SECTION 2.
Artificial Intelligence and Digital Technologies as Drivers of Economic Transformation and National Security

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2.1. DIGITAL TECHNOLOGIES AND ARTIFICIAL INTELLIGENCE IN THE MODERN ECONOMIC ENVIRONMENT

Introduction. The modern economy is undergoing rapid transformation driven by the widespread adoption of digital technologies and artificial intelligence (AI). These innovations are reshaping the business landscape, altering workflows, and influencing consumer behavior. The implementation of digital solutions enables enterprises to streamline operations, enhance customer experience, and tap into new market opportunities. At the same time, AI unlocks powerful tools for data analysis, forecasting, and decision-making automation – substantially boosting organizational efficiency. However, alongside these advantages, digitalization also brings forth challenges such as cybersecurity risks, data privacy concerns, and the need to adapt to shifting labor market demands.

Digital transformation is redefining the economic landscape. Through cutting-edge technologies, businesses are able to automate production, reduce costs, and increase productivity. AI, in particular, has emerged as a driving force behind modern economic development, fundamentally changing traditional business models and management approaches. Its applications span a wide array of sectors – from finance and manufacturing to market analytics and risk management. Beyond automating routine tasks, AI fosters the creation of innovative business models, contributing directly to economic growth.

Modern machine learning algorithms, neural networks, and big data processing tools empower both companies and public institutions to optimize costs, enhance performance, and deliver personalized solutions to customers. As a result, artificial intelligence is no longer just a novel technology but a critical factor of global competitiveness.

A review of recent academic literature highlights the growing interest in the economic implications of digital technologies and AI, both in domestic and international scholarly discourse. Prominent global studies, including those by McKinsey, PwC, and the World Economic Forum, emphasize AI's impact on productivity, labor market transformation, and business process automation. Researchers such as Gmainer R., Holey Y., Doverny P., Drik I., Likarchuk N., Qin Y., Tsesliv O., and Harper M. argue that AI is set to profoundly reshape various sectors – from manufacturing to services – through automation, efficiency improvements, and increased labor productivity [1; 2; 3; 5; 7; 8].

To fully harness the potential of AI in the economy, it is essential to address associated regulatory, social, and technological challenges.

Key research findings. The integration of digital technologies and artificial intelligence significantly enhances corporate competitiveness by automating operations, reducing costs, and improving product and service quality. The use of big data analytics enables businesses to forecast demand, optimize production processes, and manage resources more efficiently.

Nations that actively embed AI into their economic systems gain considerable advantages, as this technology helps to create new markets, disrupt conventional business models, and fuel innovation.

China and the United States remain at the forefront of AI research and implementation, granting them the ability to set global technological standards.

One of the key trends in shaping contemporary research priorities is the growing interest in systems based on artificial intelligence (AI). AI significantly enhances human capabilities by enabling the analysis and processing of vast amounts of data. When provided with high-quality input, AI systems can interpret information, draw data-driven conclusions, and generate accurate economic forecasts.

Artificial intelligence has become a powerful driver of economic development due to its innovative potential and broad applicability across various industries. Automation, data analytics, and machine learning are critical tools for improving productivity and reducing operational costs. For example, in the industrial sector, robotic systems lower labor expenses and minimize human error, resulting in higher product quality. In the service industry, AI technologies – particularly chatbots – enhance customer interactions, increasing satisfaction and stimulating demand.

Digital technologies and AI open up promising opportunities for the creation of innovative products and services, facilitating the emergence of new markets and economic sectors. In the financial domain, for instance, AI-driven algorithms allow for more accurate creditworthiness assessments, which reduce lending risks for banks and promote broader access to credit. Thus, the application of AI not only improves existing processes but also accelerates economic growth through innovation and the development of new industries.

Artificial Intelligence (AI) is a branch of computer science focused on developing programs and systems capable of performing tasks that typically require human intelligence [1].

These tasks include data analysis, decision-making, learning, speech recognition, and object identification. AI is generally categorized into two main types:

– weak AI, designed to perform specific tasks within a narrow scope;

– strong AI, a theoretical concept referring to systems that could think and learn on par with humans.

Machine learning, a subfield of AI, enables algorithms to independently detect patterns in data and improve their performance over time without explicit programming [1].

Neural networks are computational models designed to mimic the functioning of the human brain, consisting of interconnected artificial neurons [1].

Digital technologies represent a comprehensive set of contemporary tools, approaches, and solutions based on the use of computer systems, network infrastructures, and algorithms for data processing, storage, and transmission.

This category includes artificial intelligence, cloud computing, blockchain, the Internet of Things (IoT), big data analytics, and other innovations that facilitate automation and enhance efficiency across various sectors of the economy and society [3].

The primary areas of influence of digital solutions include:

– automation and robotics integration – reducing the need for manual labor by leveraging advanced technologies;

– development of financial technologies – simplifying financial transactions through blockchain, digital wallets, and electronic payments;

– growth of e-commerce – transforming consumption patterns and prompting businesses to shift toward online sales models;

– internet of things (IoT) – improving monitoring systems and optimizing operational equipment costs.

Looking ahead, the continued advancement of digital solutions is expected to drive further improvements in economic performance and overall quality of life.

In the context of the economy, artificial intelligence is classified according to its level of autonomy and functional capability into narrow AI, general (strong) AI, and artificial superintelligence.

The structure of AI encompasses key technological domains that enable its operation, including machine learning, natural language processing, computer vision, robotic systems, and process automation.

AI can be analyzed through the lens of its integration into business environments:

1) by level of integration into business processes:
- intelligent analytics systems;
- automated financial decision-making tools;
- AI-driven assistants in marketing and sales;
- logistic and production optimization algorithms;

2) by industry-specific applications:
- banking – risk assessment, credit management;
- retail – personalized recommendations, inventory control;
- logistics and transportation – route optimization, autonomous delivery systems;
- healthcare – diagnostics using big data, personalized treatment plans;
- public administration – forecasting economic trends, analyzing social data [4].

This classification provides valuable insight into how AI is transforming economic processes, enhancing business models, and creating new opportunities for enterprises.

Despite its vast potential, the application of artificial intelligence in the economy is accompanied by several critical challenges:
- lack of regulatory frameworks – many countries do not yet have clearly defined legal standards for AI use in financial and economic sectors;
- job displacement – automation may reduce employment in certain industries, necessitating the development of workforce reskilling and retraining programs;
- data security and ethical concerns – AI systems handle massive volumes of information, raising risks related to privacy violations and misuse of personal data;
- low levels of digital literacy – many organizations face a shortage of skilled professionals with the expertise required to effectively implement AI into business operations [2].

Overcoming these challenges will contribute to the more effective use of artificial intelligence (AI) in the economy, expanding its capabilities and ensuring the sustainable development of various sectors.

Despite its numerous advantages, the digitalization of the economy is not without its obstacles:

– the growing threat of cyberattacks, which calls for stronger cybersecurity measures;

– the widening digital divide between developed nations and developing countries;

– the need for innovative approaches to the regulation of digital environments;

– social and ethical concerns surrounding the use of AI and the collection of personal data [8].

According to forecasts by International Data Corporation (IDC), the implementation of AI is expected to significantly strengthen the global economy, contributing approximately $19.9 trillion to global GDP by 2030. The projected contribution of this technology is anticipated to rise from $1.2 trillion in 2024 to $4.9 trillion by 2030.

As reported in the "2024 Cloud and AI Business Survey", companies that actively invest in AI are already seeing a positive impact on key business metrics. Among leading adopters, this effect ranges from 59 % to 82 % [5].

Data from Eurostat (2023) confirm that a substantial proportion of companies in the European Union are integrating AI into their business processes. The highest levels of implementation are observed in the information and communication technology (ICT) sector.

Research indicates that countries at the forefront of AI adoption – the United States, China, and EU member states – are experiencing accelerated economic growth. This trend is primarily driven by increases in labor productivity and the dynamic development of innovation ecosystems. Over the past five years, AI technologies have reached a considerable level of maturity, transitioning from the phase of inflated expectations to practical deployment, which underscores their reliability and effectiveness.

An analysis of the global economic impact of AI reveals that by 2030, the largest economic gains are projected in China and North America. The anticipated contribution of AI to GDP in these regions is estimated at 26.1 % for China and 14.5 % for North America (figure 1) [5].

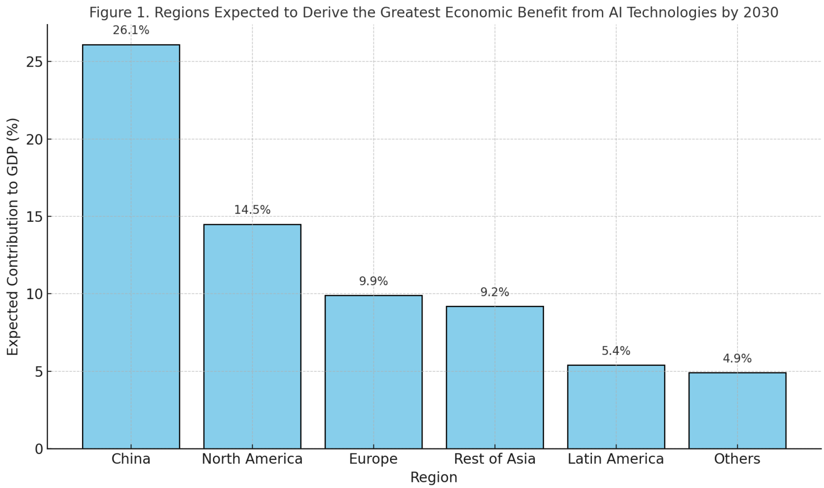

Figure 1. Regions expected to gain the greatest economic benefits from artificial intelligence technologies by 2030

Source: [5]

These projections are based on the results of a comprehensive dynamic economic model of the global economy, which takes into account inter-sectoral linkages and supply chains.

Accordingly, the implementation of AI is anticipated not only to stimulate economic growth but also to unlock new opportunities for business process optimization, enhance operational efficiency across enterprises, and contribute to the establishment of global technological standards.

In examining the regions forecasted to benefit the most from the adoption of artificial intelligence, it is essential to focus more closely on the economic sectors likely to undergo the most significant transformations. Currently, four key areas stand out: industry, the corporate sector, the tax system, and the labor market [2].

The specific applications of AI within the economy are presented in Table 1.

Table 1

Features of artificial intelligence use in the economy

Feature	Description
Process automation	Artificial intelligence can automate both routine and complex tasks, significantly improving operational efficiency
Big data analysis	AI processes large volumes of data at high speed and accuracy, surpassing human capabilities
Personalization	AI enables the creation of personalized offers and products, enhancing customer experience
Forecasting	AI delivers accurate forecasts of market trends, demand levels, and key economic indicators
Resource optimization	The application of AI contributes to more efficient resource allocation, particularly in logistics
Digital assistants and chatbots	AI-powered assistants and chatbots provide timely customer support and improve service responsiveness
Financial analysis and trading	AI performs complex financial computations, conducts market analysis, and automates stock trading
Risk management	AI supports risk assessment and management, particularly in lending and investment activities
Fraud reduction	AI helps detect and prevent fraudulent activities in the financial sector
Innovation and product development	AI drives technological innovation and accelerates the launch of new solutions to the market

Source: [2]

Artificial intelligence possesses considerable potential to enhance the efficiency of economic processes. Its integration into supply chain management, financial operations, and marketing strategies contributes to the development of more flexible and adaptive business models. Government institutions can also leverage AI to improve financial governance, automate tax administration, and enhance the forecasting of macroeconomic indicators.

Moreover, artificial intelligence opens new horizons for entrepreneurship and startups, enabling the creation of innovative products powered by machine learning and advanced algorithms.

Often, such startups operate within a specific industry: medicine, education, law or finance. This is where the greatest effect of automation is observed. For example, in the medical field, AI is used to decipher research results or predict disease risks, in finance – to combat fraud and speed up KYC checks, and in education – to create individual learning trajectories.

One of the important factors for the success of such startups is close integration into real business processes. These are no longer universal bots that understand everything, but narrowly focused tools that perform their function more efficiently than a person or allow you to significantly reduce time spent.

Startups focused on applied AI solutions are becoming increasingly important players in the technology market. They are not only creating new products, but also influencing the transformation of entire industries – from healthcare to law. Thanks to their flexibility, innovation and ability to quickly respond to user needs, these companies are shaping a new era of artificial intelligence.

And it is startups that turn powerful models into understandable and useful applications that can become the real drivers of this transformation.

Looking ahead, digital technologies and AI are expected to continue playing a pivotal role in shaping economic trends, including:

– expanded automation capabilities – the use of intelligent systems will increasingly extend across various sectors, from healthcare to industrial production;

– emergence of new professions – growth in occupations related to the development, deployment, and oversight of digital and AI-driven solutions;

– advances in cybersecurity – the creation of more secure algorithms and data protection mechanisms to safeguard digital infrastructure;

– transformation in education – the adaptation of curricula to meet the demands of the digital economy, along with the growth of AI-driven e-learning platforms;

– innovations in economic forecasting – the use of AI to conduct deeper market analysis and to design more effective business strategies;

– development of smart cities – the implementation of AI technologies for efficient urban infrastructure management, reduced energy consumption, and improved quality of life [7].

Conclusion. Digital technologies and AI serve as fundamental drivers of today's economy, equipping businesses with powerful tools to grow, boost productivity, and improve service quality. The integration of such solutions into business processes allows companies to remain competitive amid rapidly evolving market conditions. However, digital transformation also requires a careful approach to security, ethical considerations in AI use, and the establishment of effective regulatory frameworks. In the future, the digital economy is expected to offer even greater opportunities for development, benefiting both business and society as a whole. Thus, technological advancement not only fuels economic growth but also reshapes business practices, making them more efficient and innovation-oriented.

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2.2. DIGITAL TRANSFORMATION OF EXPORT-IMPORT ACTIVITIES THROUGH DISTRIBUTED TRACING

Introduction. In the context of growing globalization, the dynamic development of international trade, and the increasing complexity of supply chains, implementing digital technologies that enhance transparency, efficiency, and reliability in foreign economic activity has become critical. Among such innovative solutions, particular attention is drawn to distributed tracing, a digital system for tracking goods and operations based on distributed ledger technologies, primarily blockchain. Blockchain is a key tool for ensuring the integrity and reliability of data circulating within supply chains. Its integration eliminates critical vulnerabilities in exchanging information between counterparties while providing high transparency, traceability, and transaction security.

One of the leading sectors where blockchain has been widely applied is supply chain management, particularly in international trade, where issues such as product origin identification, logistics route control, and fraud prevention are highly relevant [1]. A notable example of the practical implementation of blockchain solutions is *Walmart's* experience. In February 2024, it reported that integrating blockchain technologies into its business processes enabled more than 200 million transactions totaling USD 2 billion during 2023 [1]. This case demonstrates the high potential of digital technologies in enhancing the efficiency of foreign trade activities and building trust among participants in global supply chains. These achievements illustrate the technological feasibility and the practical relevance of blockchain-based tracing systems in addressing key inefficiencies of modern trade logistics and governance.

Export-import activity today represents a vital component of the global economy, supporting the flow of goods and services across countries and fostering the development of international trade, increasing economic interdependence, and deepening integration. However, modern supply chains in international trade face several serious challenges, including high transaction costs, lack of transparency, difficulty in quality standards compliance, and fraud risks. The ability to accurately and reliably identify product origin, monitor logistics routes, and document key transactions in the supply chain is essential within export-import operations. Therefore, introducing digital distributed tracing systems can help eliminate fraud risks, optimize logistics processes, ensure compliance with quality standards, and improve interaction among all supply chain stakeholders.

Given digital transformation trends, OECD member countries are actively implementing digital tracking systems [2]. An illustration of the growing adoption of distributed tracing in international trade is presented in [3], which proposes a logistics system based on the Internet of Things (IoT) and blockchain for monitoring high-value international shipments. Another example is in [4], which develops a real-time blockchain-based monitoring and tracking system for cross-border shipments, addressing challenges posed by the COVID-19 pandemic. The system ensures transparent communication among delivery participants and reliable data storage. The European Union's experience in developing "green" blockchain platforms that integrate environmental sustainability, low energy consumption, and a high level of data protection is of particular academic value. Study [5] demonstrates the effectiveness of distributed ledger technology (DLT) for real-time carbon certificate monitoring. Implementing such technology ensures traceability, ownership validation, and auditing of trading records, thus contributing to enhanced transparency, fraud reduction, and regulatory compliance – factors critical for the sustainable development of digital trading platforms.

Ukrainian scholars also increasingly focus on digital technologies such as blockchain, IoT, and robotic process automation. In particular, study [6] demonstrates the potential of these modern technologies to optimize logistics processes by reducing costs and increasing productivity radically. The authors propose actively implementing innovative solutions in Ukraine's logistics sector to address pressing industry challenges and improve its efficiency and competitiveness under globalization. This approach represents an essential step toward Ukraine's integration into global supply chains, where transparency, automation, and precise tracking are key success factors. The author [7] also substantiates the need to apply blockchain technology in supply chains when forming foreign economic strategies for enterprises. The study emphasizes that blockchain can offer an optimal solution for ensuring traceability across global supply chains, enabling just-in-time practices in an ethically sound manner. Such digital technology adoption in Ukraine is a crucial step toward improving the effectiveness of export-import operations and integrating the country into international trade networks. Study [8] focuses on digitalizing international trade through blockchain implementation and highlights the legal challenges that Ukraine must address. The author emphasizes that blockchain supports optimizing administrative procedures, including certification, customs clearance, data exchange, and automating obligations through smart contracts. However, realizing these benefits requires legislative adaptation, particularly in defining the legal status of blockchain solutions, data protection, liability for data processing, dispute resolution, and recognition of electronic documents.

Thus, amid the active adoption of digital technologies in international trade processes, the scientific and practical relevance of research on distributed tracing is becoming increasingly evident. As global economies undergo digital transformation, especially in export-import operations, ensuring transparency, security, and operational efficiency across complex and often fragmented supply chains becomes critically important. Distributed tracing technologies, particularly those based on blockchain and the Internet of Things (IoT), present innovative solutions enabling real-time tracking and verifying goods and transactions throughout the supply chain. These technologies contribute to reducing fraud and mitigating logistical risks and play a significant role in building trust, enhancing data integrity, and facilitating seamless coordination among diverse stakeholders in international trade ecosystems. As such, distributed tracing is emerging as a key driver of modernization and resilience in global trade infrastructure.

This study aims to explore approaches to implementing distributed tracing in export-import operations, focusing on identifying and analyzing key aspects that ensure the effective adoption of this technology.

Presentation of key research findings. In recent years, significant attention in academic circles has been devoted to implementing distributed tracing across various sectors. Given the substantial potential of these technologies, they have become the subject of intensive investigation within the framework of international research projects and scholarly studies.

One of the primary topics actively explored in this context is the application of one of the core distributed tracing technologies – blockchain – for *tracking goods in international supply chains*. For instance, study [9] focuses on analyzing the integration of blockchain technology into supply chains and logistics processes, aiming to examine blockchain platforms and their input data as innovative solutions for managing supply chain business operations, particularly in cargo tracking, product authentication, and identification. The authors employ three research methods: expert interviews, comparative analysis of blockchain platforms, and market analysis by components, providers, and usage types. The study also analyzes the 50 largest companies globally (according to Forbes) that utilize blockchain in their supply chains to assess the benefits of transparency, reliability, traceability, and cost-efficiency. The results demonstrate that blockchain significantly enhances operational efficiency, reduces costs, and increases process reliability within supply chains, especially when implemented via platforms such as Hyperledger

Fabric and Ethereum. Study [10] addresses the challenge of complex inter-organizational interaction arising from information asymmetry, weak traceability, and low efficiency in traditional centralized supply chains. To resolve these issues, the authors propose a blockchain-based supply chain system. Using a trade and information chain platform, the study constructs a unified system architecture that standardizes data exchange formats to ensure stability and efficiency in inter-organizational collaboration. The presented experimental results confirm that the system not only fulfills the core functions of a supply chain but also significantly improves information exchange among participants. Study [10] further explores the potential of distributed tracing in the food industry, where inefficiencies and corruption frequently impede effective product tracking. Implementing blockchain technology in this domain enables complete transparency and traceability at every stage of the supply chain, which is particularly critical for food safety. As a continuation of the ideas presented in [10], study [11] elaborates on blockchain-enabled distributed tracing as a means not only to eliminate corruption and inefficiencies but also to enhance the management of food supply chains significantly. By tracking each delivery stage precisely, particularly in food production and distribution, blockchain ensures high data security, prevents product counterfeiting, and mitigates risks to end consumers. Moreover, distributed tracing enables prompt responses to product quality or safety issues, a vital component of food security strategies. Study [11] also demonstrates that adopting this technology can reduce logistics costs, decrease food waste, and promote sustainable development through more efficient resource utilization across supply chains.

In summary, the reviewed studies highlight the strong potential of blockchain technology for implementing distributed tracing in supply chains, particularly within international trade contexts. The examined approaches demonstrate the effectiveness of blockchain-based solutions in ensuring data transparency and integrity, enhancing the efficiency of logistics operations, and reducing operational costs.

A set of key criteria was identified to compare traditional tracking methods and blockchain technologies in international supply chains, based on the analysis of publications [3 – 11]. These criteria include: transparency, security, data processing speed, cost, scalability, interoperability issues, crisis resilience, environmental sustainability, real-time tracking, and international legal regulation. Together, these criteria enable a comprehensive assessment of the technical, economic, legal, and ecological aspects of both approaches to logistics management.

Transparency is crucial in ensuring access to reliable information about each stage of the supply chain, which reduces the risk of fraud and improves the enforcement of trade agreements. Transparency reflects the degree to which information is accessible to all supply chain participants. In traditional systems, transparency is limited due to the local storage of data and the reliance on trust between parties. In contrast, blockchain provides a decentralized and immutable ledger, where all transactions are available in real time [3; 4; 6].

Security in logistics processes is critical for mitigating the risks of counterfeiting, theft, and unauthorized data modifications. Traditional methods rely on centralized databases and paper-based documentation, which introduces potential vulnerabilities. Blockchain employs cryptographic mechanisms and consensus protocols, significantly enhancing system trustworthiness [3; 7; 8].

Data processing speed affects decision-making agility and overall supply chain efficiency, particularly in the fast-paced international trade environment. Paper-based workflows and multi-level verification often slow down data and transaction processing in traditional systems. Integrating smart contracts in blockchain enables automation of validation procedures, significantly accelerating logistics operations [3; 4; 6].

Costs related to the implementation and maintenance of tracking systems are also an important criterion. Although blockchain technologies may require substantial initial investments, they provide long-term savings through automation and reducing human error. Traditional models incur high costs for documentation, verification, and intermediary involvement. Blockchain reduces these costs by streamlining processes and eliminating intermediaries [5; 9].

Scalability defines the capacity of a system to adapt to increasing volumes of transactions and evolving requirements, which is critical in global supply chains. Traditional tracking methods are constrained by centralized information systems or paper records, which often lack transparency and precision. Blockchain transforms this landscape by distributing data across multiple nodes, preserving records immutably, and enabling automatic validation via smart contracts. It proves effective for small-scale tracking and high-volume monitoring in global logistics, thus demonstrating strong scalability suitable for large-scale international operations [3; 9; 10].

Interoperability issues between systems are also key in comparing traditional and distributed tracing approaches. Data entry errors, human mistakes, and manipulation risks are common in centralized systems. Distributed tracing minimizes these risks by employing automation, reducing human intervention, and relying on transparent and immutable records, enhancing data reliability, security, and trust. Blockchain supports standardized protocols and automated control mechanisms that reduce interoperability challenges [4; 6; 11].

Crisis resilience has become increasingly significant due to global challenges such as the COVID-19 pandemic and armed conflicts. Centralized systems are prone to disruptions, while the decentralized architecture of blockchain ensures process continuity and robustness [4].

Environmental sustainability is gaining recognition as an essential factor in logistics operations. Traditional methods often involve excessive paper use and inefficient delivery routing. Blockchain, especially with IoT technologies, contributes to emission reduction and resource optimization [3; 5; 10].

Real-time tracking is essential for monitoring goods in transit, managing risks, and improving customer service. Traditional systems may not offer timely updates, whereas blockchain, particularly when integrated with IoT sensors, enables real-time status updates and enhanced visibility across the supply chain [3; 10; 11].

International legal regulation is another critical consideration, especially given the complexity of cross-border trade and differing legal frameworks. Traditional systems often struggle to align with diverse jurisdictional requirements. Through smart contracts, blockchain can partially automate compliance with international legal norms and agreements [8].

Thus, the selected comparison criteria allow for a comprehensive evaluation of blockchain-based logistics solutions' technical and economic dimensions and their alignment with current global challenges and sustainable development goals.

A summary of the results of the comparative analysis of key criteria that characterize the effectiveness of traditional versus blockchain-based approaches to managing international supply chains is presented in Table 1.

Table 1

Comparison of traditional tracking methods and blockchain technology in international supply chains

Criterion	Traditional Tracking Methods	Blockchain Technologies
1	2	3
Transparency	Limited, often reliant on the trustworthiness of supply chain participants; data is fragmented.	High transparency; all participants have access to immutable records in real time.
Security	Risk of data falsification, loss, or tampering.	Cryptographically secured data; each transaction is digitally signed.
Data processing speed	Slow due to manual processing, paperwork, and verification steps.	Automated verification through smart contracts enables instant processing.
Costs	High due to document handling, verification procedures, and intermediary involvement.	Reduced costs through process automation and decentralization.

Continuation of Table 1

1	2	3
Scalability	Limited by system overload when participant numbers increase.	High scalability; capable of efficient operation under growing volumes.
Interoperability issues	High risk of errors due to human factors and incompatible systems.	Error minimization through automation; unified interaction standards.
Crisis resilience	Vulnerable to external disruptions (e.g., pandemics, wars, cyber threats).	High resilience is enabled by a decentralized and distributed data architecture.
Environmental sustainability	Use of paper documentation and inefficient logistics routing.	Process optimization, reduced resource consumption, and support for green logistics.
Real-time tracking	Delays in information updates; lacks continuous monitoring.	Continuous monitoring is enabled by IoT integration, which provides rapid response to status changes.
International legal compliance	Difficult to adapt to diverse jurisdictions; requires multi-step alignment.	Smart contracts can be tailored to meet varying legal requirements across countries.

Source: compiled by the author based on [3–11]

Thus, analyzing traditional tracking methods and blockchain technologies in international supply chains has demonstrated that blockchain represents an innovative tool that significantly enhances transparency, security, data processing speed, scalability, and the resilience of logistics systems to external shocks. In contrast to traditional centralized models, blockchain provides a decentralized architecture with immutable records, automated smart contracts, and the capability for 24/7 real-time cargo monitoring. Moreover, adopting this technology reduces transaction costs, minimizes human error, improves environmental efficiency, and enhances legal adaptability in cross-border operations. Therefore, integrating blockchain solutions into logistics processes forms a foundation for developing reliable, adaptive, and sustainable supply chains in the context of the digital transformation of international trade.

At the same time, it is essential to note that in the context of distributed tracing in export-import operations, attention should be directed toward supply chains and other dimensions that influence the effectiveness and sustainability of international trade activity. While supply chains are a key component for blockchain implementation, being directly linked to the transparency, traceability, and security of goods and services throughout their movement, it is necessary to consider other critical elements for unlocking the full potential of distributed tracing technologies in global commerce.

One such element is the *interoperability* of various tracking platforms and systems operating within international trade. Distributed tracing technologies can enable effective information exchange among diverse supply chain participants, even when these entities operate on distinct technological infrastructures. This ensures the stable performance of all elements in the supply chain, allowing for reliable data exchange between businesses, governments, and other stakeholders. In article [12], a model is proposed to facilitate interoperability between different blockchain systems in supply chains, addressing the challenge of interaction across digital platforms. This model enables asset tracking at various supply chain stages through cryptographic verification and standardized data formats, thereby reducing the need for data duplication. It fosters efficient data exchange across blockchain networks, enhancing transparency and security. The proposed model holds strong scalability potential in pharmaceuticals and the food industry, owing to its ability to preserve interoperability and seamless information exchange among different platforms. The approach outlined in the study [13] also marks an essential step toward improving interoperability among various blockchain systems within logistics supply chains. Specifically, the authors highlight the challenges posed by private blockchains, which, despite ensuring high data security, create new barriers to information exchange due to restricted data access for companies operating at lower supply chain tiers. Using private set intersection protocols, combined with blockchain technology, balances security and effective data sharing. This allows lower-tier participants to access necessary data without compromising confidentiality or requiring excessive data disclosure. Such an approach supports the development of more flexible and interconnected ecosystems, where blockchain networks can be effectively integrated to facilitate real-time information exchange, essential for the dynamic adjustment of production planning and other logistical processes. In this context, the advancement of distributed tracing and the assurance of complete data transparency help mitigate risks associated with unauthorized access to information and promote higher levels of collaboration among supply chain stakeholders. Thus, interoperability and distributed tracing are mutually reinforcing elements that enhance trust among participants in international trade and foster the stability of global trading processes.

Another critical component of distributed tracing in export-import operations is the *automation of business processes*, significantly reducing time, resource consumption, and human error. In [14], a promising solution is proposed to achieve sustainability through intelligent supply chain management automation. Specifically, the authors introduce a model integrating advanced artificial intelligence (AI) tools, such as agent-based methods and transformer architectures, to automate key tasks in international logistics and procurement processes. Unlike traditional, static systems, this framework enables dynamic adaptation to supply chain changes through its capacity to learn from real-world data, including logistics flows, procurement details, and carbon footprint information. This approach ensures operational efficiency and environmental responsibility in global trade processes, as evidenced by a reduction in costs and harmful emissions by 28.4 % and 30.3 %, respectively. The study in [15] presents a successful example of applying AI to enhance logistics efficiency at the micro level.

It focuses on implementing AI-based text recognition algorithms for processing transport documents (such as waybills), which are essential for international logistics operations. Such solutions are expected to play a key role in the digital transformation of global logistics by accelerating and standardizing documentation workflows across supply chains. Further, the findings of [16] broaden the understanding of the opportunities and challenges associated with implementing Robotic Process Automation (RPA) in the service sector. The study conducted among Polish firms during the COVID-19 pandemic demonstrates that RPA was crucial in maintaining operational continuity under crisis conditions – an especially vital consideration in global trade. RPA was positively evaluated regarding usefulness, security, and ease of application. However, the study also identifies critical barriers to effective implementation, including a low level of digitalization and the non-standardization of processes, which are common issues in international trade operations. Thus, the reviewed research highlights the pivotal role of business process automation in developing modern digital supply chain ecosystems. Distributed tracing can incorporate various technological components: product identification through QR codes, NFC chips, etc.; IoT devices for real-time data collection; and cloud platforms for data processing and visualization. Depending on the business needs or regulatory requirements, these systems can operate on public or private blockchains. Integrating AI, RPA, and blockchain enhances the efficiency, accuracy, and speed of logistics and supporting data processes. In this context, distributed tracing emerges as a powerful tool to ensure transparency, reliability, and cryptographically verified traceability of the origin and movement of goods in global networks.

Another essential dimension of distributed tracing technologies is *enhancing the security of international transactions*. Blockchain technologies offer secure and transparent records of all transactions, enabling trade participants to track the movement of goods and services throughout the supply chain, thereby reducing the risks of unfair competition or malicious behavior. In [17], blockchain is examined as a mechanism for strengthening the security of international transactions and improving the performance of distributed tracing. The authors demonstrate how blockchain's transparency, immutability, and decentralized structure support secure data exchange among global trading partners. Its implementation reduces fraud risks, increases trust in transactions, and ensures end-to-end traceability of goods, an essential condition for secure and efficient international operations. Furthermore, using blockchain technology allows for the implementation of tamper-proof audit trails, which are particularly important in high-risk sectors such as pharmaceuticals, defense, and high-value electronics. These trails enable regulatory bodies and trading partners to verify compliance, origin, and custody of goods without relying on centralized authorities. Article [18] explores the potential threats and security challenges that may arise in blockchain-based distributed systems. It shows how blockchain can revolutionize various sectors by enhancing trust and reducing risk, particularly in critical domains such as finance, supply chain management, and IoT. The ability to selectively grant access while maintaining data integrity is crucial for maintaining security in international trade environments involving multiple jurisdictions. The impact of blockchain on cyber-resilience in supply chains and its role in safeguarding international transactions is further discussed in [19]. The authors identify how blockchain-based solutions – especially tracking systems and smart contracts – improve transparency and security, notably in the food sector, thereby strengthening the integrity of cross-border operations. This increases operational efficiency and supports the legal enforceability of trade agreements under international regulatory frameworks.

Beyond security and transaction efficiency, *environmental sustainability* is a significant consideration when deploying advanced technologies in export-import activities. By increasing transparency and reliability in supply chains, distributed tracing technologies can be applied to monitor resource consumption and emissions, thereby helping reduce the ecological footprint of trade. This opens new avenues for implementing sustainable practices and more responsible use of natural resources in global logistics. In [20], the interplay between international trade and ecological sustainability is examined, particularly in the context of China's growing foreign trade. The authors identify key factors influencing sustainability and propose strategies for promoting sustainable development under expanding international trade. This study is vital in understanding the role of technologies like blockchain in advancing environmental sustainability in global commerce. Similarly, the study in [21] explores the impact of green supply chain management on innovation, environmental performance, and competitive advantage. Focusing on enterprises in Turkey, the authors show that integrating eco-oriented practices into supply chain management reduces environmental impact and enhances firms' international competitiveness. Distributed tracing technologies can play a central role in this process by offering precise monitoring and tracking of environmental indicators, which allows companies to optimize resource usage and minimize emissions. In turn, this supports adopting sustainable trade practices and enhances the environmental performance of supply chains, an essential step toward achieving global sustainability goals. Consequently, modern scholarly literature underscores the importance of incorporating environmental considerations into international trade strategies and highlights the role of digital technologies in fostering transparency and resilience in supply chains. It also points to the necessity of international cooperation and effective resource management to enable sustainable development in a globalized world.

In conclusion, distributed tracing in international trade is a multifunctional tool that facilitates efficient supply chain management and addresses various other strategic challenges, including security, automation, ecology, and interoperability. Taking these dimensions into account makes it possible to develop an optimized and resilient export-import system that meets the current demands and challenges of the global economy. A summary of the key dimensions of distributed tracing in international trade and its impact on export-import operations is presented in Table 2.

Table 2

Key functions of distributed tracing in international trade and their impact on export-import activities

Implementation aspect	**Function of distributed tracing**	**Impact on export-import activities**
1	2	3
Supply chain management	Ensures end-to-end control over all stages of product movement – from production to the final consumer. Participants have access to up-to-date real-time data, minimizing the likelihood of errors, losses, or delays. All information is stored immutably, ensuring full traceability.	Enables rapid identification and elimination of supply bottlenecks, reduces operational risks in international transportation, and simplifies communication among suppliers, carriers, and customs authorities. This is especially important given global demand and the complex geography of supply chains.
Security	Data for each transaction is encrypted, signed, and recorded in a distributed ledger, making forgery or destruction impossible. Verification is performed through consensus mechanisms that confirm the data's authenticity.	Ensuring the authenticity of documents (invoices, certificates, contracts) reduces fraud risk, lowers the need for duplicate verifications, simplifies audits, and accelerates customs clearance. This enhances trust in Ukrainian exporters on the international market.
Automation	The integration of smart contracts enables automatic execution of predefined conditions, such as transferring ownership after payment or sending	Reducing time spent on logistics and administrative operations decreases company expenses and increases competitiveness. Automatic procedure

Continuation of Table 2

1	2	3
	notifications in case of delays. Product tracking, status updates, and digital document processing occur without human intervention.	execution speeds up export-import processes, reduces human error risks, and lowers personnel costs.
Ecology	Distributed tracing allows tracking carbon footprint, energy consumption, packaging use, and other resources at each stage of the supply chain. This ensures transparency of environmental indicators, enabling ecological audits and sustainability analysis.	Enables adaptation to new environmental requirements of international markets (including the EU's "green" standards), reduces fines and barriers to export, and helps build a responsible partner image. Efficient resource management also contributes to cost reduction.
Interoperability	Digital platforms support integration with various information systems (customs, transport, warehouse, and financial) via open interfaces and international standards. This ensures compatibility between governmental and private entities.	Facilitates cooperation among foreign economic activity entities from different countries, promotes automatic data exchange without duplication of documents or format conversion. This accelerates order processing and goods declaration and reduces technical integration costs.

Source: compiled by the author based on [3–21]

The identified aspects of implementing distributed tracing in export-import activities emphasize the scientific significance of distributed tracing technologies for their development. They open new opportunities for integrating innovative approaches into the business processes of export-import operations. Such technologies foster the development of more sustainable and adaptive models of export-import activities, which is especially important in the context of shifts in economic policies oriented toward sustainable development.

Given the considerable impact of distributed tracing technologies on ensuring sustainable management of export-import activities, it is worthwhile to examine their implementation in the European Union (EU) and Ukraine in detail. EU countries have experience integrating innovative digital technologies in international trade, based on a unified regulatory framework, advanced technological infrastructure, and support for sustainable development through various strategic initiatives. A favorable political environment, harmonized standards, and a high trust in digital technologies among businesses and governments significantly facilitate the implementation of distributed tracing under such conditions. This enables effective monitoring of environmental footprints and supports transparency in supply chains on a global scale. Conversely, adopting similar technologies in Ukraine is more complex and requires consideration of several specific challenges. Firstly, there is a need to improve the national regulatory framework to ensure alignment with international standards and initiatives [8]. Secondly, considering the development of infrastructure and the diversity of the business environment, additional investments in digitalization and modernization of existing information exchange systems are necessary. These factors contribute to unavoidable delays in implementing distributed tracing technologies at the national supply chain level, necessitating the adaptation of solutions to ensure integration with international systems. Therefore, a comparative analysis of the implementation of distributed tracing technologies in the EU and Ukraine allows for a deeper understanding of the influence of economic, technological, and legal factors on the effectiveness of integrating these innovative approaches into international trade and sustainable development.

For a deeper understanding of the current state of distributed tracing implementation in export-import activities in the EU and Ukraine, key areas have been identified, each playing an essential role in ensuring the efficiency and success of integrating this technology:

– infrastructure development, a critical area as effective implementation of distributed tracing requires the presence of reliable and accessible IT infrastructure capable of supporting necessary digital technologies (for such projects, stable connections between different supply chain participants and the ability to exchange data in real time are essential);

– government support, which determines the state's ability to promote the adoption of new technologies through the creation of a favorable legal and political environment (government support can enable essential infrastructure projects, enact relevant laws and regulations, and propose incentives to facilitate the integration of distributed tracing into international trade);

– application of core digital technologies, since the successful implementation of distributed tracing directly depends on the availability of technologies capable of ensuring data security, transparency, and processing speed, particularly blockchain and IoT;

– integration into supply chains, as successful use of distributed tracing technologies is possible only with their integration into existing trade processes and interaction with other supply chain participants (this includes adapting the technology to the specific needs of various enterprises as well as its capability to effectively interact with different tools and platforms used for supply chain management);

– financing of innovative projects, which is a necessary condition for ensuring scalability and the implementation of initiatives for distributed tracing adoption (access to financial resources from both public and private sectors enables the realization of such projects under budget constraints, as well as supporting research and development of new solutions in this area);

– integration into international trade processes, which allows assessing the readiness of each region for global integration (distributed tracing has the potential to increase transparency and reduce costs in international trade significantly, thus its effective integration into international trade processes is a crucial factor in determining the success of technology adoption at the global level).

A thorough comparative analysis was undertaken to provide a solid foundation for understanding these key areas. This analysis focuses on the current state, development trends, and implementation challenges of distributed tracing technologies in export-import activities across the EU and Ukraine. By examining diverse sources and perspectives, the study aims to highlight differences and similarities in approaches, identify best practices, and offer insights into how these technologies can be effectively integrated into international trade frameworks.

The comparative analysis of digital distributed tracing technology implementation in export-import activities in the EU and Ukraine was conducted based on several groups of sources, including scientific publications [2–11; 15; 17], official documents and reports from international initiatives [22; 23; 26; 27; 35], as well as news and analytical materials [10; 11; 23; 24; 29–31; 33; 34].

Table 3 presents the results of the comparative analysis of distributed tracing technology implementation in export-import activities in the EU and Ukraine according to the identified key areas, enabling a clear understanding of the main trends and potential development pathways for these technologies.

A comparative analysis of the approaches to ensuring the implementation of distributed tracing in international trade in the EU countries and Ukraine allows us to outline several systemic trends.

First, the EU demonstrates a strategically coordinated approach that combines regulatory support, institutional integration, and advanced technical infrastructure. The EU possesses a significantly more developed infrastructure and government support for implementing blockchain technologies in international trade. It actively promotes the global integration of such technologies by creating common platforms for cross-border trade and product tracking. The implementation of distributed tracing in the EU is regarded not only as a digitization tool but also as an element of the broader European policy on transparency, security, and supply chain efficiency.

Table 3

Comparison of the implementation of distributed tracing technologies in export-import activities between the EU and Ukraine by key areas

Key areas	EU	Ukraine
1	2	3
Infrastructure development	High level of digital infrastructure development, support for innovative initiatives by the European Commission. For example, the EU Blockchain Observatory and Forum project [22].	Limited infrastructure for large-scale implementation. However, major cities actively develop digital platforms for business (e.g., the ProZorro project [23]).
	Planning the implementation of the European Logistics Services Authentication concept using blockchain-based tools to combat counterfeiting [24].	The State Customs Service of Ukraine joined the New Computerized Transit System (NCTS), simplifying the transport of goods between European countries [25].
Government support	Active support for digitalization and blockchain technologies through Horizon Europe programs and the European Blockchain Partnership (EBP) initiatives [26].	Ukraine joined the EBP as an observer, enabling participation in developing joint blockchain solutions for public services and facilitating integration of Ukrainian registries with European systems [27].
	Establishment of legal frameworks for digital trade solutions, such as the Regulation on Electronic Identification and Trust Services [28].	The Ukrainian government supports digitalization through programs like EU4Business [29], but closer cooperation with international partners is needed.

Continuation of Table 3

1	2	3
Application of core digital technologies	Widespread use of blockchain, IoT, and big data technologies [2; 5; 9; 15; 17].	Digital technology development, including blockchain, is progressing slowly (ProZorro [23] uses digital solutions for public procurement, but blockchain is not yet a core technology).
	Active integration of blockchain in financial and trade platforms, including Blockchain for Trade Finance [30; 31].	Ukraine participates in international blockchain projects such as Blockchaining Ukrainian Economy, but national-level technology use remains limited [32].
Integration into supply chains	The EU has integrated blockchain-based systems for product tracking, such as the BVL Blockchain project in the agri-food sector [2; 9–11].	Ukraine is only beginning to integrate technologies into supply chains; for example, several startups are using blockchain for innovation in agriculture [33].
	High level of integration into global supply chains, including platforms for tracking supply via port logistics such as the Port of Rotterdam [34].	Integration into international networks is limited due to a lack of standards and necessary investments; however, projects exist for small and medium enterprises [29].
Funding of innovative projects	Significant investments in digital and blockchain projects through Horizon Europe funds and other EU programs, e.g., funding for the EU Blockchain Observatory and Forum project [22].	Limited funding through state initiatives and international grants (EU4Business [29] supports startups, but venture capital in blockchain is still underdeveloped in Ukraine).

Continuation of Table 3

1	2	3
	Collaboration between governments and private investors to support innovation, e.g., within the EU Innovation Fund project [22; 26; 28].	Some pilot initiatives, such as the Ukrainian Blockchain Association, try to attract investments in innovative technologies, but funding remains limited [25; 27; 29].
Integration into international trade processes	The EU actively supports digital initiatives for international trade via the Digital Single Market, including the eIDAS regulation to ensure electronic identification in trade [22; 26; 28].	Integration into international trade processes through digital technology adoption, particularly via the "Diia" platform for electronic identification and digital signatures compliant with European standards [27]. Legal regulation and cybersecurity improvements are needed for full integration.
	Active use of technologies to reduce barriers in international trade, e.g., certification and product registration platforms through Blockchain in Global Trade [31].	Ukraine participates in initiatives such as the Digital Silk Road, but integration into international processes is limited due to a lack of standards and government support; however, the Digital Development Strategy until 2030 [35] may help overcome these barriers.

Source: compiled by the author based on [2–11; 15; 17; 22–35]

In contrast, initiatives for implementing distributed tracing in Ukraine are predominantly experimental or pilot, indicating an early stage of development for this system. Ukraine is only beginning to integrate blockchain into its international trade, with most initiatives focused on local projects and national customs procedures. The global integration of blockchain is still at an emergent stage, highlighting the need for further development and deployment of infrastructure to ensure the effective use of distributed tracing in international trade.

The second important conclusion is that the effective implementation of distributed tracing technology requires comprehensive cooperation between the public and private sectors, particularly in creating a favorable investment environment, technical standardization, and adapting digital solutions to the specifics of foreign trade. Currently, such cooperation in the EU is institutionalized through relevant partnerships, whereas it is only partially developed in Ukraine.

A deeper analysis of the implementation of distributed tracing in export-import activities in the EU countries and Ukraine can be based on statistical data reflecting the current state of this technology's development in both regions. Data provided in analytical reports demonstrates key trends that allow comparing approaches to blockchain solutions for supply chains and international trade. In EU countries, there has been steady growth in the blockchain technology market for supply chain management. According to forecasts, the market volume could reach USD 54.8 billion by 2030, with an average annual growth rate of 88.4 % during 2024–2030 [36]. Such dynamics indicate a high demand for innovative technologies in international trade, particularly for enhancing transparency and efficiency in supply chain management. However, only 3 % of organizations in the EU have implemented large-scale blockchain technologies, indicating a cautious but persistent advancement of this technology into fundamental business processes. Another 87 % of organizations are at the testing or pilot implementation stages, which further emphasizes a high level of innovation activity [37].

In turn, the primary motivations for implementing blockchain solutions in EU countries are significant cost savings, improved process transparency, and the ability to track the flow of goods effectively. According to a survey, 89 % of respondents indicated economic benefits as the primary incentive for adoption. In comparison, 81 % emphasized enhancing transparency, and 79 % highlighted the ability to control all supply chain stages [37].

In Ukraine, implementing digitalizing international trade through blockchain technology is actively developing. However, despite considerable progress, most initiatives focus on domestic processes such as optimizing customs procedures and improving national regulations.

According to Chainalysis data, from July 2023 to June 2024, Ukraine received over USD 106 billion in cryptocurrency transactions, indicating a high level of integration of digital assets into the country's financial system. Specifically, transactions on centralized exchanges amounted to about USD 70 billion. At the same time, decentralized platforms (DeFi) accounted for over USD 34 billion, representing more than 30 % of the total cryptocurrency transaction volume in the region [38].

A distinctive feature of the Ukrainian market is the significant impact of institutional and professional transactions. Large transactions exceeding USD 10 million and medium transactions ranging from USD 1 to 10 million constituted the majority of operations in 2024. This reflects growing interest in cryptocurrencies to ensure financial stability amid economic instability and inflation [38].

At the same time, Ukraine is witnessing active development of decentralized finance (DeFi), which indicates the readiness of Ukrainian companies to integrate cutting-edge digital solutions into their operations. Chainalysis data show that the volume of DeFi transactions in Eastern Europe increased by 40 % compared to the previous year, with Ukraine experiencing a significant volume growth on decentralized exchanges [38].

Despite the high level of cryptocurrency penetration in Ukraine, international platforms and integration mechanisms to ensure the effective use of blockchain technologies in global trade are still in the nascent stages. It is necessary to develop and implement appropriate legislation regulating clever contract use, protecting trade participants' rights, and facilitating Ukraine's integration into international supply chains [39].

Thus, specific statistical data confirm the conclusions drawn: the EU has already established a developed infrastructure and legal framework for implementing distributed tracing at the international level, whereas in Ukraine, blockchain technologies are only beginning to integrate into the sphere of global trade. At the same time, Ukraine demonstrates significant potential for adopting blockchain technologies in international trade. However, achieving full integration requires addressing several legal and infrastructural issues, which calls for a comprehensive approach and cooperation with global partners.

Considering the identified trends in developing digital technologies in the foreign economic sector and successful cases of blockchain solution implementation in the EU and OECD countries, several strategic recommendations for Ukraine can be formulated. First and foremost, it is necessary to develop a national blockchain technology development strategy, which should be integrated into the country's overall digital strategy and include stages of legislative adaptation, infrastructural modernization, and cross-sectoral coordination [22; 26; 27; 35]. It is essential to align with international standards of interaction in logistics and trade, particularly GS1, ISO 28005, and eIDAS, which ensure interoperability between public and private systems and effective integration into global supply chains [2; 13; 28].

The next key direction should be digitalizing customs procedures and logistics services, especially considering the positive experience of using Port Community System platforms in the EU [25; 34]. The deployment of pilot projects in priority sectors such as the agro-industrial complex and pharmaceuticals may facilitate the evaluation of the effectiveness of distributed tracing systems under the conditions of the Ukrainian market [2; 10; 33]. To stimulate businesses to adopt innovative solutions, it is advisable to consider state support mechanisms, including tax incentives, access to digital public procurement tools, or grant financing for innovation [7; 30; 31].

Particular attention should be given to cybersecurity, data protection, and developing a robust architecture for the reliable functioning of blockchain infrastructure. The experience of countries with advanced digital economies demonstrates that the reliability and trustworthiness of systems are decisive factors for their adoption in industrial and commercial sectors [17 – 19]. Equally important is the state's educational role in digital literacy. Increasing the awareness of entrepreneurs, customs agents, logistics operators, and public officials about the capabilities of distributed tracing technologies will help reduce barriers at the practical implementation stage [6; 8; 29].

Finally, Ukraine's participation in international blockchain initiatives, such as the European Blockchain Partnership, creates opportunities for regulatory harmonization, exchange of technological expertise, and involvement in joint innovative projects [26; 27]. Systematic implementation of these recommendations will contribute to the modernization of export-import activities and strengthen Ukraine's position as a reliable and transparent trading partner in the global market.

Thus, although Ukraine is currently forming the necessary prerequisites for systematically implementing distributed tracing in export-import operations, consistently realizing these recommendations will enable its integration into global digital supply chains based on modern technologies.

Conclusions. As a result of the conducted study, it was established that distributed tracing has significant potential to improve export-import activities by substantially enhancing the efficiency and transparency of international trade processes. One of the key advantages is the ability to track goods in real time, which allows for more effective supply chain management, reducing risks associated with documentation errors, transportation delays, and product counterfeiting. This enables more accurate forecasting and timely responses to potential issues arising during delivery.

Furthermore, the main factors ensuring the effective implementation of distributed tracing in international trade include data security, process automation, environmental benefits, and interoperability between different systems. The distributed ledger guarantees data integrity and immutability, which is critical for international trade operations as it eliminates the possibility of information manipulation. Automation of processes reduces operational costs, increases efficiency, and accelerates transaction execution. The environmental aspect of the technology is also significant, as it contributes to optimizing logistics processes and reducing the ecological footprint, particularly by minimizing the need for paper documentation and eliminating unnecessary stages in supply chains. This positively impacts the environment by lowering resource consumption and pollution. Interoperability is a crucial condition for the successful adoption of distributed tracing. Ensuring interaction among various participants in international trade – customs authorities, enterprises, and financial institutions – through a unified platform allows for increased process efficiency and speed, thereby reducing risks and errors in international trade operations.

A comparative analysis of European and Ukrainian practices in the context of distributed tracing implementation demonstrated that while Ukraine is actively improving digital tools, integrating technologies such as distributed tracing is still at a developmental stage. This is due to the absence of a unified standard and sufficient state-level support. The EU, in turn, has developed a regulatory framework for effectively implementing such technologies in trade, enabling member countries to integrate distributed tracing into their trade processes actively.

In addition, it is essential to emphasize that the European experience illustrates the significance of institutional support and strategic coordination among stakeholders. EU countries benefit from regulatory clarity, targeted funding programs, and public-private partnerships that accelerate the deployment of innovative technologies. Adopting a similar approach for Ukraine could significantly reduce the technological gap and enhance competitiveness in global markets. Moreover, implementing pilot projects and testbeds in specific export-oriented industries could catalyze wider technology diffusion. These initiatives would allow businesses to evaluate the benefits and challenges of distributed tracing in real operational conditions, thus reducing the entry barrier for broader market adoption. Therefore, for the effective adoption of this technology in Ukraine, it is necessary to continue efforts to improve the regulatory framework, raise the digital readiness of enterprises, and ensure government support. It is also essential to enhance cooperation between business and government, which will facilitate the integration of distributed tracing into export-import activities at both national and international levels. Only through a comprehensive and coordinated approach involving policy reform, technological modernization, and stakeholder engagement will it be possible to unlock the full potential of distributed tracing and align Ukraine's trade infrastructure with global standards.

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2.3. THE ROLE OF ARTIFICIAL INTELLIGENCE IN STRENGTHENING NATIONAL SECURITY

Introduction. Modern security threats to Ukraine, which have both physical and digital dimensions, require the implementation of new approaches to national defense. In this context, artificial intelligence

(AI) emerges not only as an innovative technology but as a key strategic tool that provides an advantage in countering hybrid challenges. The use of AI has been studied by researchers such as Voronkova V. H., Cherep A. V., Nikitenko V. O., Cherep O. H. [1], Zaluzhnyi V. F. [2], Bonnie E. J., Newell A. [3; 4], Stephen Hawking [5], Yefremov M. F., Yefremov Yu. M. [6], Cherep A. V., Voronkova V. H., Dashko I. M., Ohrenych Yu. O., Cherep O. H. [7], Cherep A. V. [8], Cherep O. H., Oleinikova L. H., Bekhter L. A., Veremieienko O. O. [9]. Thus, the application of AI makes it possible to enhance defense efficiency, strengthen cybersecurity, ensure the stability of the information space, and optimize decision-making at all levels.

Presentation of main research results. In the military sphere, AI is increasingly viewed as a “digital ally” of the modern soldier. Its use significantly transforms the conduct of combat operations, enabling faster, more accurate actions with fewer losses.

Key areas of application [10]:

- Intelligence and surveillance. AI-based systems can analyze satellite images, data from drones and sensors in real time. For example, the Ukrainian system Griselda, which processes thousands of reports from the front line, allows for rapid filtering and transmission of data to command within seconds.
- Drone and robotic system control. Combat drones with AI elements can autonomously conduct reconnaissance, identify targets, carry out attacks, or return to base. This is especially important in high-risk conditions for personnel.
- Decision-making systems. Predictive algorithms assist in risk assessment, scenario modeling, and operation planning. Such systems are already used to analyze enemy movements, forecast attacks, and manage logistics.
- Video stream analysis. Cameras with built-in AI can automatically identify equipment, weaponry, object types, and even enemy behavior, detecting deviations from the norm.
- Electronic warfare. AI helps detect enemy signals, encryption, sources of radio interference, and also carry out counteractions through jamming or distorting signals [11].

All these capabilities allow Ukrainian military units to act more flexibly and effectively, reducing dependence on human resources in critical situations. The areas of AI application in the military sector are shown in Figure 1.

AI plays an extremely important role in strengthening the state's cyber and information security, especially under conditions of hybrid aggression, where the enemy actively employs cyberweapons and information operations to destabilize the situation.

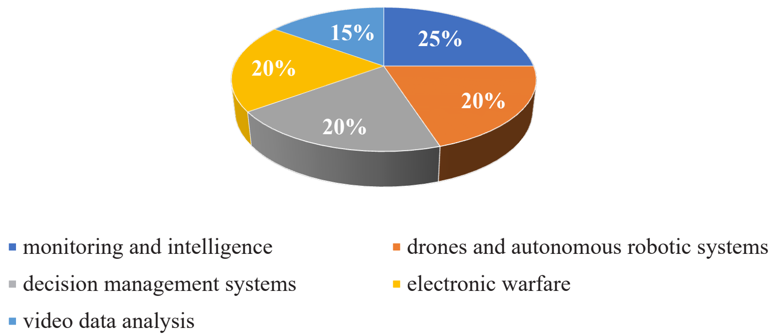

Figure 1. Areas of AI Application in the Military Sector

Source: compiled by the authors based on [12]

Main vectors of AI use in this sphere:

- Cyber threat analysis. AI systems can analyze network activity in real time, detect suspicious behavior, malware, and intrusions into systems. This enables the prevention of attacks before they cause harm.
- Identification of phishing attacks and viruses. Instead of traditional antivirus software, AI systems use behavioral analysis to detect malicious activity, even if it lacks known signatures.
- Protection of state information systems. AI can detect unauthorized access to databases, block malicious actions, analyze network vulnerabilities, and eliminate them automatically.
- Countering disinformation. Modern tools like Mantis Analytics, developed by Ukrainian IT specialists, use AI to monitor the information

space, analyze social media and news outlets to identify fake news, manipulations, and hostile information-psychological operations (IPSO).

- Automated modeling of attack consequences. AI systems can forecast the scale and impact of potential attacks – from infrastructure shutdowns to mass social reactions.
- Protection of critical infrastructure. Energy, transport, and water supply systems are all potential targets. Intelligent systems detect operational anomalies, signaling interference or disruptions [12].

Together, these capabilities support a proactive defense model – where threats are detected before they are realized, not after damage is done. The dynamics of cyber threats in Ukraine (2020–2024) are shown in Figure 2.

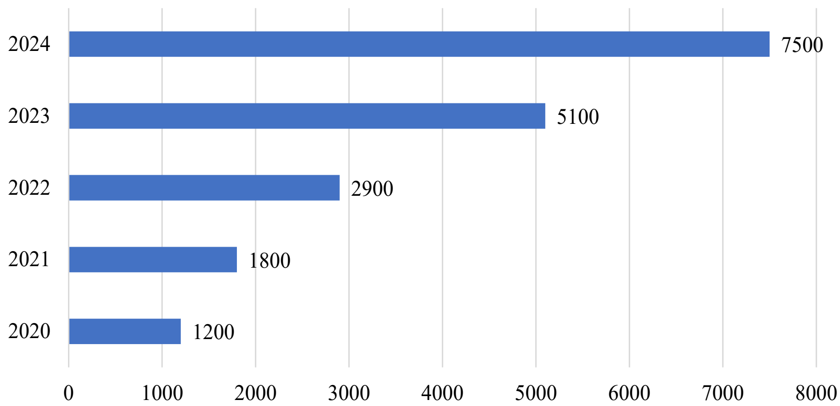

Figure 2. Dynamics of cyber threats in Ukraine (2020–2024)

Source: compiled by the authors based on [13]

As seen in Figure 2, cyber threats showed an upward trend during the Russo-Ukrainian war, reaching their peak in 2024. In 2023, the number of cyber threats nearly doubled, indicating that the Russian aggressors place significant emphasis on using cyberattacks as tools of propaganda and information warfare.

Despite its enormous potential to enhance national security, artificial intelligence also introduces new types of threats that require an immediate response from the state, society, and the expert community. The main risks include:

- The potential misuse of these technologies by adversaries.
- The growing, uncontrolled influence of autonomous systems.
- Existing ethical and legal gaps that can be exploited to undermine state stability.
- Addressing these challenges is a critical step in shaping an effective security policy in the digital era.

While AI can be an extremely powerful tool for strengthening security, in the hands of malicious actors it becomes a potent weapon. The adversary actively uses AI-based tools in hybrid warfare against Ukraine, creating new types of threats that are difficult to counter with traditional methods.

The role of AI in the cybersecurity system is illustrated in Figure 3.

Evaluation of the effectiveness of various AI tools for cybersecurity (scored from 1 to 10).

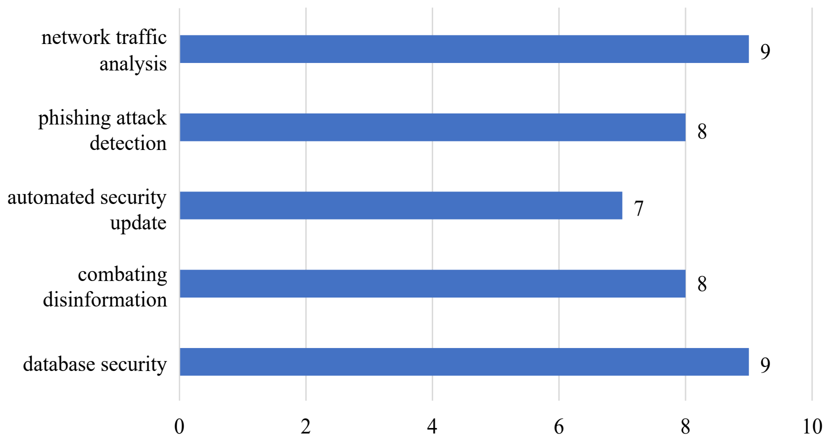

Figure 3. The Role of AI in the Cyber Defense System

Source: compiled by the authors based on [14]

Key vectors of potential misuse:

- Next-generation cyberweapons. AI algorithms can independently detect vulnerabilities in systems, modify malicious code in real time, and bypass security mechanisms. Such cyberattacks can be fast, adaptive, and hard to detect, posing serious threats to state and military IT systems.
- Autonomous weapons and combat drones. AI enables the creation of autonomous systems capable of independently deciding to engage targets without human intervention. This complicates control over combat operations and increases the risk of uncontrolled use of force.
- Deepfake and social media manipulation. AI-based image and video generation technologies allow for creating convincing fake statements attributed to leaders, photos, and messages that can disorient society, spread panic, and undermine trust in institutions.
- Mass information-psychological operations (IPSO). AI is used to analyze user behavior on social networks, deploy bots, and carry out targeted propaganda. This enables shaping public moods, manipulating public opinion, and demoralizing the population.
- AI technologies in the hands of terrorists. Uncontrolled access to open AI tools can be used to prepare or execute terrorist acts – from developing explosive devices to hacking infrastructure systems or influencing mass behavior.

All these threats become especially relevant in wartime conditions, as the adversary continuously adapts their methods, with AI greatly accelerating this process. This requires from the state not only technological countermeasures but also the development of appropriate legislative, ethical, and organizational protections.

The 2023 report of the Center for Countering Disinformation under Ukraine's National Security and Defense Council visualizes the main directions of AI use by the enemy to destabilize the situation in Ukraine [15]. The main threats to national security from the misuse of AI technologies are shown in Figure 4.

MAIN AREAS OF ARTIFICIAL INTELLIGENCE APPLICATION BY THE ADVERSARY AIMED AT DESTABILIZING THE SITUATION IN UKRAINE

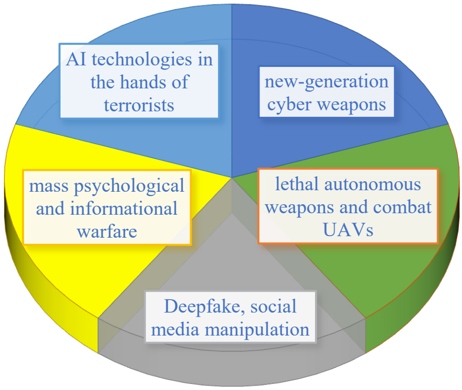

Figure 4. Main threats to national security from the misuse of AI technologies

Source: compiled by the authors based on [15]

The development and application of AI in the security sector are accompanied by challenges that currently lack established solutions at both national and international levels.

Main problems:

- Uncertainty of responsibility: In the event of an error by an autonomous system (e.g., a combat drone or analytical platform), it is difficult to determine who is responsible – the commander, developer, operator, or the state.
- Lack of algorithmic transparency: Many systems operate as "black boxes," making it impossible to verify the rationale behind their decisions. In the security sector, this creates potential space for abuse and mistakes.
- Bias in data and decisions: AI, learning from historical or incomplete data, can produce discriminatory or erroneous decisions that misdirect state resources inefficiently or unjustly.
- Violation of human rights: Without clear regulations for AI use in surveillance systems, behavioral prediction of citizens, or

decision-making in law enforcement agencies, there is an increased risk of transforming the state into a "digital dictatorship."

- Absence of legal regulation: Ukraine still lacks comprehensive AI legislation and normative legal acts regulating its use in defense, the Ministry of Internal Affairs, the Security Service of Ukraine, or cybersecurity [16].

Artificial intelligence opens new horizons in security, defense, governance, and analytics. At the same time, it creates fundamentally new challenges with both technical and societal dimensions. Issues related to AI use include risks of technology abuse, legal uncertainties, ethical dilemmas, and risks of systemic failures. All these demand a strategic approach to policy development, legal regulation, and fostering a culture of responsible use of advanced technologies [16].

Conclusions. The study revealed that artificial intelligence is not only a technological innovation but also a strategic tool capable of radically transforming approaches to ensuring Ukraine's national security.

Ukraine, facing a hybrid war, actively integrates AI tools into its defense and security structures, demonstrating adaptability and technological flexibility. Intelligence systems, drone management, cyber defense, and social media analysis are examples of effective AI integration into the national security architecture.

However, broad AI deployment is accompanied by significant challenges – notably, risks of misuse by adversaries, lack of clear legal frameworks, ethical dilemmas, and technical unpredictabilities. Autonomous weapons, deepfakes, algorithmic bias, and the opacity of some systems constitute a new dimension of threats that cannot be ignored.

Thus, the future of Ukraine's national security depends on the state's ability to develop a balanced AI policy that considers both the technology's potential and risks. This requires an interdisciplinary approach, coordination among state institutions, the scientific community, and technology companies. Only through comprehensive, ethical, and controlled AI implementation can Ukraine achieve a sustainable, innovative, and secure digital transformation of national security.

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