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Ptytsia N.V., Ptytsia H.Hr.
Kharkiv National Automobile and Highway University, Kharkiv, Ukraine

THE ROLE OF ARTIFICIAL INTELLIGENCE IN BUILDING ADAPTIVE AND SUSTAINABLE SUPPLY CHAINS

The article explores the role of artificial intelligence (AI) in the digital transformation of logistics systems. It highlights the practical benefits of AI integration, including optimization of supply chain management, predictive demand modeling, reduction of operational costs, increased delivery speed, and improved customer service quality. Particular attention is given to the contribution of AI to sustainability by analyzing CO_2 emissions, supporting the use of alternative fuels, optimizing packaging cycles, and providing tools for ESG-oriented strategies. The study also identifies new professional roles emerging within logistics, such as logistics data analysts, AI system architects, digital twin engineers, and specialists in AI ethics in supply chains. At the same time, challenges related to data unification, cybersecurity, standardization of APIs, and compliance with regulations on automated data processing are underlined. From an engineering perspective, successful AI implementation requires compatibility of hardware and software infrastructure, reliable communication channels, and protection against cyberattacks. The article emphasizes that the effectiveness of AI deployment depends not only on technology availability but also on organizational maturity, readiness for change, and data-driven decision-making culture. It is concluded that logistics of the future will evolve into an intelligent ecosystem where human and artificial intelligence complement each other, forming autonomous, adaptive, and sustainable supply chains, thus strengthening global competitiveness and resilience in conditions of uncertainty.

Keywords: artificial intelligence, supply chain management, digital transformation, sustainability, predictive analytics, automation.

INTRODUCTION

Over the past decades, logistics has undergone significant transformation, evolving from a supporting business function into an independent field of knowledge and a technological platform that determines both the competitiveness of companies and the efficiency of global markets. Its technical evolution is characterized by the widespread implementation of cyber-physical systems, digital twins, automation solutions, and integration with information platforms capable of self-learning and autonomous management [1]. In this context, logistics is no longer limited to the coordination of material flows. It has become a complex adaptive network that operates in real time, utilizing big data analytics, predictive algorithms, intelligent information processing systems, and autonomous robotic devices that interact with each other through open communication protocols.

LITERATURE REVIEW AND PROBLEM STATEMENT

Modern logistics processes are built upon automated warehouses, autonomous vehicles, transportation management systems (TMS), warehouse management systems (WMS), as well as advanced telemetry, which includes real-time monitoring of transportation conditions, object location, and equipment technical status [2]. From the perspective of engineering system integration, logistics today represents a combination of physical infrastructure, hardware-software complexes, network environments, and control algorithms that function as a unified intellectualized system with elements of decentralized management. Such systems enable enterprises to achieve flexibility, adaptability, and high levels of customer service in an unpredictable environment of global risks. Another important trend in the technological development of logistics is the proliferation of IoT solutions that ensure full digital visibility of the supply chain. According to [1], more than 70 % of logistics companies in Europe and the USA already employ IoT devices to monitor cargo, equipment, and routes. Sensors measuring temperature, humidity, pressure, and spatial positioning are integrated directly with pallets, containers, or cargo platforms, thereby creating a distributed sensor network with the capability of dynamic real-time data acquisition. The collected information is transmitted via 5G or LTE-M networks to cloud computing environments or edge devices, where it is pre-processed prior to further analysis [1, 3, 4]. All the collected information forms the foundation of analytical modules, enabling anomaly detection, failure prediction, route optimization, and minimization of cargo spoilage risks. Large manufacturing and transportation enterprises increasingly adopt digital twins – precise virtual replicas of real objects or processes – which make it possible to model various behavioral scenarios of logistics systems without physical intervention. Major logistics corporations actively apply such digital models for simulating port operations and managing railway logistics at the interregional level. All these components constitute part of a new engineering paradigm in logistics that requires deep automation, interoperability, and adaptive management [3, 5]. Another significant vector of technological development in the industry has been the introduction of autonomous mobile platforms and robotic systems in warehouses. Solutions based on AMR (Autonomous Mobile Robots) and AGV (Automated Guided Vehicles) are employed in leading logistics hubs, including Amazon, DHL, FedEx, and XPO Logistics [4, 6]. Robots perform automated pallet delivery, barcode scanning, cargo transportation between warehouse zones, and interaction with sorting systems. Collaborative robots (cobots), particularly those operating within hybrid human-machine systems, help reduce the workload on personnel and increase the accuracy of operations. The programming of such robots is carried out through visual learning modules and reinforcement learning algorithms, which make them adaptable to changing environmental configurations.

PURPOSE AND OBJECTIVES OF THE STUDY

The purpose of this study is to analyze the role of artificial intelligence in the transformation of logistics systems, to identify the benefits and challenges of its integration, and to outline prospects for building sustainable and adaptive supply chains.

RESEARCH RESULTS

The automation of logistics operations in transportation has also reached a new level. Many countries are conducting pilot projects in autonomous truck management (TuSimple, Einride, and Aurora), integrating computer vision, LIDAR, GPS, deep learning, and real-time environmental modeling [7]. Such solutions enhance the efficiency of long-haul transportation, especially under driver shortages. The development of drones for last-mile delivery, although limited, is gaining traction. In the United States, giants such as Walmart and UPS already carry out regular deliveries of small cargoes to rural areas using AI-enabled navigation drones, reducing operating costs by 30–40% compared to traditional methods.

However, despite the impressive progress of automation, artificial intelligence itself has become the system-forming element of modern technical logistics. Its implementation enables the creation of adaptive, self-organizing, and self-optimizing logistics networks capable of responding to changes in real time without human intervention. Machine learning algorithms, neural networks, deep learning, fuzzy logic, and heuristic methods have become fundamental tools for analysis and decision-making in environments characterized by a high number of variables. Demand forecasting systems based on LSTM and XGBoost achieve high accuracy even under unstable markets and seasonal fluctuations, which is critically important for distribution centers. Further integration of artificial intelligence in logistics is being implemented through intelligent route management systems, which account for numerous real-time variables—including traffic conditions, weather, technical specifications of vehicles, customer service time windows, and delivery constraints. Dijkstra's algorithms, genetic algorithms, Q-learning, as well as deep neural networks can generate optimal routes that simultaneously minimize costs and prioritize service requirements [8]. Such systems are already in use by global operators: UPS applies its ORION (On-Road Integrated Optimization and Navigation) platform, which, according to reports, saves the company over 100 million miles of travel annually and reduces fuel consumption by 10 million gallons. Amazon, FedEx, and DHL are actively testing solutions for autonomous route selection, combining GPS monitoring with predictive analytics and machine learning systems for environmental recognition.

Artificial intelligence is also widely applied in inventory management, particularly in demand forecasting, service level evaluation, safety stock management, and order generation. The use of algorithms such as ARIMA, Prophet, CatBoost, and LSTM significantly reduces forecasting errors compared to traditional statistical methods. For instance, by implementing AI-based demand forecasting systems, companies can reduce excess inventory by approximately 30–35 % while simultaneously decreasing stockouts on retail shelves by around 20 % [3, 4, 6]. Furthermore, integrated AI-based platforms can automatically generate orders in ERP systems, taking into account time periods, service levels, multi-warehouse logic, and minimum supply lots.

In the field of vehicle and logistics equipment maintenance, the concept of predictive maintenance is being increasingly adopted, based on the analysis of IoT sensor data combined with machine learning methods. This approach enables the reduction of equipment downtime by up to 40%, lowers service costs by 25–30 %, and extends equipment lifespan [9]. Logistics centers of major technology corporations have implemented equipment condition monitoring systems with AI modules that generate alerts before a critical wear threshold is reached. One of the key directions of development is the implementation of the «control tower» concept, which ensures centralized coordination of logistics processes based on artificial intelligence [8, 10]. Such systems aggregate data from all levels of the logistics chain: GPS positioning, order statuses, vehicle load indicators, transportation conditions, warehouse data, customs clearance, payment processing, and more. AI-powered analytics capabilities are used to detect critical deviations, predict disruptions, and automatically generate recommendations or decisions. Through cognitive modules built on fuzzy logic, these systems are capable of making decisions under uncertainty, even when data is incomplete or contradictory.

Blockchain is also finding wide application as a complement to artificial intelligence systems. It provides transparency and trust among logistics stakeholders by creating an immutable chain of records on product origin, routing, and condition [11]. In combination with AI analytics, blockchain enables real-time cargo tracking, supply source verification, and automatic execution of smart contracts, which, in turn, trigger subsequent actions – such as shipment from an alternative warehouse in the event of a delay. IBM Food Trust and VeChain are examples of platforms that integrate AI and blockchain to enhance transparency and decision-making speed. Recent developments increasingly utilize generative models that are capable not only of analyzing but also of creating new behavioral scenarios for logistics systems. In particular, large language models (LLMs) such as GPT are used for generating logistics documentation, modeling routes, communicating with suppliers through virtual assistants, and managing tender processes. Moreover, generative models are applied in the visualization of current and forecasted conditions in transport corridors, risk assessment related to supplier changes or country of origin, and the creation of simulations for new supply chain configurations.

Growing interest is also directed toward the concept of AIoT (Artificial Intelligence of Things), which involves the integration of artificial intelligence directly at the edge-device level [3, 5, 6, 10]. This allows data processing without transmission to the cloud, thereby reducing latency and enhancing autonomy. In logistics, this is particularly relevant for warehouses, ports, and transportation systems where decision-making within milliseconds is critical. For example, edge-AI modules are used in drones for navigation, in autonomous robots for decision-making within distribution centers, and in monitoring devices that process images or detect anomalies in real time without reliance on a central server.

It is also important to highlight the contribution of artificial intelligence to enhancing the environmental sustainability of logistics systems. AI algorithms analyze CO_2 emissions, identify routes with the lowest ecological footprint, and model the use of alternative fuels and electric transport. Companies oriented toward ESG strategies employ AI to assess environmental impact, build sustainability reporting, reduce waste disposal costs, and optimize packaging circulation.

DISCUSSION OF RESEARCH RESULTS

Alongside technological development, there is a growing demand for professionals capable of integrating, maintaining, and advancing AI solutions in logistics. This has led to the emergence of new professions: logistics data analyst, logistics AI systems architect, digital twin engineer, and AI ethics specialist in supply chains. At the same time, companies face a number of challenges, including data unification, cybersecurity, API standardization, compliance with national regulations on personal data processing, and automated management.

Despite the existing barriers, the trends of AI adoption in logistics remain irreversible. Commercial benefits such as cost reduction by 15–35 %, order processing acceleration by 25–40 %, forecast accuracy improvement up to 95 %, and flexibility in adapting to changing market conditions stimulate investors, governments, and the scientific community to continue integration efforts. Clearly, logistics is no longer merely a technical system but a digitally intelligent environment where machine agents collaborate with humans in decision-making, creating the foundation for self-regulated supply chains of the future.

Thus, against the backdrop of deep digital transformation, logistics emerges as a complex adaptive system evolving through the interaction of digital technologies, automation, intelligent solutions, and self-learning algorithms. Artificial intelligence, in particular, serves not only as a tool for productivity enhancement but also as a catalyst for a paradigm shift in supply chain management – from reactive to proactive, from manual to automated, from isolated to integrated. Modern solutions make it possible to manage logistics assets effectively in a dynamic environment, forecast demand, optimize routes, reduce losses, improve customer service quality, and strengthen the environmental sustainability of business operations. From an engineering standpoint, the integration of artificial intelligence into logistics represents a complex technical challenge that requires compatibility of hardware (edge devices, sensors, robotic platforms), flexibility in configuring software infrastructure, high reliability of data transmission channels, protection against cyberattacks, and compliance with data processing regulations. At the same time, the advancement of artificial intelligence in logistics systems necessitates a rethinking of planning methodologies, staff retraining, and the creation of hybrid teams consisting of logisticians, data analysts, security specialists, model developers, and managers capable of systemic team-oriented thinking under technological complexity.

The effectiveness of AI implementation depends not only on the availability of relevant technologies but also on the organizational maturity of enterprises, their readiness for change, strategic vision, and data-driven decision-making culture. The logistics of the future is not simply an automated warehouse or a self-driving truck – it is an ecosystem in which human intelligence is augmented by artificial intelligence, ensuring the capacity for continuous adaptation, learning, improvement, and development.

CONCLUSIONS

The expansion of artificial intelligence applications in logistics will enable the formation of fully autonomous supply chains, where all operations – from demand generation to final delivery – will be coordinated in real time with minimal human intervention [12]. Under such conditions, enterprise competitiveness will be determined not only by the availability of vehicles or warehouse capacity but also by the ability to create digital logistics platforms with powerful analytics, advanced decision-making algorithms, and deep integration with global data networks. The integration of artificial intelligence into logistics is no longer a prospect but a present reality that is transforming the technological landscape, economic approaches, environmental standards, and management practices. The successful use of these technologies will determine the level of national innovation capacity, business efficiency, supply chain continuity, and market stability under global challenges.

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Птиця Н.В., Птиця Г.Г. **Роль штучного інтелекту у формуванні адаптивних і сталих ланцюгів постачання**

У статті розглянуто роль штучного інтелекту (ШІ) у цифровій трансформації логістичних систем. Проаналізовано практичні переваги впровадження ШІ, зокрема оптимізацію управління ланцюгами постачання, прогнозування попиту, зниження операційних витрат, підвищення швидкості доставки та покращення якості обслуговування клієнтів. Особливу увагу приділено внеску ШІ у забезпечення екологічної стійкості, аналізу викидів CO_2, підтримці використання альтернативних видів палива, оптимізації циклів пакування та інструментам для ESG-стратегій. Визначено нові професійні напрями у сфері логістики, серед яких – аналітик даних, архітектор AI-систем, інженер цифрових двійників і фахівець з етики використання ШІ у ланцюгах постачання. Окреслено основні виклики, пов'язані з уніфікацією даних, кібербезпекою, стандартизацією API та дотриманням регламентів щодо автоматизованої обробки даних. Підкреслено, що ефективність використання ШІ залежить не лише від доступності технологій, а й від організаційної зрілості підприємства.

Ключові слова: логістика, штучний інтелект, управління ланцюгами постачання, цифрова трансформація, екологічна стійкість, прогнозна аналітика, автоматизація.

ПТИЦЯ Наталія Василівна, кандидат технічних наук, доцент кафедри транспортних систем і логістики, Харківський національний автомобільно-дорожній університет, Харків, Україна, e-mail: nataliya.ptitsa@gmail.com. https://orcid.org/0000-0002-4559-7651

ПТИЦЯ Геннадій Григорович, кандидат технічних наук, доцент кафедри організації і безпеки дорожнього руху, Харківський національний автомобільно-дорожній університет, Харків, Україна, e-mail: gennadij.ptitsa@gmail.com. https://orcid.org/0000-0002-5061-0144

PTYTSIA Natalia, Ph. D. of Engineering, Associate Professor at the Transport Systems and Logistics Department, Kharkiv National Automobile and Highway University, Kharkiv, Ukraine, e-mail: nataliya.ptitsa@gmail.com. https://orcid.org/0000-0002-4559-7651

PTYTSIA Hennadii, Ph. D. of Engineering, Associate Professor at the Department of Traffic Management and Safety, Kharkiv National Automobile and Highway University, Kharkiv, Ukraine, e-mail: gennadij.ptitsa@gmail.com. https://orcid.org/0000-0002-5061-0144

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