection and risk management. The methodology includes additional measurements, such as delay risk and digital route transparency, which increases the practical applicability of the model. Delay risk is formalized as the probability of exceeding the acceptable transit time, and digital transparency as an integral index of the availability and relevance of data in real time. This provides the ability to intervene quickly and adaptively reconfigure logistics flows. The proposed approach creates a scientific and practical basis for the development of digital sustainability management platforms. It allows for increased transparency, reduced variation in key indicators, and effective response to permanent market instability, transforming exogenous risks into controllable decision-making parameters in container logistics.

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MARKETING LOGISTICS AS A DETERMINANT OF CUSTOMER LOYALTY IN THE CONTEXT OF DIGITAL TRANSFORMATION AND SUSTAINABLE ECONOMIC DEVELOPMENT

Iryna Suvorova, Oksana Pozniak, Viktor Sibruk. «Marketing logistics as a determinant of customer loyalty in the context of digital transformation and sustainable economic development». The article presents a comprehensive theoretical and conceptual analysis of marketing logistics as a key determinant of customer loyalty formation, maintenance, and strengthening in the context of the accelerated digital transformation of the economy and the strengthening of the global paradigm of sustainable development. The study argues that traditional operational approaches to logistics no longer provide sustainable competitive advantages in the e-commerce environment, where customer experience is becoming a determining factor in brand choice, repeat purchases, and recommendations. In the context of the introduction of artificial intelligence, the Internet of Things (IoT), big data analytics, and blockchain technologies, marketing logistics is transforming from a supporting function of the supply chain into a strategic

tool for creating a unique customer experience at the last-mile delivery stage. It is the integration of logistics processes with marketing strategies that enables delivery to become a powerful channel for building emotional attachment, customer retention, and long-term customer value. The scientific novelty of the work lies in the development and theoretical justification of an innovative extended cyclical sustainable model of marketing logistics based on artificial intelligence. The model systematically combines digital technologies, sustainable development principles, and customer-oriented marketing mechanisms. It is structured as an eight-stage continuous cycle: data analysis and demand forecasting → personalization of logistics options → integration of green practices → digital transparency and proactive communication → ethical integration → scaling of solutions → monitoring and evaluation of loyalty → iteration and correction. The practical significance of the model lies in its high adaptability to the conditions of Ukrainian enterprises, where the implementation of a sustainable marketing logistics model based on artificial intelligence makes it possible to simultaneously: significantly increase customer loyalty and repeat purchases, reduce operating costs by optimizing processes, reduce environmental impact, and strengthen competitive positions in conditions of geopolitical instability, growing consumer environmental awareness, and limited resources. The model can serve as a methodological basis for the development of modern marketing logistics strategies focused on long-term customer value and responsible business.

Keywords: marketing, logistics, customer loyalty, customer experience, digital transformation, sustainable development, marketing logistics model

Ірина Суворова, Оксана Позняк, Віктор Сібрук «Маркетингова логістика як детермінанта клієнтської лояльності в умовах цифрової трансформації та сталого розвитку економіки». *Стаття присвячена комплексному теоретичному та концептуальному аналізу маркетингової логістики як ключової детермінанти формування, підтримки та посилення клієнтської лояльності в умовах прискореної цифрової трансформації економіки та посилення глобальної парадигми сталого розвитку. Дослідження обґрунтовує, що традиційні операційні підходи до логістики вже не забезпечують стійких конкурентних переваг у середовищі електронної комерції, де досвід клієнтів стає визначальним фактором вибору бренду, повторних покупок і рекомендацій. У контексті впровадження технологій штучного інтелекту, Інтернету речей, аналітики великих даних, технологій блокчейн, маркетингова логістика трансформується з допоміжної функції ланцюга постачань у стратегічний інструмент створення унікального клієнтського досвіду на етапі доставки «останньої милі». Саме інтеграція логістичних процесів із маркетинговими стратегіями дозволяє перетворювати доставку на потужний канал формування емоційної прив'язаності, рівня утримання клієнтів та довгострокової цінності клієнта. Наукова новизна роботи полягає в розробці та теоретичному обґрунтуванні інноваційної розширеної циклічної сталої моделі маркетингової логістики на основі штучного інтелекту. Модель системно поєднує цифрові технології, принципи сталого розвитку та клієнтоорієнтовані маркетингові механізми. Вона структурована як восьмиетапний безперервний цикл: аналіз даних і прогнозування попиту → персоналізація логістичних опцій → інтеграція зелених практик → цифрова прозорість і проактивна комунікація → етична інтеграція → масштабування рішень → моніторинг та оцінка лояльності → ітерація та корекція. Практична значущість моделі полягає в її високій адаптивності до умов українських підприємств, де впровадження сталої моделі маркетингової логістики на основі штучного інтелекту дає змогу одночасно: суттєво підвищувати клієнтську лояльність і рівень повторних покупок, знижувати операційні витрати за рахунок оптимізації процесів, зменшувати екологічний вплив та посилювати конкурентні позиції в умовах геополітичної нестабільності, зростання споживчої екологічної свідомості та обмежених ресурсів. Модель може слугувати*

методологічною основою для розробки сучасних стратегій маркетингової логістики, орієнтованих на довгострокову клієнтську цінність і відповідальний бізнес.

Ключові слова: маркетинг, логістика, клієнтська лояльність, клієнтський досвід, цифрова трансформація, сталий розвиток, модель маркетингової логістики

Introduction. In today's economy, which is undergoing rapid digital transformation and increasing demands for sustainable development, marketing logistics is significantly changing its role. It is no longer just a supporting operational function in the supply chain, but has become a key strategic factor that determines a company's competitiveness and ability to build long-term customer loyalty.

Digital transformation, based on the introduction of artificial intelligence, the Internet of Things, big data analytics and blockchain technologies, is radically changing customer interactions. Logistics processes are no longer limited to the technical support of deliveries — they are becoming a central element of the customer experience. It is during delivery that consumers finally evaluate the value promised by the brand, which directly affects their perception of the brand, level of trust, and emotional attachment.

At the same time, the rapid growth of e-commerce both in Ukraine and worldwide is placing new, stricter demands on marketing logistics: customers expect a high level of personalization, complete transparency at all stages, guaranteed speed and reliability of delivery, as well as compliance with sustainability principles. Traditional logistics models that do not integrate these aspects with marketing strategies lead to lower customer retention, weakened trust and reduced long-term customer value.

Therefore, the relevance of the study lies in the need for a new conceptual approach to marketing logistics. It should be viewed as an integrated system that comprehensively combines modern digital technologies, sustainable development principles, and customer-oriented practices. This approach makes it possible to systematically increase customer loyalty, ensure a higher level of customer retention and form sustainable competitive advantages for enterprises in the era of digitalization and responsible economic development.

Analysis of the latest research and publications. The issue of marketing logistics as a factor in customer loyalty is actively researched in contemporary scientific literature, particularly in the context of digital transformation, the integration of marketing with logistics, and the principles of sustainable development. Ukrainian scientists focus on local characteristics and practical aspects of adapting marketing logistics in a transitional economy and martial law: Fedotova I. and co-authors interpret marketing logistics as an integrated enterprise management system that ensures the formation of competitive advantages [1]. Bortnik A. and Milcheva V. study the integration of marketing and logistics in modern business processes with a focus on customer orientation [2]. Zharska I.O. analyses current trends in sustainable development logistics, in particular environmental aspects [3]. Kharchenko T. and Sagaydak Yu. assess the prospects for the development of green logistics in Ukraine with an emphasis on ethical practices [4]. Parsyak V.N. and Zhukova O.Yu. substantiate modern trends and useful experience in the organization of marketing logistics [5]. Tiazhun E. examines the integrative interaction between marketing and logistics, emphasizing digitalization trends [6]. Vasyltsova S. and Hasiuk M. study the impact of marketing logistics on the formation of an enterprise's pricing policy in conditions of martial law [7].

In addition, some works are devoted directly to customer loyalty as an object of marketing management: Makarova V. and Nechiporenko V. analyses customer loyalty as

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a key object of marketing management [8]. Shevchenko V.M., Mishustina T.S., and Bondarenko A.A. study consumer preferences and loyalty as a tool for achieving the company's marketing goals [9]. Oliver's loyalty model remains the classic theoretical basis, which identifies four stages and is widely used to explain the formation of loyalty in the context of customer experience [10].

A review of the scientific literature shows that individual aspects are actively considered in research: the integration of marketing and logistics, digital transformation, green logistics, the impact of martial law on pricing and logistics decisions. At the same time, comprehensive models that systematically combine marketing logistics, customer loyalty, modern digital technologies, and sustainable development principles into a single cyclical conceptual model with an emphasis on last-mile delivery and customer experience remain underdeveloped, especially in the context of countries with transitional economies such as Ukraine.

Objectives statement. The purpose of the article is to provide scientific justification for the transformation of marketing logistics from a supporting operational function to a key strategic determinant of customer loyalty in the context of digital transformation and sustainable economic development, as well as to develop and theoretically substantiate an innovative, expanded conceptual sustainable model of marketing logistics based on artificial intelligence, which comprehensively integrates digital technologies, sustainable development principles and customer-oriented marketing mechanisms to systematically increase customer loyalty, retain the customer base and form long-term competitive advantages for enterprises.

Basic material and results. Marketing logistics is the integration of logistics processes and marketing strategies of an enterprise with the aim of creating added value for the customer, increasing their satisfaction and loyalty, and strengthening the company's competitive advantages [1,2,5,6]. The main differences between logistics and marketing logistics are presented in Table 1.

Table 1. Differences between logistics and marketing logistics

Aspect	Logistics	Marketing logistics
Main objective	Minimize costs, ensure availability	Create a positive customer experience, increase loyalty
Focus	Efficiency, speed, reliability	Customer experience, personalization, emotions
Key KPI	Delivery cost, percentage of on-time deliveries	retention rate, repeat purchase rate
Approach to the customer	Standardized	Individualized, personalized

Source: compiled by the authors

Marketing logistics transforms delivery from an operational expense into a strategic marketing asset. It turns a standard transaction of delivering goods into a positive experience that promotes loyalty, repeat purchases, and organic brand awareness [2,5,8]. In today's environment, companies that ignore the integration of logistics into their marketing strategy risk losing their customer base to competitors who systematically use logistics processes as an element of the brand experience [1,6].

Marketing logistics is the integration of logistics processes into a company's marketing management system, aimed at building and strengthening customer loyalty by optimizing the customer experience during delivery and after-sales service. In the current environment of e-commerce development and growing consumer

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demands for convenience, transparency and business accountability, marketing logistics is becoming a key tool for differentiation and competitiveness [3,4,7]. The main elements of marketing logistics are presented in Fig. 2.

Figure 1 – Key elements of marketing logistics
Source: [2-6]

The main elements of marketing logistics include:

- *Personalized delivery*. Giving customers the opportunity to independently determine delivery parameters, including the exact time interval, delivery point, delivery method, environmentally friendly options, and additional attributes such as packaging type or colour. This approach helps to increase the perception of the individual value of the service and form emotional attachment to the brand.

- *Transparency and proactive communication*. Providing continuous real-time tracking of order status, automatic informative notifications about the stages of goods movement, and the use of AI-based chatbots to quickly resolve queries and issues. Proactive communication reduces customer uncertainty and prevents negative emotions associated with delays [6].

- *Integration of logistics with marketing tools*. Transformation of the delivery process into a component of the customer journey: introduction of incentives, such as discounts for choosing 'slow' but environmentally friendly delivery, inclusion of branded gifts in the parcel, conducting satisfaction surveys immediately after delivery. Such integration allows you to turn operational interaction into a marketing event that encourages repeat purchases and recommendations [2,5].

- *Consistency and ethics of logistics processes.* The use of environmentally friendly solutions - electric or low-carbon transport, biodegradable and minimalist packaging, cooperation with local suppliers to reduce the transport footprint. These practices are positioned as marketing arguments that correspond to consumers' growing values regarding social and environmental responsibility [3,4].

- *Optimization of the 'last mile' with a focus on marketing*. Use of artificial intelligence algorithms for demand forecasting, dynamic routing, and generation of personalized offers. Optimization is aimed not only at reducing costs, but also at improving the quality of the customer experience, which directly affects customer loyalty and long-term value [6].

Marketing logistics is defined as the systematic integration of logistics processes with marketing strategies to create value for the customer and strengthen loyalty. In today's environment, it is being transformed by digital transformation and sustainable development, evolving from an operational

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function to a strategic asset. Digital transformation, in particular the introduction of AI and IoT, enables automated demand forecasting, route optimization and real-time tracking, which improves efficiency and customer experience.

Customer loyalty in the context of marketing logistics is defined as a complex behavioral, affective and cognitive attachment of the consumer to the brand, manifested in repeat purchases, willingness to recommend the company and resistance to competitive offers, and is largely shaped by the quality and value of the logistics experience [8,9]. Oliver's classic loyalty model identifies four consecutive stages: cognitive (belief in advantages), affective (emotional attachment), conative (intention to repurchase) and active (actual behavior). In marketing logistics, it is the behavioral stage that is most dependent on the physical and emotional experience of delivery, making it a key channel for the transition from intention to actual loyalty [10].

Based on a synthesis of contemporary theoretical approaches and empirical generalizations, we can identify the key determinants of customer loyalty that are directly shaped and controlled by marketing logistics:

- Speed and reliability of delivery are the most powerful predictors of cognitive and behavioral loyalty. Critical parameters include same-day or next-day delivery, as well as high accuracy in meeting time intervals [2,6].

- Personalization of the logistics experience significantly affects the cognitive and affective components of loyalty. Customers are given the opportunity to choose their own delivery time slot, delivery method, packaging type, and environmentally friendly options [5].

- Transparency and proactive communication reduce perceived risk and significantly increase trust. Key tools include a real-time system, automatic order status notifications at all stages, and technologies that ensure full traceability, particularly those based on blockchain [6].

- Environmental and ethical responsibility in logistics is having an increasingly strong impact on the loyalty of conscious consumers. Important elements include the introduction of 'green' delivery, the use of biodegradable or reusable packaging, reducing the carbon footprint of the supply chain, and adhering to the principles of ethical trade [3,4].

- Quality of feedback and effectiveness of problem solving - plays a decisive role in restoring trust after service failure. Quick response to deviations (delays, damage), adequate compensation, personalized apologies, and preventive measures to avoid repeating mistakes directly contribute to the transition from a negative experience to maintaining or even strengthening loyalty [8,9].

The algorithm for building customer loyalty through marketing logistics is shown in Fig. 2. The proposed algorithm is a systematic, cyclical process aimed at the consistent formation, maintenance, and strengthening of customer loyalty using marketing logistics tools.

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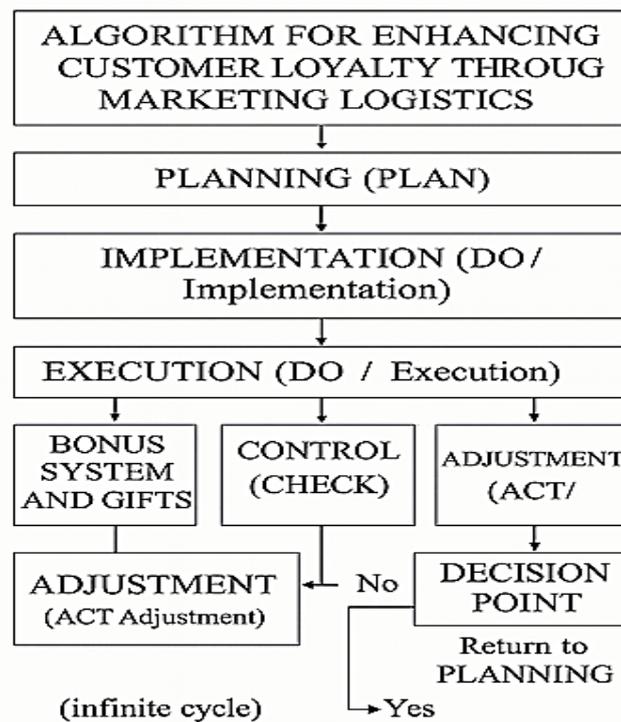
Figure 2 – Algorithm for building customer loyalty through marketing logistics.
Source: Compiled by the authors

The algorithm structure consists of:

- Identifying target customer segments, analyzing their expectations regarding logistics experience, setting specific KPI, developing a strategy for bonuses, compensation and communication scenarios.

- Implementation of planned logistics solutions: infrastructure configuration, integration of digital tracking and personalization tools, launch of logistics-related loyalty programmes (bonuses for choosing green delivery, flexible slots, etc.).

- Direct customer order fulfilment using three parallel modules: bonus and gift system (increasing the value of the experience); control and monitoring of deviations; prompt correction in case of problems.

- Collection of data on actual performance, analysis of deviations from planned values, assessment of the impact on different types of loyalty.

- Decision-making based on the 'sufficient/insufficient' principle. If target loyalty levels are achieved → transition to a new planning cycle with more ambitious goals. If the indicators are unsatisfactory → immediate implementation of corrective measures and return to the planning stage.

The algorithm functions as a continuous cycle, ensuring the gradual accumulation of loyalty and adaptation to changes in customer behavior, technological capabilities and sustainability requirements [1,6].

This approach allows marketing logistics to be viewed not as a support function, but as a strategic lever for building a sustainable competitive advantage through customer loyalty.

In today's economy, characterized by rapid digitalization, increased competition in e-commerce and growing demands for environmental responsibility, traditional approaches to marketing logistics no longer provide a sufficient level of competitiveness and customer retention [7]. That is why there is an urgent need to develop and implement innovative conceptual models that comprehensively combine digital technologies, sustainable development principles, and customer loyalty mechanisms.

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Our proposed Sustainable AI-Driven Marketing Logistics Model is an advanced conceptual approach that integrates artificial intelligence (AI) as a central optimization tool, sustainable development principles, and marketing strategies aimed at systematically increasing customer loyalty.

Figure 3 – Sustainable AI-Driven Marketing Logistics Model
Compiled by the authors

The relevance of the model is determined by several key trends in the modern market, namely:

- Accelerated digital transformation of logistics makes AI an integral part of demand forecasting, route optimization, delivery personalization, and ensuring real-time process transparency. Without AI integration, companies lose the ability to respond quickly to individual customer requests and offer competitive advantages in speed, accuracy, and convenience.

- The strengthening of sustainable development imperatives is transforming the environmental responsibility of logistics from an additional option to a mandatory factor in brand selection.

- The growing role of customer experience as the main driver of loyalty.

The novelty and advantages of the proposed model lie in its cyclical, continuous nature, where each stage of the model takes into account both tangible and intangible factors.

The model functions as a closed cycle of continuous improvement: data → forecasting → personalization and green integration → transparency and ethics → scaling → loyalty monitoring → correction → return to planning. This approach not only optimizes operational efficiency and reduces environmental impact, but also systematically builds customer loyalty, increases customer lifetime value, and creates sustainable competitive advantages.

Therefore, the development and implementation of the Sustainable AI-Driven Marketing Logistics Model is a relevant and necessary response to the challenges of the modern economy, where marketing logistics is becoming a strategic tool for combining digital efficiency, environmental responsibility, and a deeply customer-centric approach.

Conclusions. In today's environment of digital transformation and sustainable development, marketing logistics is becoming a strategic tool for building

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customer loyalty, where the key determinants are speed and reliability of delivery, personalization, transparency, proactive communication, environmental responsibility and effective problem solving. Traditional approaches no longer meet customer expectations, which reduces retention, trust, and customer lifetime value. The proposed Sustainable AI-Driven Marketing Logistics Model provides a systematic increase in loyalty and enhances the competitiveness of enterprises in conditions of uncertainty. Its cyclical nature allows for continuous improvement of processes, adaptation to change, and accumulation of trust and brand reputation, making marketing logistics a powerful strategic asset of the digital age.

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DIGITAL PLATFORMIZATION OF ENTERPRISE LOGISTICS ACTIVITIES: A BIBLIOMETRIC ANALYSIS OF THE STRUCTURING AND TRENDS OF GLOBAL RESEARCH

Nataliia Trushkina, Oleh Harmash, Yuliya Shkrygun. «Digital platformization of enterprise logistics activities: a bibliometric analysis of the structuring and trends of global research». *This article presents a comprehensive bibliometric analysis of global research on the digital platformization of enterprise logistics activities based on metadata extracted from the international scientometric database Scopus for the period 2006–2026. The purpose of the study is to identify the structural parameters of the scientific field, its dynamic evolution, sectoral composition, concentration of intellectual influence, and thematic clustering. To ensure the reproducibility of the findings, a formalized search design was implemented with precise specification of the query parameters, coverage period, and data export date.*

The study employs a two-block analytical approach. Block A (n=249) reflects the interdisciplinary structure of the research domain, whereas Block B (n=166) was constructed following thematic screening in order to ensure the subject validity of the logistics focus. The results demonstrate an exponential increase in the number of publications after 2019 and reveal a structural turning point in the development of the field associated with the diffusion of Industry 4.0 technologies, the scaling of platform architectures, and the growing attention to supply chain resilience.

The analysis identifies a core-periphery citation structure and a high concentration of intellectual influence within the field. Keyword cluster analysis using VOSviewer enabled the identification of five interrelated thematic domains: platform ecosystems in supply chain management; digital transformation and Industry 4.0; applications of artificial intelligence and machine learning in logistics; digital twins and cyber-physical systems; and blockchain as an infrastructure of trust and traceability. The findings are interpreted through the lens of platform economy theory and two-sided market theory, allowing digital platformization to be conceptualized as an institutional and technological mechanism for coordinating actors within logistics ecosystems.

The practical significance of the study lies in its potential application for designing strategies of digital transformation in enterprise logistics, developing models for integrating platform-based solutions into supply chains, and substantiating investment decisions in digital ecosystems. The generalized cluster structure facilitates the identification of key technological development trajectories and supports consideration of platform dependency risks, cybersecurity challenges, and data governance issues in the implementation of digital solutions.

Keywords: enterprise economics, digital platform, logistics platformization, logistics activities, logistics management, supply chain management, logistics costs, global logistics flows, risk management, digital transformation, Industry 4.0, platform economy, two-sided markets, digital ecosystem, bibliometric analysis, cluster analysis, artificial intelligence in logistics, digital twin, blockchain in supply chain management, customer relationship management strategy, omnichannel interaction, big data, digital infrastructure, geopolitical shock, economic crises, threats; uncertainty, sustainable development, globalization

Наталія Трушкіна, Олег Гармаш, Юлія Шкригун. «Цифрова платформізація логістичної діяльності підприємств: бібліометричний аналіз структуризації та трендів глобальних досліджень». У статті здійснено комплексний бібліометричний аналіз глобальних досліджень цифрової платформізації логістичної діяльності підприємств на основі метаданих міжнародної наукометричної бази Scopus за період 2006–2026 років. Метою дослідження є виявлення структурних параметрів наукового поля, його динаміки, галузевої композиції, концентрації інтелектуального впливу та тематичної кластеризації. Для забезпечення відтворюваності результатів застосовано формалізований дизайн пошуку з чіткою фіксацією параметрів запиту, періоду охоплення та дати експорту даних. У роботі використано двоблоковий підхід: блок А (n=249) відображає міждисциплінарну структуру тематики, тоді як блок B (n=166) сформовано після тематичного скринінгу для забезпечення предметної валідності логістичного фокусу.

Результати засвідчили експоненційне зростання кількості публікацій після 2019 року та структурний перелом у розвитку досліджень, пов'язаний із поширенням Industry 4.0, масштабуванням платформних архітектур і підвищенням уваги до стійкості ланцюгів постачання. Виявлено ядерно-периферійну структуру цитованості та високу концентрацію інтелектуального впливу. Кластерний аналіз ключових слів із використанням VOSviewer дозволив виокремити п'ять взаємопов'язаних тематичних напрямів: платформні екосистеми SCM; цифрова трансформація та Industry 4.0; застосування AI/ML у логістиці; цифрові двійники та кіберфізичні системи; blockchain як

інфраструктура довіри та трасованості. Отримані результати інтерпретовано через призму платформної економіки та теорії двосторонніх ринків, що дозволяє розглядати платформізацію як інституційно-технологічний механізм координації учасників логістичних екосистем.

Практична значущість дослідження полягає у можливості використання його результатів для формування стратегій цифрової трансформації логістичної діяльності підприємств, розроблення моделей інтеграції платформних рішень у ланцюги постачання та обґрунтування інвестицій у цифрові екосистеми. Узагальнена кластерна структура дає змогу ідентифікувати ключові технологічні напрями розвитку та враховувати ризики платформної залежності, кібербезпеки й управління даними під час впровадження цифрових рішень.

Ключові слова: економіка підприємства, цифрова платформа, платформізація логістики, логістична діяльність, логістичний менеджмент, управління ланцюгами постачання, витрати на логістику, глобальні логістичні потоки, ризик-менеджмент, цифрова трансформація, Industry 4.0, платформна економіка, двосторонні ринки, цифрова екосистема, бібліометричний аналіз, кластерний аналіз, штучний інтелект у логістиці, цифровий двійник, blockchain у SCM, CRM-стратегія, омніканальна взаємодія, Big Data, цифрова інфраструктура, геополітичний шок, економічні кризи, загрози, невизначеність, сталий розвиток, глобалізація

Introduction. The current stage of development of the global economy is characterized by the simultaneous intensification of globalization linkages and the reconfiguration of value chains under the influence of digital transformation, geopolitical shocks, and increasing logistical uncertainty. In this context, logistics can no longer be viewed as a purely operational function. It is evolving into a critical mechanism for ensuring enterprise competitiveness, facilitating access to international markets, and sustaining business process continuity. However, traditional models of organizing logistics activities are increasingly misaligned with the requirements of the global economy, where speed, data consistency, and decision-making flexibility have become decisive factors.

The rapid expansion of data volumes and digital interactions is reshaping the logic of coordination within supply chains. According to the United Nations Conference on Trade and Development [1], the digital economy accounts for more than fifteen percent of global gross domestic product, while digital platforms increasingly serve as infrastructures for value creation and redistribution in international markets. This indicates the systemic impact of digitalization on the structure of the global economy. Consequently, logistics, which integrates material and information flows, has become one of the central domains of platform-based transformation.

The transition from linear interaction schemes to platform-based coordination mechanisms, including digital matching, real-time dispatching, and integrated stakeholder interaction, necessitates a reconsideration of traditional management models. Expert assessments by McKinsey [2] confirm the scale of the potential benefits of digitalization: the implementation of the Supply Chain 4.0 concept may lead to up to a thirty percent reduction in operational costs through enhanced data transparency and process synchronization. Digital platforms therefore establish a qualitatively new level of manageability of logistics flows.

An additional argument arises from the transformation of global data flows. The McKinsey Global Institute [3] demonstrates that digital flows have become an independent driver of economic growth and international integration, with cross-border data transfers expanding multiple times over the past decade. This intensifies the demand for digital infrastructure solutions capable of

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scaling coordination across international logistics networks.

The growing uncertainty within global supply chains further highlights the importance of resilience and risk management. According to the Digital Trends in Supply Chain Survey conducted by PwC in 2023 [4], eighty-six percent of operations executives emphasize the necessity of investing in digital technologies for risk monitoring. The PwC Digital Factory Transformation Survey of 2022 [5] reports a sixty-seven percent increase in the share of companies identifying flexibility and resilience as key drivers of digital investment. These findings indicate that platformization represents a strategic response of business to an increasingly risk-intensive environment.

The World Bank, in its report Connecting to Compete 2023 [6], underscores that disruptions in global value chains have reinforced the critical role of logistics systems, with supply security and predictability emerging as strategic priorities. Within this framework, digital platforms are viewed as instruments for integrating physical and information flows, thereby enhancing transparency and accelerating international trade.

The Organisation for Economic Co-operation and Development [7] notes that online platforms are characterized by network effects, scalability, and reduced transaction barriers, which reshape market structures and competitive dynamics. For logistics, this implies a transition from localized optimization toward ecosystem-based interaction. Similarly, the DHL Logistics Trend Radar [8] identifies artificial intelligence, data analytics, and digital infrastructure as key drivers of logistics transformation in the coming years.

Therefore, the digital platformization of enterprise logistics activities constitutes an objective response to the structural challenges of the global economy, including data fragmentation, rising transaction costs, heightened risks, and the need for flexible coordination of international flows. Its study is both scientifically and practically significant for the development of effective mechanisms for transforming logistics systems in the digital era.

Literature and researches review. Digital platformization of enterprise logistics activities is interpreted in contemporary scholarly discourse as a multidimensional transformation process encompassing changes in business models, the restructuring of value chain architectures, institutional shifts, and the implementation of algorithmic governance. An analysis of relevant publications indexed in the Scopus database makes it possible to distinguish several interrelated theoretical and methodological strands, each emphasizing different dimensions of platform-driven transformation in logistics.

The first strand conceptualizes the digital platform as a mechanism for transforming the enterprise business model. P. Bajec et al. [9] demonstrate that the implementation of a business-to-business multimodal platform alters the structure of the Business Model Canvas, generating a new configuration of resources, channels, and value creation flows. R. Agarwala et al. [10] further develop this perspective by showing that digital business-to-business platforms reshape the architecture of value creation and value capture through the integration of search, matching, and transaction functions within a unified digital environment. O. Purba et al. [11] provide empirical evidence on the effectiveness of a national digital logistics ecosystem, identifying a statistically significant relationship between system and information quality and user satisfaction. Collectively, these studies conceptualize platformization as an instrument of strategic modernization in logistics management.

The second strand focuses on the institutional and structural consequences of platformization. S. Hardaker [12] analyzes the role of digital platforms in the formation of Digital Free Trade Zones, interpreting them as instruments of infrastructural power. V. Helwing, P. Verfürth, and M. Franz [13], as well

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as M. Franz, V. Helwing, and P. Verfürth [14], demonstrate that business-to-business platforms transform global production networks in logistics, influencing competitive structures and labor relations. In this context, the platform emerges not merely as a technological solution but as a mechanism for redistributing economic power within global value chains.

The third strand emphasizes algorithmic governance and socio-organizational aspects of platformization. F. De Stavola [15] introduces the concept of forced synchronization, illustrating how algorithms coordinate physical logistics processes. S. Haddad and N. Nasib [16] examine the impact of online platforms on the operational efficiency of logistics firms, while I. Ibrahim et al. [17] conceptualize digital logistics tools as elements of the communication infrastructure of public platforms.

The interdisciplinary nature of the phenomenon is confirmed by the work of K. Parker et al. [18], which demonstrates the universality of the platform-based coordination model across economic sectors. A macro-level theoretical generalization is proposed by O. Vyshnevskyi [19], who interprets digital platformization as an institutional mechanism for the strategic development of the national economy.

It should be noted that the authors' previous studies [20–23] concentrated on applied mechanisms of logistics digitalization, including smart contracts, digital customer relationship management solutions, and enterprise logistics management systems. The present research logically extends this body of work by moving from an instrumental perspective toward a systemic structuring of the global scientific field.

To synthesize the identified approaches, it is appropriate to compare them in terms of theoretical framework, level of analysis, and limitations (Table 1). The analysis demonstrates that the majority of studies exhibit a clearly delineated single-level orientation, focusing either on the micro level of business models, the meso level of production networks, or the macro level of institutional transformation. Cross-level integration remains limited.

Table 1. Comparison of Theoretical and Methodological Approaches

Representatives of Scholarly Schools	Theoretical Framework	Level of Analysis	Primary Focus	Limitations
P. Bajec et al.	Business Model Canvas	Micro	Business model transformation	Limited number of cases
R. Agarwala et al.	Value architecture	Micro	Value creation and capture	Single-case design
S. Hardaker	Infrastructural power	Macro	Geoeconomic influence of platforms	Regional specificity
V. Helwing et al.	Global Production Networks	Meso	Redistribution of value and labor	Qualitative design
F. De Stavola	Labour process theory	Micro	Algorithmic governance	Contextual localization

Source: compiled by the authors based on [9; 10; 12; 13; 15].

Further systematization makes it possible to structure scholarly approaches according to levels of transformation: technological, organizational, and institutional (Table 2). At the technological level, research predominantly concentrates on digital platform architectures and the algorithmization of processes [10; 11]. The organizational level encompasses the restructuring of business models and management mechanisms [9; 16]. The institutional level focuses on the

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redistribution of power and the transformation of global production networks [12–14; 19].

Table 2. Classification of Scholarly Approaches to the Digital Platformization of Enterprise Logistics Activities by Levels of Transformation

Level of Transformation	Nature of Change	Main Research Emphases	Representatives
Technological	Integration of digital infrastructure, process algorithmization, automation of flows	Artificial intelligence, blockchain, data integration, platform architecture	R. Agarwala et al.; O. Purba et al.
Organizational	Business model restructuring, transformation of logistics processes and management mechanisms	Value creation, business-to-business ecosystems, operational efficiency	P. Bajec et al.; S. Haddad & N. Nasib
Institutional	Redistribution of power, formation of new interaction rules, transformation of global production networks	Infrastructural power, labor relations, strategic governance	S. Hardaker; V. Helwing et al.; M. Franz et al.; O. Vyshnevskyi

Source: compiled by the authors based on [9–14; 16; 19].

Thus, contemporary scholarly discourse on the digital platformization of enterprise logistics activities is characterized by thematic heterogeneity and methodological fragmentation. The absence of a comprehensive quantitative analysis that integrates technological, organizational, and institutional dimensions while simultaneously reflecting the dynamics, geographical distribution, and institutional concentration of research justifies the application of bibliometric methods. This determines the logic of the subsequent empirical analysis based on the Scopus publication dataset.

Aim and objectives. The thematic heterogeneity and methodological fragmentation identified in the preceding sections indicate the absence of a comprehensive systematization of the global scholarly discourse on the digital platformization of enterprise logistics activities. Existing studies predominantly concentrate on specific technological, organizational, or institutional aspects of transformation, while an integrated understanding of the structure, developmental dynamics, and institutional concentration of scientific research in this field remains insufficiently developed. This

circumstance necessitates the application of quantitative analytical instruments for a comprehensive assessment of the evolution of the scientific domain.

The purpose of this study is to conduct a comprehensive bibliometric analysis of global research on the digital platformization of enterprise logistics activities in order to identify its structural characteristics, developmental dynamics, thematic clusters, and the geographical and institutional concentration of scholarly activity.

The achievement of this objective required the application of a set of interrelated *general scientific and specialized research methods*. At the theoretical level, methods of analysis and synthesis were employed to generalize existing approaches to the interpretation of digital platformization. In addition, the system approach was applied, enabling the phenomenon to be conceptualized as a multi-level process encompassing technological, organizational, and institutional dimensions of logistics system transformation.

The core empirical instrument of the study is the bibliometric method, which involves the quantitative processing and interpretation of a body of scientific

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publications indexed in the international scientometric database Scopus. Within the bibliometric framework, statistical analysis was applied to assess publication dynamics, calculate absolute and relative growth rates, and determine the structural distribution of documents by type, subject area, country, organization, and funding sponsor. Classical formulas for relative increase and compound annual growth rate were used to ensure the methodological validity and temporal comparability of indicators.

Keyword content analysis was employed to determine the subject structure of the research field and to identify dominant thematic directions. Network analysis, including co-occurrence analysis, co-citation analysis, and citation analysis, enabled the identification of intellectual linkages among authors, countries, and thematic clusters. Elements of cluster analysis were applied to group related research streams and to reveal the internal configuration of the scientific domain. The visualization of network structures was performed using VOSviewer software, which made it possible to map the intellectual architecture of the research field, assess the density of relationships among key concepts, and trace the evolution of research trends over time.

The integrated combination of these methods ensures not only the quantitative measurement of publication activity but also a structural interpretation of the development of research on the digital platformization of enterprise logistics activities within the broader context of global economic transformation.

Results, analysis and discussion. In this study, the platformization of enterprise logistics activities is conceptualized as the transfer of coordination and transactional functions of logistics to digital platforms that: (a) connect at least two distinct groups of participants, such as shippers, carriers, and warehouse operators; (b) enable the matching of demand and supply for logistics capacities; (c) standardize access rules, data structures, and interaction protocols through interfaces and regulatory frameworks defined as platform governance; and (d) generate network effects while creating conditions for ecosystem integration of services, including artificial intelligence analytics, digital twin technologies, and blockchain-based traceability, among others [24–27]. Such a theoretical framework makes it possible to interpret bibliometric findings not as a fragmented collection of technologies in logistics, but as evidence of the development of a platform-based infrastructure of logistics activities.

The bibliometric analysis was conducted using metadata extracted from the Scopus database. The search was performed within the TITLE-ABS-KEY field using the following query logic: (digital platform OR electronic platform OR platformization) AND (logistics activity), with the application of filters PUBSTAGE = final and LANGUAGE = English, and the exclusion of affiliations from the Russian Federation. The explicit specification of search parameters and the date of data extraction is essential for ensuring the reproducibility of bibliometric procedures, as indexing and metadata in Scopus are subject to change over time. This approach is consistent with established recommendations for transparent reporting of bibliometric research [28–30]. As a result, the initial dataset comprised 249 documents published between 2006 and 2026 (Table 3).

During the initial relevance screening, a systematic homonymy effect was identified. A portion of the documents entered the dataset due to references to logistic regression in a statistical context and physical activity within a health-related discourse.

This methodological issue is significant for two reasons. First, it directly affects the validity of logistics-related conclusions due to domain mixing. Second, it reveals the cross-domain nature of the platform category, as digital platforms constitute an infrastructural phenomenon applied across multiple sectors. For this reason, a dual-corpus design was implemented.

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Table 3. Scopus Search Parameters and Dataset Formation (n = 249)

Parameter	Description
Database	Scopus (Elsevier)
Search field	TITLE-ABS-KEY
Query logic	(digital platform OR electronic platform OR platformization) AND (logistics activity)
Filters	PUBSTAGE = final; LANGUAGE = English; EXCLUDE (AFFILCOUNTRY = Russian Federation)
Coverage period	2006–2026
Total records	249 documents

Source: compiled by the authors based on processing of the Scopus database.

Block A (n=249) was used to describe the boundaries of the interdisciplinary field, whereas Block B (n=166) was constructed for subject-specific analysis of the platformization of enterprise logistics activities after excluding health-dominant records and records where logistic was used in a statistical sense (Table 4). The selection logic is presented in a PRISMA format as an instrument for transparent reporting of bibliometric dataset refinement [31].

Table 4. PRISMA Reporting of the Formation of Blocks A and B

Stage	Number of Records	Comment
Identification: Scopus records after filters	249	Initial dataset (final stage; English; excluding Russian Federation)
Deduplication	0	Single database; duplicates not expected
Baseline bibliometric analysis	249	Block A (general overview of the field)
Additional thematic screening: logistics focus	83 excluded	Records where logistic refers to a statistical term or where health context dominates
Final Corpus (Block) A	249	Full dataset retained for transparency
Final Corpus (Block) B	166	Focused analysis of logistics platformization

Source: compiled by the authors based on processing of the Scopus database.

Accordingly, structural bibliometric characteristics, including document types, sources, countries, and citation patterns, are reported for Corpus A with explicit caution regarding the presence of health-related content. Thematic conclusions regarding logistics platformization are derived through keyword normalization, application of a VOSviewer thesaurus, and cluster interpretation with emphasis on the logistics core.

The distribution of document types (Table 5) reflects both the institutionalization of the topic and its technological dynamism. Journal articles account for 46.6 percent of publications, indicating the gradual formation of a theoretical and methodological core. At the same time, the substantial share of conference papers (30.5 percent) and conference reviews (8.8 percent) corresponds to the technological nature of digital platforms in logistics, where integration architectures, optimization algorithms, and Industry 4.0 modules are actively tested within conference settings before transitioning into journal publications for conceptual consolidation [28; 30]. It is also significant that citations are predominantly concentrated in journal articles and reviews, while conference materials receive comparatively lower citation counts. This pattern is typical of interdisciplinary technological fields and aligns with recommendations to interpret bibliometric influence through distributional analysis rather than relying solely on mean values [28; 30].

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Table 5. Distribution of Documents by Type

Document Type	Number	Share, percent
Article	116	46.6
Conference paper	76	30.5
Conference review	22	8.8
Book chapter	20	8.0
Review	6	2.4
Book	6	2.4

Source: compiled by the authors based on processing of the Scopus database.

The subject area distribution (Table 6) indicates that the technological core of the field is formed by Computer Science and Engineering. However, logistics platformization also demonstrates a pronounced organizational and economic dimension represented by Business, Decision Sciences, and Economics. This finding is consistent with platform theory, which conceptualizes platforms as institutional and technological environments. In logistics, a platform does not merely introduce information technologies; it establishes transaction rules, capacity access conditions, and data standards, thereby reshaping the coordination structure of supply chains through platform governance mechanisms [24–27]. The presence of Medicine (19.3 percent) in Corpus A empirically confirms the homonymy effect and justifies the use of Corpus B and keyword normalization for logistics-specific conclusions.

Table 6. Distribution by Scopus Subject Areas

Subject Area	Number of Documents	Share, percent
Computer Science	108	43.4
Engineering	87	34.9
Medicine	48	19.3
Social Sciences	48	19.3
Business, Management and Accounting	37	14.9
Mathematics	29	11.6
Decision Sciences	28	11.2
Economics, Econometrics and Finance	19	7.6
Environmental Science	17	6.8
Earth and Planetary Sciences	15	6.0
Energy	15	6.0

Note: The cumulative percentage may exceed one hundred because Scopus assigns a single document to multiple subject categories.
Source: compiled by the authors based on processing of the Scopus database

The temporal dynamics (Table 7) demonstrate a pronounced shift from sporadic publications to sustained growth after 2019. Importantly, 224 of 249 documents, approximately ninety percent, were published between 2019 and 2026, indicating the relative novelty of the domain in its contemporary configuration. The compound annual growth rate for the period 2006–2025 is approximately 23.8 percent, calculated by the authors based on Scopus data. The 2026 indicator does not reflect a genuine decline, as the dataset was extracted at the beginning of the year.

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Table 7. Dynamics of the Number of Publications (2006–2026) and Annual Growth Rates

Year	Number of Publications	Absolute Increase	Growth Rate, percent	Increase Rate, percent
2006	1	not applicable	not applicable	not applicable
2007	1	0	100.0	0.0
2008	3	+2	300.0	200.0
2009	0	−3	0.0	−100.0
2010	2	+2	not applicable	not applicable
2011	0	−2	0.0	−100.0
2012	0	0	not applicable	not applicable
2013	4	+4	not applicable	not applicable
2014	5	+1	125.0	25.0
2015	0	−5	0.0	−100.0
2016	2	+2	not applicable	not applicable
2017	3	+1	150.0	50.0
2018	4	+1	133.3	33.3
2019	15	+11	375.0	275.0
2020	16	+1	106.7	6.7
2021	23	+7	143.8	43.8
2022	27	+4	117.4	17.4
2023	29	+2	107.4	7.4
2024	45	+16	155.2	55.2
2025	58	+13	128.9	28.9
2026*	11	−47	19.0	−81.0

Note: For years with a base value equal to zero, growth rates are not calculated. The 2026 data reflect an incomplete year, as the dataset was extracted in February 2026.

Source: compiled by the authors based on processing of the Scopus database.

From an interpretative perspective, the structural shift observed after 2019 can be explained by the convergence of three processes: first, the technological maturation of platform architectures and application programming interface integration; second, the scaling of Industry 4.0 in manufacturing and logistics; and third, the growing emphasis on supply chain resilience, within which platforms are conceptualized as infrastructures of transparency, rapid coordination, and capacity allocation. During this period, logistics increasingly began to be interpreted as an ecosystem-based platform environment rather than merely a set of operations supported by information technologies [24–27].

To assess intellectual influence, citation indicators were applied, including total citation counts, median citation value, and the h-index according to the methodology proposed by Hirsch [32]. Within Corpus A, the dataset accounts for 4,745 citations, a median citation value of 1, and an h-index of 22 [32]. The citation distribution is highly asymmetric: ten percent of documents, representing twenty-five publications, accumulate 85.7 percent of all citations, whereas the lower fifty percent of documents account for only 0.53 percent of citations. Approximately 39.8 percent of documents have received no citations. The Gini coefficient for citation inequality equals 0.908, indicating an extremely high concentration of intellectual influence (Figure 1).

This distribution reveals a pronounced core–periphery structure within the field. A relatively small group of foundational publications shapes the theoretical language and conceptual framework of the domain, while a substantial proportion of works represent applied extensions or sector-specific adaptations [28; 30].

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For the specific topic of logistics platformization, this conclusion has an additional methodological implication. Within Corpus A, high citation counts are partially generated by publications from the health domain, which enter the dataset due to query homonymy. This underscores the necessity of distinguishing between impact and relevance. High citation performance does not automatically ensure substantive alignment with logistics. Therefore, key thematic conclusions are derived from Corpus B and from normalized keyword datasets to ensure domain-specific validity [28; 31].
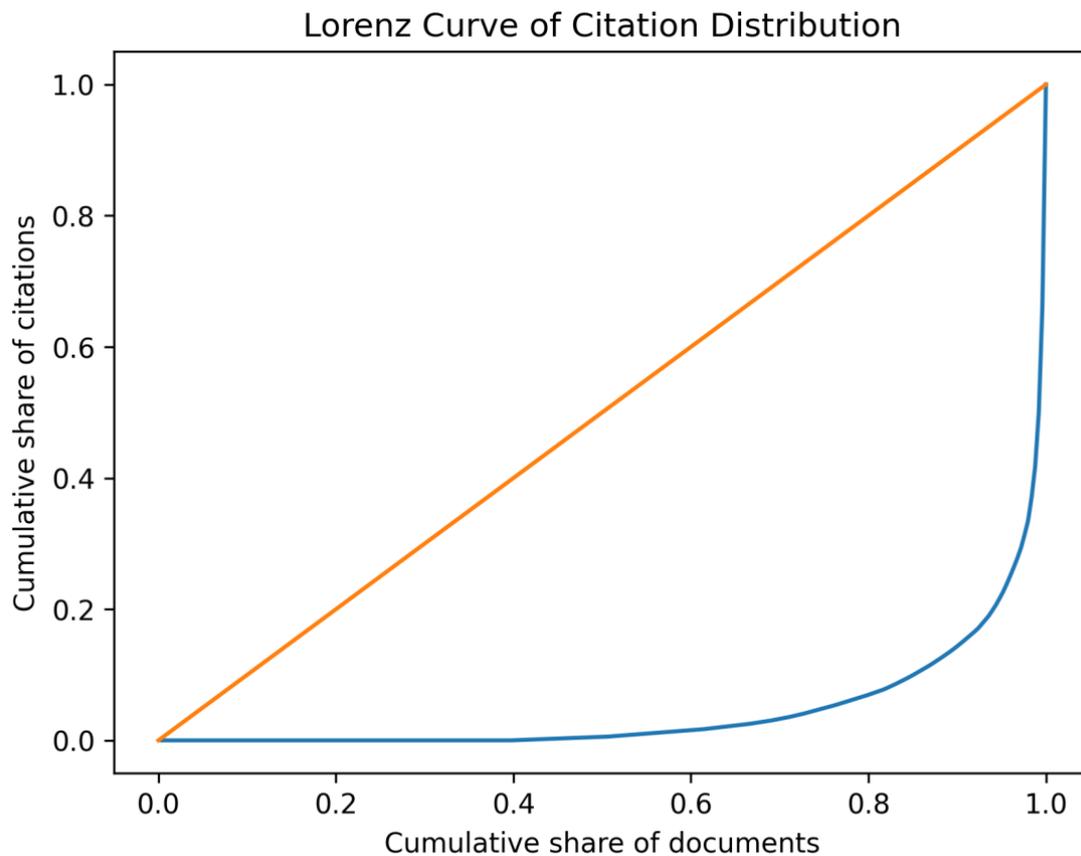
Figure 1. Lorenz Curve for the Distribution of Citations
Source: calculated and constructed by the authors based on processing of the Scopus database and with the use of artificial intelligence technologies.

The next analytical step involves the identification of knowledge centers through the analysis of source titles and the most highly cited publications. Table 8 demonstrates that, in terms of total citations, leading positions are occupied by journals that shape conceptual understandings of digital integration and platform-based coordination, such as MIS Quarterly. At the same time, highly cited health-oriented journals are also present, which confirms the homonymy effect within Corpus A (Table 8).

For logistics platformization, key foundational works within the dataset include studies on digitally enabled supply chain integration and reviews of blockchain applications in supply chain management. These publications conceptually explain how platforms create added value through data integration, enhanced transparency, and the reduction of coordination costs [33–35].

To avoid the methodological fallacy that equates high citation counts with logistics relevance, Table 9 presents the top ten most cited documents along with a concise interpretation of their thematic focus. This enables a clear distinction between foundational works directly relevant to supply

chain management platformization [33–38] and publications that entered the dataset due to homonymy within the health-related cluster.

Table 8. Leading Sources by Total Citations in Corpus A (n=249)

Source Title	Number of Documents	Total Citations	Interpretative Relevance
MIS Quarterly: Management Information Systems	1	1614	Methodological core of digitally enabled supply chain integration
Journal of Medical Internet Research	5	1011	Health cluster (homonymy); indirect relevance
IEEE Access	2	406	Review of blockchain solutions in supply chain management
JAMA – Journal of the American Medical Association	1	225	Health domain
Sensors	2	109	Industry 4.0 and digital twin context
Journal of Cleaner Production	1	104	Production and logistics risk models
Frontiers in Psychiatry	2	75	Health domain
Computers & Industrial Engineering	1	66	Applied manufacturing-logistics platform research
Computers and Electrical Engineering	1	62	Adjacent algorithmic domain
Sustainability	2	60	Broad sustainability discourse

Source: compiled by the authors based on processing of the Scopus database.

Table 9. Top 10 Most Cited Documents in Corpus A

Authors	Shortened Title	Year	Journal	Citations	Key Focus
A. Rai, R. Patnayakuni, N. Seth	Firm performance impacts of digitally enabled supply chain integration capabilities	2006	MIS Quarterly	1614	Digitally enabled supply chain integration; capability approach; performance impact
E. Kontos et al.	Predictors of eHealth usage…	2014	JMIR	759	eHealth platforms; digital divide (not logistics)
S.E. Chang, Chen Y.	When blockchain meets supply chain…	2020	IEEE Access	386	Blockchain in supply chain management; trust; traceability; smart contracts
C.K. Ra et al.	Association of digital media use…	2018	JAMA	225	Digital media platforms in health research (not logistics)
K.Parker et al.	The use of digital platforms for physical activity…	2021	JMIR	171	Physical activity; digital platforms (not logistics)
C.Z. Li et al.	A model for simulating schedule risks…	2018	J Cleaner Production	104	Risk modeling in production-logistics cycles
A. Martínez-Gutiérrez et al.	Digital twin for automatic transportation in Industry 4.0	2021	Sensors	94	Digital twin; automated guided vehicles; cyber-physical logistics systems
L. Giusti et al.	Everything Will Be Fine… on a digital platform	2020	Frontiers in Psychiatry	73	Mental health on digital platforms (not logistics)

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| D. Battini et al. | WEM-Platform… manufacturing and logistics systems | 2022 | Computers & Industrial Engineering | 66 | Real-time platform in manufacturing-logistics integration |
| V. Chang et al. | Digital payment fraud detection methods… | 2022 | Computers and Electrical Engineering | 62 | Machine learning methods; adjacent analytical domain |

Source: compiled by the authors based on [33–38].

The geographical structure of the field is particularly important for interpreting platformization, as digital platforms scale through network effects, integration standards, and transnational supply chains [24–27]. Table 10 indicates that the leading countries by publication volume are the United States, India, China, and Italy. In contrast, in terms of total citations, the leading positions are held by the United States, Taiwan, Australia, and Italy.

An important conclusion follows: productivity measured by publication count is not equivalent to intellectual influence. This discrepancy is partially explained by the extreme concentration of citation distribution and by time-lag effects, as older publications have had more time to accumulate citations [32].

Table 10. Top Countries by Publication Volume and Total Citations (n=249)

Countries by Publication Volume	Documents	Countries by Citation Count	Citations
United States	32	United States	2833
India	29	Taiwan	386
China	28	Australia	334
Italy	23	Italy	320
United Kingdom	12	China	275
Germany	9	United Kingdom	170
Malaysia	8	Hong Kong	166
Greece	6	Spain	107
Spain	6	Germany	97
Sweden	6	Malaysia	94

Source: compiled by the authors based on processing of the Scopus database.

The institutional funding context further confirms the dual structure of Corpus A. Among funding sponsors, both innovation-oriented European programs, such as the European Commission and Horizon 2020, and health-oriented institutions, including the National Institutes of Health and the National Health and Medical Research Council, are represented (Table 11). For substantive conclusions regarding logistics platformization, this reinforces the necessity of relying on Corpus B and on keyword normalization procedures.

Table 11. Top Funding Sponsors Supporting Research in the Selected Domain

Funding Sponsor	Documents	Share, percent
European Commission	6	2.41
National Institutes of Health	4	1.61
National Natural Science Foundation of China	4	1.61
CAPES	3	1.20
Horizon 2020	3	1.20
Horizon 2020 Framework Programme	3	1.20
National Health and Medical Research Council	3	1.20
VINNOVA	3	1.20

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| FCT (Portugal) | 2 | 0.80 |
| GACR (Czech Republic) | 2 | 0.80 |

Source: compiled by the authors based on processing of the Scopus database.

Because bibliometric maps are sensitive to metadata quality, keyword cleaning and normalization constituted a crucial analytical stage. The original Index Keywords in Corpus A contained dominant medical and social descriptors, such as female, male, human, as well as methodological markers including logistic regression, which distort the thematic interpretation of logistics platformization (Table 12).

To mitigate this effect, established recommendations for co-word analysis and thesaurus-based normalization in VOSviewer were applied: first, merging synonyms and alternative spellings, for example block-chain into blockchain, machine-learning into machine learning, and electronic commerce into electronic commerce; second, removing non-informative index terms such as human, male, female, adult, as well as purely methodological expressions such as logistic regression; and third, focusing thematically on the logistics core through the use of Corpus B [29]. A minimum frequency threshold was applied to ensure network interpretability. In practical terms, this means that dominant visible terms typically exhibit frequencies of approximately five occurrences or higher (Table 12).

Table 12. Most Frequent Terms Before and After Keyword Cleaning

Index Keywords "Before Cleaning"	Frequency	Author Keywords "After Cleaning" (Logistics Focus)	Frequency
female	45	machine learning	25
male	41	logistics	19
human	36	digital transformation	11
adult	35	blockchain	9
article	29	digital platform	8
information management	24	electronic commerce	7
adolescent	22	random forest	7
humans	20	fraud detection	7
young adult	18	artificial intelligence	6
logistic regression	18	supply chain	5
social media	18	deep learning	5
cross-sectional study	17	supply chain management	5
physical activity	16	digitalization	5
machine-learning	16	Industry 4.0	5
middle aged	16	digital twin	5

Source: compiled by the authors based on Scopus data and keyword normalization using VOSviewer tools.

As a result of the conducted analysis, several types of visualizations were generated using VOSviewer: cluster visualization representing the thematic structure; overlay visualization by average publication year; overlay visualization by average citation impact; density visualization highlighting areas of conceptual concentration; and country-level maps displaying citation intensity and network linkages. These visualizations are not merely illustrative elements but empirical instruments demonstrating how technological and managerial narratives converge within the concept of logistics platformization.

The cluster map (Figure 2) reveals two principal regularities. First, a distinct health-related cluster, including terms such as humans, female, male, and cross-sectional study, clearly emerges. This cluster directly reflects the homonymy effect and supports the methodological decision to construct

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Corpus B and normalize terminology. Second, within the logistics-digital segment, several interconnected contours become visible: an information and management contour, including information management, digital transformation, logistics, and electronic commerce; an algorithmic and analytical contour, comprising machine learning, learning systems, data mining, and predictive analytics; and an institutional and transactional contour centered around blockchain, trust, and traceability in supply chain management. This configuration corresponds to the theoretical logic of the platform ecosystem. A platform does not generate systemic effects without the integration of data and processes, decision-support analytics, and mechanisms of trust and compliance [24–27].
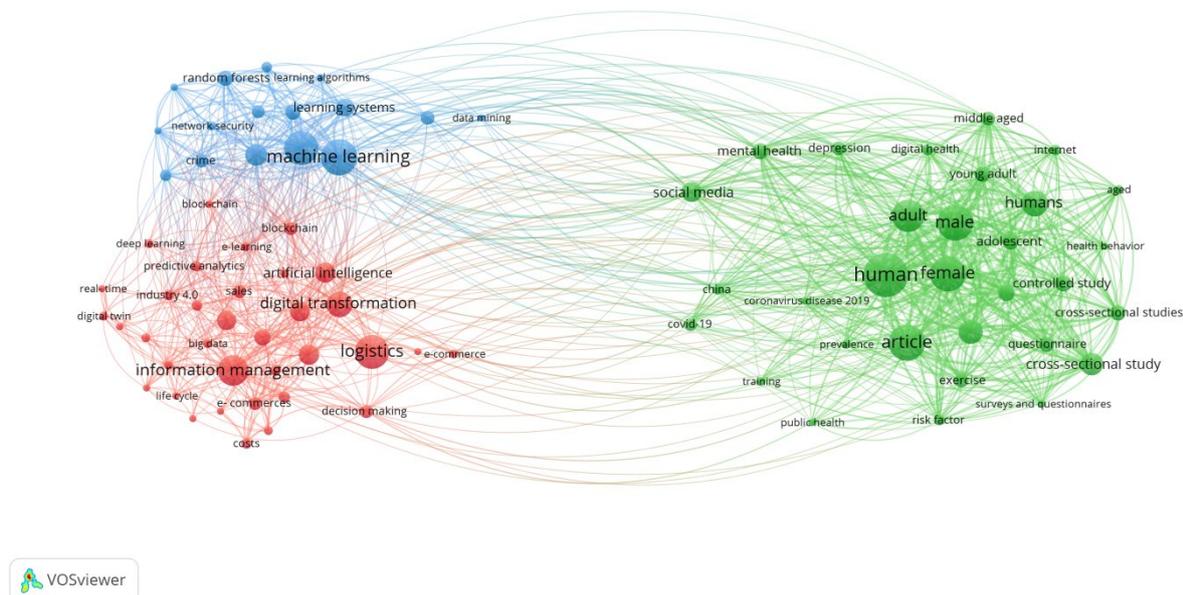

Figure 2. Keyword Co-occurrence Network
Source: constructed by the authors based on processing of the Scopus database using VOSviewer software.

The overlay visualization by publication year (Figure 3) indicates that the most recent terms are concentrated around algorithmic and digital infrastructure solutions, including terminology related to artificial intelligence and machine learning, Industry 4.0, and digital twin technologies. In contrast, a portion of the managerial and process-oriented vocabulary, such as information management, demonstrates an earlier average temporal appearance within the dataset. This pattern corresponds to the phase-based logic of platformization. In the initial phase, emphasis is placed on digital integration, particularly the structuring and synchronization of data architectures and information flows. In the subsequent phase, analytical, predictive, and cyber-physical modules are layered onto the platform environment as an advanced functional superstructure. Thus, the evolution of the research field reflects a transition from connectivity and interoperability toward intelligent automation, real-time analytics, and digitally synchronized logistics ecosystems.

Such temporal differentiation of terms confirms that logistics platformization is not a

single-stage technological adoption process but a cumulative transformation trajectory. The platform first establishes a standardized coordination infrastructure, and only thereafter enables the scalable deployment of artificial intelligence tools, digital twins, and advanced decision-support mechanisms within enterprise logistics systems.

Figure 3. Overlay Visualization by Publication Year
Source: constructed by the authors based on processing of the Scopus database using VOSviewer software.

The overlay visualization by citation impact (Figure 4) makes it possible to identify which terms are associated with higher average scientific influence. In the context of logistics platformization, these typically include concepts related to supply chain integration and infrastructures of trust, such as blockchain in supply chain management [34], as well as digitally enabled integration capabilities and their effect on firm performance [33]. These terms form part of the conceptual core of the field, linking technological infrastructure with measurable organizational outcomes.

The density visualization (Figure 5) further confirms the dual structure of the dataset. Two distinct density centers can be observed: a logistics-digital core and a health-related core. This empirical configuration methodologically justifies the dual-corpus

design, as it demonstrates that without thematic refinement the intellectual architecture of the field would be distorted by cross-domain contamination.

Geographical maps (Figure 6 and Figure 7) reveal the dominance of the United States as the principal citation hub, accompanied by secondary levels of activity in countries such as Italy, China, and India. The international collaboration network displays moderate connectivity: several relatively strong cross-national linkages are visible, yet the overall density of cooperation remains limited. This pattern is typical of emerging or technologically evolving domains, where a substantial proportion of research is grounded in local datasets, national digitalization programs, and the specific institutional characteristics of domestic logistics markets.

Taken together, these visualizations provide empirical evidence that logistics platformization is developing as a globally distributed yet structurally concentrated research field, characterized by a strong core of high-impact conceptual works, growing technological specialization, and still-maturing patterns of international scholarly collaboration.
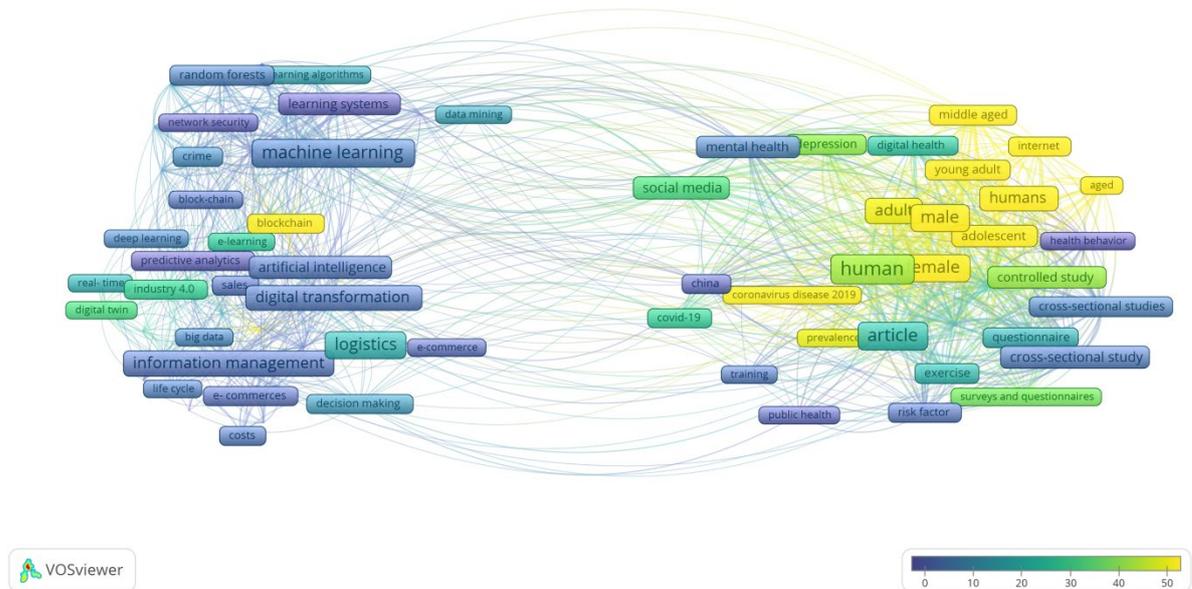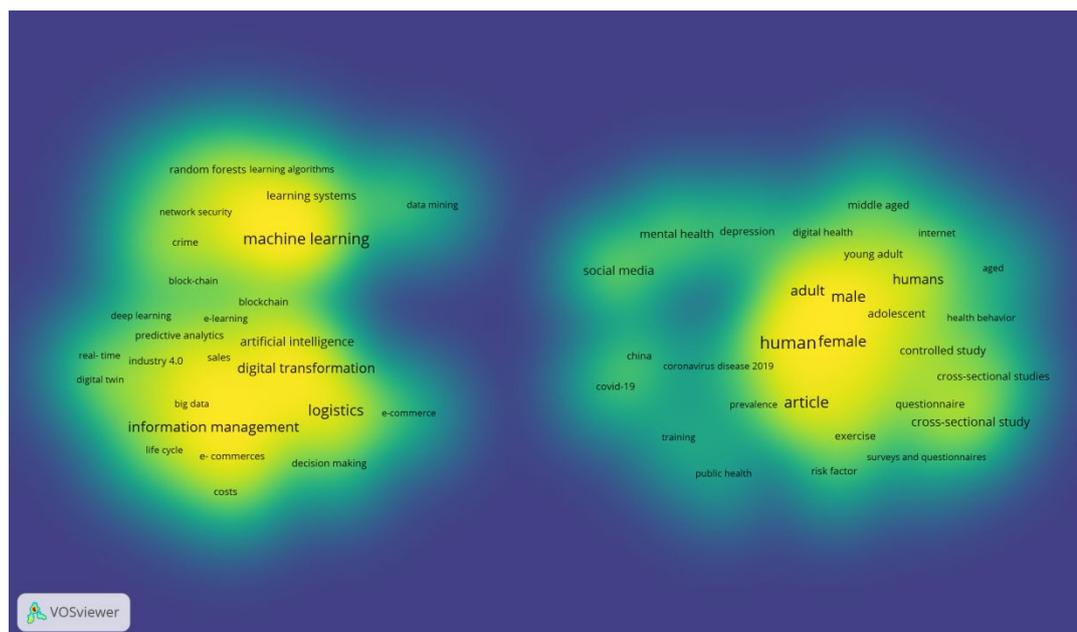

Figure 4. Overlay Visualization by Average Citation Impact of Terms
Source: constructed by the authors based on processing of the Scopus database using VOSviewer software.

Figure 5. Density Visualization of Keywords
Source: constructed by the authors based on processing of the Scopus database using VOSviewer software.

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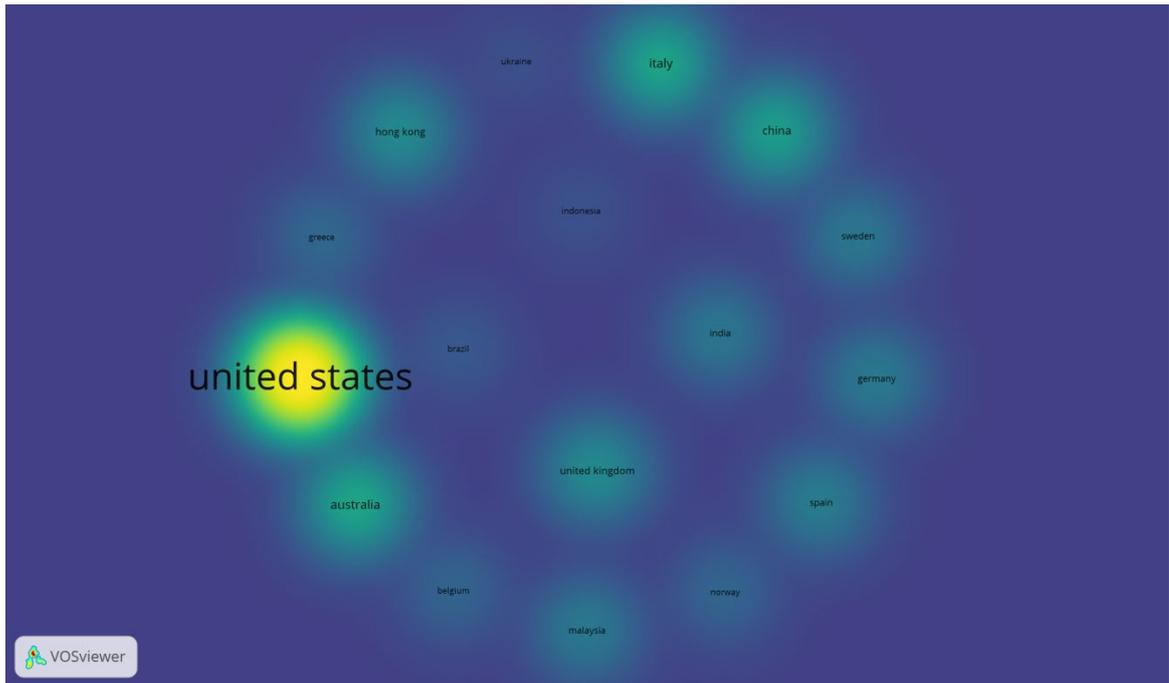ISSN 2708-3195

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Figure 6. Country Map by Total Citation Count
*Source: constructed by the authors based on processing of the Scopus database using VOSviewer
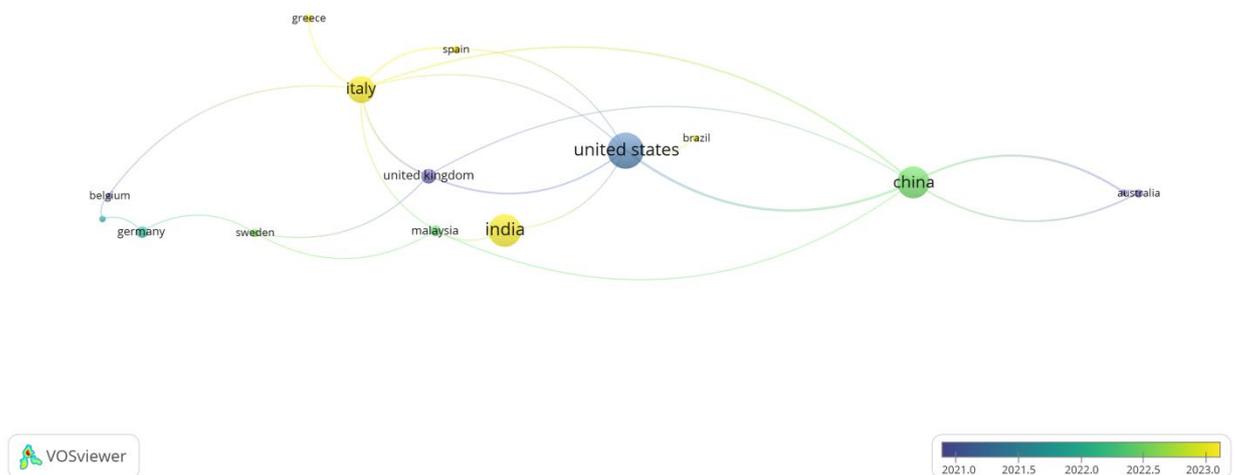software.*

Figure 7. Network of International Collaboration Among Countries
*Source: constructed by the authors based on processing of the Scopus database using VOSviewer
software.*

The thematic generalization of clusters is presented in Table 13, which provides a synthesized structure, and in Table 14, which contains a detailed analytical matrix. In combination with Figures 2–7, these results allow the platformization of enterprise logistics activities to be interpreted as an integrated ecosystem in which the platform performs the role of a coordination core, while artificial intelligence and machine learning technologies, digital twin systems, and blockchain solutions function as

complementary ecosystem modules that collectively generate value [24–27].

Accordingly, logistics platformization should not be reduced to a single technological instrument. Rather, it represents an architecture of data, rules, and services capable of scaling interaction among supply chain management participants.

Table 13. Thematic Clusters of Global Research on the Digital Platformization of Enterprise Logistics Activities (Co-word Analysis)

Cluster	Conceptual Core	Typical Keywords	Dominant Dimension	Central Research Questions
Platform logistics and supply chain management ecosystems	Platform as a mechanism of coordination, matching, and transactions in supply chains	digital platform; logistics; supply chain; marketplace; electronic commerce	Organizational and market	How do platform models transform coordination and access to logistics capacity?
Digital transformation and Industry 4.0	Process digitalization and system integration in supply chains	digital transformation; digitalization; Industry 4.0; data integration	Processual	Which data architectures generate measurable performance effects?
Artificial intelligence and machine learning in logistics	Forecasting and optimization based on platform data	machine learning; artificial intelligence; deep learning; predictive analytics	Analytical	How can forecast accuracy be improved and data quality managed?
Digital twin and cyber-physical systems	Simulation and management of physical flows	digital twin; simulation; automation; automated guided vehicles	Engineering	How can scenarios be tested and automation integrated?
Blockchain in supply chain management	Trust, traceability, and compliance	blockchain; smart contracts; traceability; trust	Institutional	How can data immutability and transparent accountability be ensured?

Note: Corpus A contains a health-related cluster as a consequence of query homonymy; logistics-specific conclusions are based on Corpus B and keyword normalization [31].
Source: constructed by the authors based on processing of the Scopus database using VOSviewer software.

Table 14. Detailed Matrix of Thematic Clusters in Logistics Platformization

Cluster Name	Conceptual Core	Dominant Dimension	Typical Research Questions	Practical Implications for Enterprises
Logistics platforms and service marketplaces	Multisided markets; matching; network effects; service-level agreements and ratings	Market and organizational	How does the platform alter partner selection, pricing structures, negotiation speed, and access to capacity?	Faster carrier and warehouse search; risk of platform lock-in; data access asymmetry
Supply chain integration as	Application programming interface	Processual and infrastructural	How can data compatibility across	Increased transparency and

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platform infrastructure	integration; interoperability; data standards; enterprise resource planning, warehouse management systems, transportation management systems, Internet of Things		supply chain actors be ensured? Which integration standards enable scalability?	controllability of flows; cybersecurity requirements; need for data governance
Artificial intelligence and machine learning enabled logistics	Demand and delay forecasting; route optimization; inventory management; machine learning operations	Analytical	How can model bias and drift be mitigated? How can platform data quality be secured?	Cost reduction and service improvement; risks of erroneous decisions and regulatory exposure
Digital twin and cyber-physical logistics	Digital twins; simulation; robotics; scenario management	Engineering	How can digital and physical systems be integrated? How can implementation scenarios be evaluated?	Reduced downtime and improved safety; high capital intensity and data requirements
Blockchain and trust in supply chains	Data immutability; traceability; smart contracts; compliance	Institutional and transactional	Which supply chain segments benefit from immutable records? How can solutions be scaled?	Reduced disputes and counterfeiting; integration and interoperability challenges
Platform risks and cybersecurity	Fraud detection; security by design; privacy; access management	Managerial	How can risks of platform dependency and data leakage be managed? How can secure platforms be designed?	Increased resilience; additional cybersecurity and compliance costs

Source: constructed by the authors based on processing of the Scopus database using VOSviewer software.

The obtained results allow logistics platformization to be conceptualized as a transition from localized digitalization initiatives to an ecosystem-based coordination infrastructure. The structural shift observed after 2019 indicates that the scholarly field increasingly conceptualizes platforms not as isolated online tools but as environments in which data, processes, and transactions in supply chain management are systematically coordinated.

Within the framework of platform economy theory, this corresponds to the expansion of multisided markets for logistics services and the strengthening of network effects [24–25]. From the perspective of ecosystem theory, it reflects the emergence of a network of complementary services,

including analytics, automation, identification, and compliance, orchestrated around the platform as a central node [26–27]. From an institutional perspective, the platform functions as a governance mechanism: it establishes data standards, access rules, and trust infrastructures, thereby reshaping bargaining positions within the supply chain and potentially generating platform lock-in, data asymmetry, and new forms of risk.

The cluster results and VOSviewer maps demonstrate that technological directions such as artificial intelligence and machine learning, digital twins, and Industry 4.0 do not operate in isolation. Instead, they form an integrated package of platformization. In practical terms, the effectiveness of logistics

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platformization emerges only when three components are simultaneously implemented: first, integration of data and processes across supply chain systems; second, analytical manageability based on platform data; and third, trust, traceability, and compliance in transactions, including blockchain-enabled mechanisms [33–36]. In this sense, the logistics platform constitutes not only a technological infrastructure but also an organizational one, transforming contracting practices, planning procedures, dispatching, service quality control, and data exchange.

At the same time, several limitations define the boundaries of generalization. First, the analysis is based exclusively on the Scopus database, and thus reflects the structure of the field within this indexing system; certain regional or specialized publications may remain unindexed. Second, the English language filter may lead to underrepresentation of research published in national languages. Third, the homonymy of the terms logistic, activity, and platform generates interdisciplinary noise; although a dual-corpus design was implemented, residual cross-domain contamination may persist. Fourth, citation indicators are subject to time lag effects: publications from 2024 to 2026 have not yet had sufficient time to accumulate citations, and comparisons between recent and older works require caution. Fifth, clustering results in VOSviewer depend on inclusion thresholds, normalization procedures, and parameter settings; alternative configurations could alter cluster boundaries, although the overall thematic architecture remains stable. Finally, bibliometric analysis describes the structure of scientific discourse but does not directly measure the economic effects of platformization, such as cost reduction, productivity gains, or supply chain resilience, and therefore requires further empirical validation.

Future research should integrate bibliometric mapping with empirical models assessing the performance effects of logistics platformization. Priority directions include evaluation of platform impact on key performance indicators, including cost efficiency, lead time, reliability, service level, and resilience; analysis of risks related to platform dependency and data asymmetry; modeling of governance mechanisms within supply chain platforms, including access rules and interoperability standards; investigation of the integration of artificial intelligence, machine learning, and digital twins as the operational intelligence layer of the platform; and assessment of the economic feasibility of blockchain-based trust infrastructures in specific supply chains. Such a transition from bibliometric description to empirical verification will enable not only the mapping of knowledge structures but also the identification of causal relationships between platformization and enterprise logistics performance.

Conclusions. In today's environment of digital transformation and sustainable development, marketing logistics is becoming a strategic tool for building customer loyalty, where the key determinants are speed and reliability of delivery, personalization, transparency, proactive communication, environmental responsibility and effective problem solving. Traditional approaches no longer meet customer expectations, which reduces retention, trust, and customer lifetime value. The proposed Sustainable AI-Driven Marketing Logistics Model provides a systematic increase in loyalty and enhances the competitiveness of enterprises in conditions of uncertainty. Its cyclical nature allows for continuous improvement of processes, adaptation to change, and accumulation of trust and brand reputation, making marketing logistics a powerful strategic asset of the digital age.

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