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Колективна монографія

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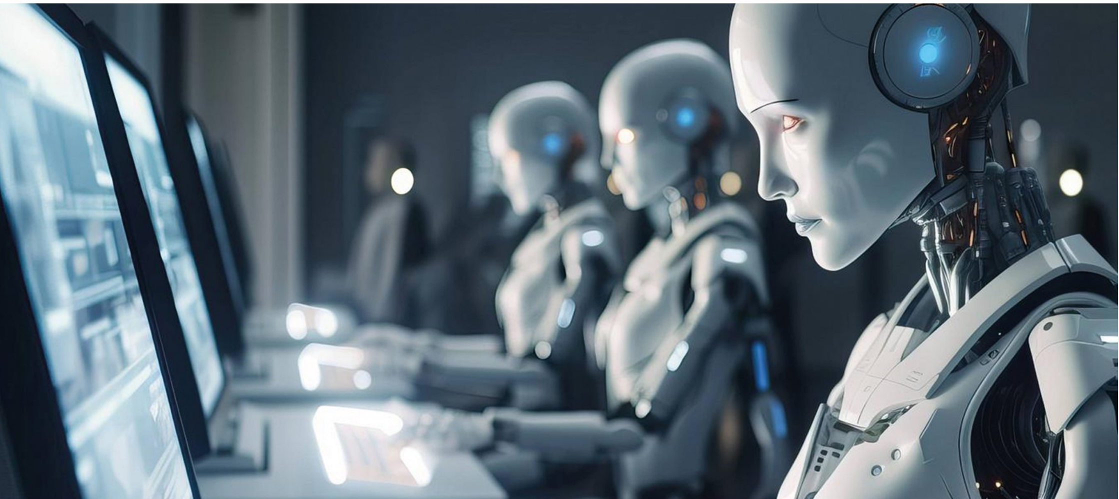

ARTIFICIAL INTELLIGENCE AS A TOOL TO PROTECT THE ECONOMY FROM DISINFORMATION: INNOVATIVE SOLUTIONS AND INTERNATIONAL PRACTICES

ШТУЧНИЙ ІНТЕЛЕКТ ЯК ІНСТРУМЕНТ ЗАХИСТУ ЕКОНОМІКИ ВІД ДЕЗІНФОРМАЦІЇ: ІННОВАЦІЙНІ РІШЕННЯ ТА МІЖНАРОДНІ ПРАКТИКИ

MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE
ZAPORIZHZHIA NATIONAL UNIVERSITY

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The monograph is based on the results of research within the framework of the project of basic scientific research, applied scientific research, scientific and technical (experimental) developments on the topic № 2/25 "Artificial intelligence as a tool to counter disinformation during the war and post-war economic recovery in Ukraine" (state registration number 0125U000996) (01.01.2025–31.12.2027).

The collective monograph is intended for scholars, teachers, students of higher education institutions, graduate students, doctoral students, practitioners, representatives of state authorities and local self-government, business, university administrative staff, representatives of civil society, the public and all interested persons.

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МІНІСТЕРСТВО ОСВІТИ І НАУКИ УКРАЇНИ
ЗАПОРІЗЬКИЙ НАЦІОНАЛЬНИЙ УНІВЕРСИТЕТ

Запорізький
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Колективна монографія присвячена розкриттю ролі штучного інтелекту у забезпеченні захисту економіки від дезінформації; визначенню особливостей впровадження європейського досвіду щодо використання штучного інтелекту та цифрових технологій в економіці; дослідженню ролі штучного інтелекту та цифрових технологій у здійсненні економічної трансформації та забезпеченні національної безпеки; формуванню теоретичних, методичних і практичних засад впровадження штучного інтелекту, здійснення цифрової трансформації з метою захисту економіки та підвищення її конкурентоспроможності, забезпечення інформаційної безпеки.

Монографія виконана за результатами досліджень у рамках проєкту фундаментальних наукових досліджень, прикладних наукових досліджень, науково-технічних (експериментальних) розробок за темою № 2/25 «Штучний інтелект як інструмент протидії дезінформації в період війни та повоєнного відновлення економіки України» (державний реєстраційний номер 0125U000996) (01.01.2025–31.12.2027).

Колективна монографія розрахована на науковців, викладачів, здобувачів закладів вищої освіти, аспірантів, докторантів, фахівців-практиків, представників державних органів влади та місцевого самоврядування, бізнесу, адміністративного персоналу університетів, представників громадянського суспільства, громадськості та всіх зацікавлених осіб.

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CONTENT

PREFACE

In the context of large-scale digitalization of society and the economy, rapid growth of information, including manipulative and destructive information, the use of artificial intelligence to protect the economy from disinformation is becoming increasingly important. In addition, the problem of disinformation, in the context of hybrid warfare, information attacks, cyber aggression and economic instability, has become extremely acute, as it has a negative impact on economic processes, weakens the financial system, and affects the reputation of enterprises and their business activity. Accordingly, there is a need to introduce innovative approaches to preventing, detecting, analyzing and neutralizing information threats, and artificial intelligence is a powerful technological tool that allows automating the monitoring of the information space, forecasting possible risks, detecting fake news, and processing data to make appropriate decisions. The experience of the European Union demonstrates cases of implementing AI-based systems to combat disinformation in the economic sphere. Therefore, the issue of introducing artificial intelligence technologies to protect the economy from information influence is an important task for Ukraine, which will help ensure socio-economic security and adaptation to global challenges. Scientists have covered a wide range of issues in terms of researching the use of artificial intelligence to protect Ukraine's economy from disinformation in order to ensure information security and economic development.

The collective monograph is devoted to revealing the role of artificial intelligence in protecting the economy from disinformation; determining the peculiarities of implementing European experience in the use of artificial intelligence and digital technologies in the economy; studying the role of artificial intelligence and digital technologies in economic transformation and ensuring national security; to formulate theoretical, methodological and practical foundations for the introduction of artificial intelligence, digital transformation in order to protect the economy and increase its competitiveness, and ensure information security.

The first chapter discusses the integration of European approaches to the use of artificial intelligence and digital technologies into Ukrainian realities. The successful practices of the European experience of using artificial intelligence in education and the knowledge economy are studied. The directions of digitalization of local government finances are identified. Prospects for the introduction and use of artificial intelligence in the Ukrainian economy are formed.

The second section is devoted to the study of the role of artificial intelligence and digital technologies in economic transformation and national security. In particular, the specifics of the introduction of digital technologies and artificial intelligence in the current economic environment are determined. The features of digital transformation of export-import activities are considered. The role of artificial intelligence in strengthening national security is determined. The directions of implementation of artificial intelligence to ensure national security are determined.

The third section reveals the synergy of artificial intelligence, digital competence, and analytical modeling in the context of economic modernization. The impact of artificial intelligence on the national security of Ukraine is studied. The directions of development of digital competencies of the population in the digital economy are formed. The expediency of introducing information modeling at enterprises to improve economic efficiency is determined. The directions of ensuring information security and increasing economic development are proposed.

The collective monograph offers theoretical and methodological generalizations, conclusions, and practical recommendations that will be useful for researchers, teachers, students of higher education institutions, postgraduates, doctoral students, practitioners, representatives of state authorities and local governments, business, university administrative staff, representatives of civil society, the public, and all interested parties.

The collective monograph is based on the results of research within the framework of the project of basic scientific research, applied scientific research, scientific and technical (experimental) developments on the topic № 2/25 "Artificial intelligence as a tool to counter disinformation during the war and post-war economic recovery in Ukraine" (state registration number 0125U000996) (01.01.2025–31.12.2027).

ПЕРЕДМОВА

В умовах масштабної цифровізації суспільства та економіки, швидкого зростанням обсягів інформації, у тому числі маніпулятивного та деструктивного характеру, набуває актуальності питання використання штучного інтелекту для захисту економіки від дезінформації. Крім того, проблема дезінформації, в умовах гібридної війни, інформаційних атак, кіберагресії та економічної нестабільності, набула надзвичайної гостроти, оскільки вона має негативний вплив на економічні процеси, послаблює фінансову систему, впливає на репутацію підприємств, їх ділову активність. Відповідно постає потреба у впровадженні інноваційних підходів до попередження, виявлення, аналізу та нейтралізації інформаційних загроз та саме штучний інтелект є потужним технологічним інструментом, який дозволяє автоматизувати моніторинг інформаційного простору, здійснити прогноз можливих ризиків, виявляти фейкові повідомлення, а також обробити масив даних для прийняття відповідних рішень. Досвід країн Європейського Союзу демонструє випадки впровадження систем на основі штучного інтелекту для боротьби з дезінформацією в економічній сфері. Тому питання впровадження технологій штучного інтелекту з метою захисту економіки від інформаційного впливу є важливим завданням для України, що сприятиме забезпеченню соціально-економічної безпеки, адаптації до глобальних викликів. Науковцями розкрито широке коло питань в аспекті дослідження напрямів використання штучного інтелекту для захисту економіки України від дезінформації з метою забезпечення інформаційної безпеки та економічного розвитку.

Монографія присвячена розкриттю ролі штучного інтелекту у забезпеченні захисту економіки від дезінформації; визначенню особливостей впровадження європейського досвіду щодо використання штучного інтелекту та цифрових технологій в економіці;

дослідженню ролі штучного інтелекту та цифрових технологій у здійсненні економічної трансформації та забезпеченні національної безпеки; формуванню теоретичних, методичних і практичних засад впровадження штучного інтелекту, здійснення цифрової трансформації з метою захисту економіки та підвищення її конкурентоспроможності, забезпечення інформаційної безпеки.

У першому розділі розкрито питання інтеграції європейських підходів використання штучного інтелекту та цифрових технологій в українські реалії. Досліджено успішні практики європейського досвіду використання штучного інтелекту в освіті та економіці знань. Визначено напрямки цифровізації фінансів місцевих органів самоврядування. Сформовано перспективи впровадження та використання штучного інтелекту в економіці України.

Другий розділ присвячений дослідженню ролі штучного інтелекту та цифрових технологій у здійсненні економічної трансформації та забезпеченні національної безпеки. Зокрема, визначено специфіку впровадження цифрових технологій та штучного інтелекту в сучасних економічних умовах. Розглянуто особливості цифрової трансформації експортно-імпортної діяльності. Встановлено роль штучного інтелекту у зміцненні національної безпеки. З'ясовано напрямки впровадження штучного інтелекту для забезпечення національної безпеки.

У третьому розділі розкрито синергію штучного інтелекту, цифрової компетентності й аналітичного моделювання в умовах економічної модернізації. Досліджено вплив штучного інтелекту на національну безпеку України. Сформовано напрямки розвитку цифрових компетентностей населення в умовах цифрової економіки. Визначено доцільність впровадження інформаційного моделювання на підприємствах для підвищення економічної ефективності. Запропоновано напрямки забезпечення інформаційної безпеки та підвищення економічного розвитку.

У колективній монографії запропоновано теоретико-методичні узагальнення, висновки та практичні рекомендації, які стануть в нагоді для науковців, викладачів, здобувачів закладів вищої освіти, аспірантів, докторантів, фахівців-практиків, представників державних органів влади та місцевого самоврядування, бізнесу, адміністративного персоналу університетів, представників громадянського суспільства, громадськості та всіх зацікавлених осіб.

Колективна монографія виконана за результатами досліджень у рамках проєкту фундаментальних наукових досліджень, прикладних наукових досліджень, науково-технічних (експериментальних) розробок за темою № 2/25 «Штучний інтелект як інструмент протидії дезінформації в період війни та повоєнного відновлення економіки України» (державний реєстраційний номер 0125U000996) (01.01.2025–31.12.2027).

SECTION 1.
Artificial Intelligence and Digitalization of the Economy: Integration of European Approaches into Ukrainian Realities

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1.1. EUROPEAN EXPERIENCE IN THE APPLICATION OF ARTIFICIAL INTELLIGENCE IN EDUCATION AND THE KNOWLEDGE ECONOMY

Introduction. Education and the knowledge economy, which are grounded in the creation, dissemination, and utilization of knowledge and information, constitute a key driver of competitiveness and sustainable development in modern states. A significant share of GDP in these economies derives from activities related to generating, processing, storing, and distributing information and know–how. In this context, artificial intelligence (AI) offers unprecedented opportunities to enhance efficiency, spur innovation, and generate new forms of value. The European Union, recognizing this potential, has been actively developing and implementing strategies and regulatory frameworks to foster the responsible and effective deployment of AI across various economic sectors, including education and the knowledge economy.

The European Union's experience in the AI domain provides a valuable roadmap for Ukraine, which aspires to integrate into the European economic area and to cultivate its own knowledge–based potential. Studying and adapting successful European practices can significantly accelerate Ukraine's digital transformation and bolster the competitiveness of its businesses, educational institutions, and research organizations.

Summary of Key Findings. Since 2018, the European Union has been systematically establishing a comprehensive legislative framework for AI governance. Aware of both the immense opportunities and the potential risks associated with AI development and deployment, the EU strives to craft a legal environment that promotes innovation, ensures the ethical use of technology, and safeguards fundamental citizens' rights (see Table 1).

Table 1

Stages in the Development of the Legislative Framework for AI Regulation in the EU

Years	Key Milestones in EU AI Legislation and Governance
1	2
2025	– April 9: AI Coalition Action Plan published
	– March 12: Six additional consortia selected to build European AI research "factories"
	– February 4: Adoption of Recommendations on prohibited AI practices
	– February 11: President von der Leyen launches "Invest AI" at the AI Action Summit in Paris
	– December 10: Seven consortia chosen to establish AI research factories in the EU
2024	– September: Start of drafting the Code of Practice for general-purpose AI
	– September: Companies sign EU commitments to the AI Pact (Component II)
	– August 1: Entry into force of the Law on AI

Continuation of Table 1

1	2
	– April: Establishment of the European AI Office
	– March: Innovative AI Package to support startups and small and medium-sized businesses with AI
2023	– December: Political agreement on the AI Act reached by co-legislators
	– June: European Parliament agrees its negotiating position on the AI Act
2022	– December: Council confirms its general approach on the AI Act
	– September: EC Proposal for a Directive on liability for AI
	– June: Launch of the first AI regulatory sandbox in Spain
2021	– December: Committee of the Regions, opinion on the Law on AI
	– December: European Central Bank, Opinion on the Law on AI (.PDF)
	– November: Council of the EU: the EU Council Presidency announced a compromise text on the Artificial Intelligence Act (PDF)
	– November: High-Level Conference on Artificial Intelligence – From Ambition to Action (3rd Assembly of the European AI Alliance)
	– November: European Economic and Social Committee issues its Opinion on the AI Act
	– June: Public consultation on civil liability – adaptation of liability rules to the digital age and artificial intelligence
	– June: European Commission – Proposal for a Regulation on Product Safety
	– April: European Commission – Communication on Promoting a European Approach to AI
	– April: European Commission – Proposal for a Regulation establishing harmonized rules on AI
	– April: European Commission – Updated Coordinated Plan on AI

Continuation of Table 1

1	2
2021	– April: European Commission – Impact assessment of AI regulation
2020	– October: 2nd Assembly of the European AI Alliance
	– July: Initial impact assessment – Ethical and legal requirements for artificial intelligence
	– July: High-Level Expert Group on AI – Final Assessment List for Trustworthy AI (ALTAI)
	– July: High-Level Expert Group on AI – Sectoral Recommendations for Trustworthy AI
	– February: European Commission – White Paper on AI: A European Approach to Excellence and Trust
	– February: Public consultation on the European approach to excellence and trust in artificial intelligence
2019	– December: High-Level Expert Group on Artificial Intelligence – Pilot of the Assessment List for Trustworthy AI
	– June: First Assembly of the European AI Alliance
	– June: High-Level Expert Group on Artificial Intelligence – Policy and Investment Recommendations on AI
	– April: European Commission – Communication "Building Trust in Human-Centric AI"
	– April: High-Level Expert Group on AI – Ethics Guidelines for Trustworthy AI
2018	– December: European Commission – Coordinated Plan on AI
	– December: European Commission (Press release) – "Artificial Intelligence Made in Europe"
	– December: European Commission – Communication "Artificial Intelligence Made in Europe"
	– December: Stakeholder consultations on the draft ethics guidelines for Trustworthy AI
	– June: Launch of the European AI Alliance
	– June: Establishment of the High-Level Expert Group on AI

Continuation of Table 1

1	2
	– April: Press release – “Artificial Intelligence for Europe”
	– April: Communication – “Artificial Intelligence for Europe”
	– April: Staff working document – “Responsibility for Novel Digital Technologies”
	– April: Declaration on Cooperation in the Field of AI
	– March: Press release – Establishment of the High-Level Expert Group on AI and launch of the European AI Alliance

Source: summarized by the author based on [1]

On the official website of the European Union, the glossary defines AI as follows: “*Artificial intelligence (AI)* refers to systems that display intelligent behavior by perceiving their environment and taking actions, with some degree of autonomy, to achieve specific goals. AI-based systems may be purely software-based, operating in a virtual environment (for example, voice assistants, image-analysis software, search engines, speech and facial recognition systems), or AI may be embedded in hardware devices (for example, advanced robots, autonomous vehicles, drones, or Internet-of-Things applications)” [2].

In 2020, the EU’s High-Level Commission on Artificial Intelligence published its White Paper on Artificial Intelligence [3], setting out policy options to ensure the trustworthy and safe development of AI in Europe. The White Paper emphasized the critical importance of a European approach – one that prioritizes overcoming the shortfall in digital competencies and skills. This emphasis was also reflected as a cornerstone of the updated European Skills Agenda.

As part of its digital strategy, the European Commission proposed a comprehensive legal framework for AI – the AI Act, which entered into force on August 1, 2024 [4]. The Act establishes mandatory requirements for “high-risk” AI systems across a number of domains, including education and vocational training. It represents the world’s first horizontal legal instrument grounded in the EU’s regulatory and policy work on AI and data, encompassing the 2019 Ethics Guidelines for Trustworthy AI (issued by the AI High-Level Expert Group – AI HLEG), the General Data Protection Regulation (GDPR), and the proposed Data Act.

The EU AI Act's key provisions include:

– Setting EU-wide minimum requirements for AI systems based on a risk-management approach;

– Protecting fundamental rights, the rule of law, democracy, and the environment from potential harms posed by AI;

– Classifying AI systems into four risk levels: unacceptable risk, high risk, limited risk (requiring transparency obligations), and minimal or no risk;

– Determining the Act's success by its ability to balance potential benefits and challenges, and by how swiftly industry, public authorities, and civil society adapt to the new legal framework.

The AI Act aims to ensure that Europeans can trust what AI has to offer. While most AI systems are safe – or even beneficial – for society, certain applications carry risks that the EU must regulate to prevent adverse outcomes. In particular, the "black-box" nature of some AI decision-making processes can make it difficult to understand or predict their behavior. Existing EU legislation provides only partial protection; the AI Act fills these gaps by addressing AI-specific challenges.

Accordingly, the AI Act adopts a risk-based methodology, defining *four levels of AI risk*:

Level 1: *unacceptable risk* – these are all EU-banned artificial intelligence systems that are considered a clear threat to security, livelihoods, and human rights. "*The AI Act prohibits eight practices, namely*:

1. AI-driven harmful manipulation and deception.
2. AI-enabled exploitation of vulnerabilities.
3. Social scoring by public authorities.
4. Prediction or forecasting of individual criminal behavior.
5. Non-targeted scraping of the internet or video surveillance data to create biometric recognition databases.

6. Emotion recognition in the workplace or educational settings.
7. Biometric categorization to infer protected characteristics.
8. Real-time remote biometric identification for law enforcement purposes in public spaces" [4].

Level 2: *high risk* – these are uses of AI systems and technologies that may pose serious risks to health, safety, or fundamental rights. "*Such high-risk use cases include*:

– AI safety components in critical infrastructure (e.g., transport);
– AI systems used in education or vocational training that determine access to education or professional pathways (e.g., automated exam scoring);
– AI-based safety components in products (e.g., AI-assisted robotic surgery);
– AI tools for recruitment, workforce management, or access to self-employment (e.g., CV-screening software);
– AI systems used to grant access to essential private or public services (e.g., credit scoring);
– AI for remote biometric identification, emotion recognition, and biometric categorization (e.g., retrospectively identifying a shoplifter);
– Law-enforcement AI that may infringe fundamental rights (e.g., evidential assessment systems);
– AI for migration management, asylum processing, and border control (e.g., automated visa-application screening);
– AI in judicial and democratic processes (e.g., AI-assisted sentencing recommendations)" [4].

High-risk systems must comply with:

– Adequate risk-assessment, mitigation, and minimization systems;
– High-quality datasets to prevent bias and discrimination;
– Logging requirements to ensure traceability;
– Comprehensive documentation detailing system design and intended purpose;
– Clear and adequate developer information;
– Appropriate human oversight measures to minimize risk;
– High levels of reliability, safety, and accuracy" [4].

Level 3: *transparency risk* – these are AI applications that require transparency obligations to ensure public awareness and maintain trust. For instance, users interacting with AI chatbots must be informed that they are communicating with a machine. Moreover, developers of generative AI must clearly label AI-generated content, particularly deepfakes and AI-generated texts on matters of public importance.

Level 4: *minimal risk or no risk*. The AI Act does not regulate AI systems that pose minimal or no risk. Most AI applications currently in use across the EU fall into this category – examples include AI-enhanced video games and spam-filtering tools.

The establishment of this comprehensive legal framework for AI regulation is complemented by *an EU-wide innovation support ecosystem*. Through initiatives such as European Digital Innovation Hubs, AI factories, and the AI Skills Academy, the European Commission promotes AI research, innovation, and leadership in Europe [5].

At the core of these ecosystem initiatives is the creation of specialised institutions and facilities:

European Digital Innovation Hubs (EDIHs) are one-stop shops that assist companies in becoming more competitive in their business and manufacturing processes, products, or services by integrating digital technologies, including AI.

Testing and Experimentation Facilities (TEFs) are large-scale, specialized reference centers that help technology providers transition products from the laboratory to the market. They support full integration, testing, and experimentation of cutting-edge, mature AI technologies.

AI Factories (AI Factories) are specialized institutions designed to provide supercomputing capabilities for the development and training of advanced AI models. They will also foster talent development by offering upskilling, training, and reskilling programs for the relevant stakeholders in the AI ecosystem.

AI Regulatory Sandboxes (AIRS) offer controlled environments where innovators can trial AI systems under the supervision of National Competent Authorities (NCAs), receiving regulatory guidance and training that encourage both innovation and competitiveness.

AI-on-Demand Platforms offer access to a wide range of algorithms, tools, and expertise, as well as opportunities for knowledge sharing and collaboration. Key features of these platforms include a unified interface for exploring and importing AI datasets from multiple sources, enabling users to customize models and datasets and to conduct experiments within an open-source environment.

AI Skills Academy will serve as a one-stop shop for a suite of educational and training programs across two main streams:

– Skills for deploying and integrating AI, particularly generative AI into key economic sectors;

– Skills related to the operations and workflows of AI Factories.

The European Commission's commitment to developing AI-related skills and expertise is embodied in the forthcoming AI Skills Academy, which will prepare the workforce for the demands of an AI-driven future and ensure that Europe remains a leader in AI excellence. Upskilling efforts are a joint mission of the Commission's ecosystem initiatives, with European Digital Innovation Hubs and AI Factories also offering workforce training.

On the other hand, *the education sector itself holds significant potential for AI and data use*. This involves leveraging AI-processed data in teaching to enhance and personalize learning for groups or individual students, and to help educators and staff use data more effectively and securely.

Under the auspices of the European Commission and with the support of the High-Level Expert Group on AI and Data in Education and Training, *Ethics Guidelines for the Use of Artificial Intelligence and Data in Teaching and Learning* have been developed for educators [6]. These guidelines align with the AI Act and build on the EU's broader regulatory and policy framework for AI and data, including the GDPR and the proposed Data Act, which impose mandatory requirements on high-risk AI systems across multiple domains such as education and vocational training. They are tailored to the specific context of teaching and learning, offering educators both the necessary awareness-raising measures and practical recommendations as they increasingly integrate AI into their pedagogical practice.

According to the *Digital Education Action Plan (2021–2027), the European Union has defined two strategic priorities*:

1. "To achieve the *Fostering High-Performing Digital Education Ecosystems*, needs:

– Robust infrastructure, connectivity, and digital equipment;

– Effective planning and development of digital capacities, including modern organizational capabilities;

– Digitally competent and confident teachers, trainers, and educational staff;

– High-quality content, user-friendly tools, and secure platforms that respect privacy and ethical standards.

2. *Enhancing Digital Skills and Competences for the Digital Age*:

2.1. *Ensuring Basic Digital Skills and Competences from an Early Age*:

– Digital literacy, including managing information overload and identifying misinformation;

– Computer science education;

– Solid understanding of data-intensive technologies such as AI.

2.2. *Promoting Advanced Digital Skills*:

– Increasing the number of digital specialists;

– Encouraging more girls and women to pursue careers in digital sciences and related fields" [6].

To implement them, it is proposed to get rid of prejudices regarding the possibilities of using AI and data in teaching and learning in the field of education. The most common misconceptions regarding AI, its short-term and long-term impact on education systems and society in general, are considered to be the following:

• "*AI is too complex to understand*": Many non-technical educators are deterred by AI jargon. Rather than mastering every technical detail, teachers should understand AI's core mechanisms, limitations, and how to apply AI tools safely and ethically to support teaching and learning.

- "*AI has no role in education*": AI is already transforming how we learn, work, and live – and education is no exception. Everyone should be empowered to contribute to and benefit from AI-driven innovation.
- "*AI is not inclusive*": While AI can exacerbate existing inequalities if poorly designed, it also has the potential to improve access and engagement for underrepresented learners, notably by providing tailored resources for students with disabilities or special needs.
- "*AI systems cannot be trusted*": As AI augments or replaces certain human tasks, concerns arise around fairness, transparency, and data protection. Although existing EU legislation offers partial safeguards, the AI Act ensures that "high-risk" systems – those capable of significant harm to health, safety, or fundamental rights – are developed under mandatory risk-mitigation measures. Educational authorities and schools must be able to verify AI compliance and focus on ethical AI use to support both teachers and learners while adhering to data-protection rules.
- "*AI will undermine the role of the teacher*": Rather than replacing educators, AI can free them from repetitive administrative duties and enable more creative, problem-based, and collaborative learning experiences, tasks beyond AI's current autonomous capabilities. The teacher's role is thus likely to evolve and expand, provided AI applications are developed and deployed with an emphasis on supporting – not supplanting – human instruction [summarized from: 6].

Contrary to these misconceptions, the use of AI in schools, universities, and vocational institutions across Europe is growing. AI supports teaching, learning, and assessment practices. However, evidence-based research on AI's educational impact remains limited, underscoring the need for a critical and monitored approach to its implementation. The types of artificial intelligence systems used for teaching, learning, assessment, and school administration usually distinguish between "student", "teacher", and "system-oriented" AI systems.

Options for using AI and data in education in the EU are:

– *Student-facing*: using AI to teach students;

– *Student support*: Using AI to support student learning;

– *Teacher-facing* (supporting educators): using AI to support teachers;

– System-facing (assisting administrative or systemic planning and diagnostics) [summarized from: 6].

Table 2 presents *examples of AI and data uses in EU education*, illustrating how AI systems can assist teachers and students in teaching, learning, and assessment.

Table 2

Examples of using AI and data capabilities in the European Union's education sector

Using AI to teach students	
1	2
Smart tutoring	The student completes a step-by-step sequence of tasks and receives individual instructions or feedback without requiring teacher intervention.
Dialog learning systems	The learner completes a sequence of tasks step by step through natural language conversation. More advanced AI systems can automatically adapt to the level of engagement to keep the learner motivated and on task.
Learning the language of the program	AI-powered learning applications are used in formal and informal education contexts. They support learning by providing access to language courses, dictionaries, and provide real-time automated feedback on pronunciation, comprehension, and fluency.
Search learning environment	Students are offered several ideas to help them identify their own paths to achieving their learning goals.
Formal assessment of written performance	Curricula provide students with regular automated feedback on their written work.

Continuation of Table 2

1	2
Collaborative learning based on AI	Data about each student’s work style and past performance is used to divide them into groups with similar ability levels or a suitable combination of abilities and talents. AI systems provide input/suggestions on how the group works together by tracking the level of interaction between group members.
Using AI to support teachers	
Overall assessment of written performance, essay assessment	Using AI to automatically assess and grade students’ written work. AI and machine learning techniques identify characteristics such as word usage, grammar, and sentence structure to assess and provide feedback.
Monitoring student forums	Keywords in student forum posts trigger automatic feedback. Discussion analytics provide insights into student forum activity and can highlight students who may need help or are not engaging as expected.
AI-based teaching assistants	AI agents or chatbots provide answers to frequently asked questions from students with simple instructions and directions. Over time, the AI system is able to expand the range of answers and options provided.
Using AI to support teachers	
Recommendations for pedagogical resources	AI-based recommendation engines are used to recommend specific learning activities or resources based on each student's preferences, progress, and needs.
Intelligent analysis of educational data for resource allocation	Schools collect data about students, which they analyze and use to plan the optimal allocation of available resources for tasks such as creating student groups, assigning teachers, scheduling, and identifying students who may need additional learning support.

Continuation of Table 2

1	2
Using AI to support teachers	
Diagnosis of learning difficulties	Using learning analytics, cognitive skills such as vocabulary, listening, spatial reasoning, problem solving, and memory are measured, which helps diagnose learning difficulties, including hidden problems that are difficult for a teacher to detect but can be detected by AI systems at an early stage.
Consulting services	AI-driven advising services provide continuous prompts and options for designing personalized educational pathways. Users can build a competency profile, encompassing their prior qualifications and individual interests. By combining these data with an up-to-date course catalog or information on available learning opportunities, the system can generate relevant learning recommendations using natural language processing.

Source: summarized by the author based on [6]

In line with Priority 1: Fostering High-Performing Digital Education Ecosystems, the Digital Education Action Plan (2021–2027) outlines specific measures to promote this ecosystem, including the dissemination of the AI & Data Ethics Guidelines for Teaching and Learning to educators, school leaders, and other stakeholders.

At the same time, the EU's High-Level Expert Group on AI and Data in Education and Training has noted that "the Ethics Guidelines for the use of AI and data in teaching and learning represent an ongoing process of reflection and learning" [6]. Accordingly, when evaluating any AI system, it is essential that the institution – whether a school, college, or university – and its teaching staff are empowered to pose the right questions and to engage in constructive dialogue with AI providers or relevant regulatory authorities.

These guiding questions are embedded within the *Ethical Considerations and Requirements underpinning the EU Ethics Guidelines*. They reflect the core requirements for trustworthy AI systems and serve to structure an ethical dialogue about their use in teaching and learning. Some questions focus on practical implementation, while others address foundational ethical concerns:

1. Requirement is *human-centeredness and control of the AI system*, for which the following questions should be answered:

- Is the teacher's role clearly defined to ensure their involvement whenever the AI system is in use?
- How does the AI system affect the teacher's didactic role?
- Are decisions impacting learners made with teacher participation, and can teachers detect anomalies or potential bias?
- Are there clear procedures enabling teachers to monitor the system and intervene, for example, in situations that demand empathy when interacting with students or parents?
- Is there a mechanism allowing learners to opt out of AI-driven instruction if their concerns are not adequately addressed?
- Are monitoring controls in place to prevent overreliance on or blind trust in the AI system?
- Do teachers and school leaders have the training and information necessary to use the AI system effectively, safely, and in full respect of learners' rights?

2. Requirements are *the transparency* of the AI system, for which it is necessary to answer the following questions:

- Are teachers and school leaders aware of the AI methods and functionalities employed by the system?
- Is it clear which tasks the AI system can and cannot perform?
- Do educators understand how specific assessment or personalization algorithms operate?
- Are system processes and outputs aligned with intended learning outcomes?
- How reliable are the system's predictions, assessments, and classifications in terms of justifying its ongoing use?

- Are user instructions and explanatory materials accessible and comprehensible to both teachers and learners?

3. Requirements: *Diversity, Non-Discrimination, and Fairness*:

- Is the AI system equally accessible to all users without barriers?
- Does it offer appropriate interaction modes for learners with disabilities or special educational needs?
- Has the system been designed to respect learners by adapting to their individual requirements?
- Is the user interface age-appropriate and user-friendly?
- Has usability testing been conducted with the target age group to validate the user experience?
- Are there procedures to ensure the AI's use does not lead to discrimination or unfair treatment?
- Do the system's documentation and training processes clarify potential data biases?
- Are there mechanisms to detect and mitigate bias or unintended inequities?

4. Requirements: *Social and Environmental Well-Being*:

- How does the AI system affect the social and emotional well-being of learners and educators?
- Does the system clearly signal that its social interactions are simulated, lacking genuine feelings or empathy?
- Are students and their guardians involved in decisions about deploying and supporting the AI system?
- Are data used to help educators and administrators monitor learner well-being, and if so, how is this tracked?
- Does the use of the AI system cause any harm or distress to individuals or society at large?

5. Requirements: *confidentiality and data management*:

- Are there mechanisms to anonymize sensitive data?
- Are procedures in place to restrict data access to authorized personnel only?
- Is learner data stored securely and used solely for its intended educational purposes?

- Can teachers and administrators flag privacy or data-protection concerns?
- Are learners and staff informed about how their data is processed and for what purposes?
- Are privacy and data-protection settings configurable by users?
- Does the system comply with the General Data Protection Regulation (GDPR)?

6. Requirements: *technical reliability and security*:

- Is the system secured against data breaches and unauthorized access?
- Is there a monitoring and verification strategy to ensure the AI system meets its objectives and stays within its defined scope?
- Are oversight mechanisms in place for data collection, storage, processing, minimization, and usage?
- Is technical documentation available to reassure learners and parents of the AI system's reliability and safety?

7. Requirement: *accountability*:

- Who is responsible for the continuous monitoring of the AI system's outcomes, and how are those outcomes used to improve teaching, learning, and assessment?
- How is the system's effectiveness and impact evaluated, and how are core educational values incorporated into that evaluation?
- Who holds ultimate responsibility for procurement and deployment decisions regarding the AI system?
- Is there a clear service-level agreement defining support, maintenance services, and escalation procedures for reported issues? [summarized from: 6]

Depending on the goals, AI and data can be useful in various ways:

– Selecting appropriate resources and planning lessons or courses;
– Adopting adaptive learning technologies tailored to each learner's abilities;
– Using student dashboards to guide learners through their educational journey;
– Providing personalized interventions for special needs;

– Automating essay grading via AI-driven tools;
– Forecasting potential student dropout;
– Managing student recruitment and resource planning;
– Using chatbots for consulting students and parents in administrative tasks.

Considering the possibilities of using AI and data in education and training, the EU emphasizes that the school/educational institution must prepare and implement a joint and reflective process of internal self-assessment. This requires teachers to examine how they can use AI systems to positively support the teaching and learning of students, as predicting the consequences and impact of using data and AI in education can be very challenging. Therefore, a gradual approach to the development and implementation of these technologies and their evaluation is necessary. The idea is to gradually introduce these tools into their context and continuously monitor the societal consequences that may arise, leaving open the possibility to retreat when unforeseen consequences occur. The ethical application of AI in education requires the involvement of the student, the teacher, school leadership, and the institutional level.

Effective planning for the use of AI and data in schools/educational institutions in the European Union involves the following steps:

1. *Planning the effective use of AI and data in the school*. For this, it is useful to list the data that the school collects and clarify what purpose it serves. Schools should consider whether there is less specific information that could be gathered to achieve the same outcome. They should also consider how long the data will be needed and how the school can store it for as little time as possible.

2. *Initiation of policies and procedures*. Before implementing the AI system, it is necessary to establish a school-wide policy and procedures to define expectations and provide guidance on how to consistently address issues as they arise. These may include measures for:

– Procurement of trustworthy, human-centred AI;
– Human oversight mechanisms;

– Ensuring input data aligns with the AI system's intended purpose;
– Training requirements for staff;
– Ongoing monitoring and corrective actions;
– Compliance with GDPR obligations, including conducting Data Protection Impact Assessments.

3. *Conducting a pilot test of the AI system*. It is useful to test the AI system on a specific group of students. It is important to have a clear understanding of what the school aims to achieve with the new technology so that a reasoned decision can be made with the involvement of students and their parents. Specific evaluation criteria are needed to make a reasoned judgment about the effectiveness of the AI system in terms of improving learning outcomes, cost-effectiveness, and ethical use.

4. *Collaboration with the AI system provider*. It is important to maintain contact with the AI system provider before deployment and throughout the entire life cycle of the AI system. Look for clear technical documentation and seek clarification on any unclear aspects. An agreement on the service level (SLA) should be established with the provider, which outlines the support and maintenance services, as well as the steps that need to be taken to address reported issues. Guarantees should be obtained from the provider regarding compliance with applicable legal obligations.

5. *Monitoring the operation of AI systems and assessing risks*. The use of AI systems should be continually monitored to evaluate their impact on teaching, learning, and assessment methods. At the school level, it will be important to decide how monitoring will be organized and conducted, who will be responsible for monitoring, and how progress will be determined and reported. Evidence gathered from continuous monitoring should inform and influence the future use of AI systems or the decision not to use them under certain circumstances [summarized from: 6].

Planning for the effective use of AI and data in schools/educational institutions in the European Union is recommended to be accompanied by *planning for community awareness and engagement, which involves the following steps*:

1. *Discussion with colleagues*. Encourage cross-staff discussions to share insights and delegate tasks, fostering collective effectiveness.
2. *Collaboration with other schools*. This is an effective way to exchange experiences and best practices, as well as to learn how other schools implement AI systems. It is also useful for identifying reliable AI and data system providers that meet key requirements for reliable AI. It is important for schools to participate in controlled projects and experiments organized at regional, national, or European levels through initiatives such as Erasmus+.
3. *Communication with parents, students, and the school community*. Involving parents and students in discussions and decision-making leads to better understanding and trust in what the school aims to achieve through AI systems. It is essential to carefully consider how to explain what data is being collected, what is being done with it, how and why it is collected, and how it is protected.
4. *Be aware of developments*. As AI systems continue to evolve and the use of data increases, it is very important to develop a better understanding of their impact on the surrounding world, including education and training. Educators will need to continue to stay informed about innovations and developments through participation in continuous professional learning and engagement in collaborative practices. School leaders will need to provide opportunities for staff to upskill and continue to develop competence for the ethical use of AI and data. [summarized from: 6].

The *Ethical Guidelines for the Use of AI and Data in Teaching and Learning for Educators* outline new competencies for the ethical use of AI and data. Their relevance is justified by the fact that educators and school/educational institution leaders play a central role in the successful implementation of AI systems and in realizing the potential benefits of digital data in the education sector in the European Union. Therefore, it is important for educators and school leaders to understand and appreciate the opportunities and challenges of using AI systems and how they can enhance teaching, learning, and assessment practices.

This will give rise to new digital competences, which should be considered within the context of the European Framework for the Digital Competence of Educators (DigCompEdu). DigCompEdu provides a common reference framework to support the development of specific digital competences for educators across Europe [7]. Its structure is designed for teachers at all educational levels–from early childhood to higher and adult education, including general, vocational, special, and informal learning. The framework aims to establish a shared coordinate system for all stakeholders who design digital-competence models: EU Member States, regional authorities, national and regional agencies, educational organizations, and public or private professional-training providers in the European Union.

Below are the potential indicators of new competences for educators and school leaders in the ethical application of AI and data in teaching and learning in the European Union (Table 3).

Thus, the challenges and risks of the ethical use of AI and data in teaching and education lie in the need for ethical education, where educators must be specifically trained to understand the ethical aspects of AI use. The lack of such training can lead to unethical use of these technologies.

In 2016, the European Commission launched the *New Skills Agenda for Europe* [8]. Within this initiative, recommendations were developed for member states to implement the program *Upskilling Pathways: New Opportunities for Adults*,' aimed at improving the basic skills of the population in the areas of literacy, mathematics, and digital competence.

Additionally, the Commission issued a *Recommendation on Key Competences for Lifelong Learning*, with a particular emphasis on developing skills in STEM (science, technology, engineering, and mathematics), digital literacy, entrepreneurial thinking, and creativity.

To foster digital skills and competences among all EU citizens, *the Digital Education Action Plan* was adopted. A key component of this Plan is the examination of artificial intelligence's impact on education and learning processes, carried out through targeted pilot projects.

Table 3

Potential Indicators of New Competences for Educators and School Leaders in the Ethical Use of AI and Data in Teaching and Learning in the EU

Element of competence	Potential Indicator
1	2
Sphere 1: Professional engagement – the use of digital technologies for communication, collaboration, and professional development.	
Able to critically describe	– Actively participates in continuous professional development in AI and learning analytics, and their ethical use.
	– Able to provide examples of AI systems and describe their relevance.
Positive and negative impact of AI and data use in education	– Knows how the ethical impact of AI systems is assessed in schools.
	– Knows how to initiate and promote strategies in the school and its wider community that encourage the ethical and responsible use of AI and data.
	– Understands how to initiate and advance strategies within the school and its wider community to promote the ethical and responsible use of AI and data.
Understands the basics of AI and analytics study	– Aware that AI algorithms operate in ways that are not typically visible or easily understandable to end users.
	– Capable of interacting with AI systems and providing feedback to influence their subsequent recommendations.
	– Recognizes that sensors embedded in many digital technologies and applications generate large volumes of data, including personal data, which can be used to train AI systems.
	– Familiar with the EU's ethical principles on AI and with available self-assessment tools.

Continuation of Table 3

1	2
Sphere 2: Digital resources – searching, creating, and sharing digital resources	
Data Management	– Knows the various types of personal data used in education and training.
	– Understands the obligations to ensure data security and confidentiality.
	– Knows that the processing of personal data is governed by national laws and EU regulations, including the GDPR.
Data Management	– Knows that in compulsory education, personal data processing generally cannot rely on user consent.
	– Knows who has access to student data, how access is controlled, and how long the data is retained.
	– Knows that all EU citizens have the right not to be subject to automated decision-making.
	– Can cite examples of confidential data, including biometric data.
	– Can weigh the benefits and risks before permitting third parties to process personal data, especially when using AI systems.
AI Management	– Understands that AI systems are subject to both national and EU regulations.
	– Can explain the risk-based approach as defined in the EU AI Act.
	– Knows high-risk use cases of AI in education and the corresponding requirements according to the AI Act.
	– Knows how to integrate AI-edited or AI-processed digital content into their own practice and how to evaluate it.
	– Able to explain the key principles of data quality in AI systems.

Continuation of Table 3

1	2
Sphere 3: Teaching and Learning – management and organization of the use of digital technologies in teaching and learning	
Learning models	– Knows that AI systems implement the designer's understanding of what learning is and how it can be measured; can explain the key pedagogical assumptions underlying this digital learning system.
Objectives of education	– Knows how this digital system addresses various social goals of education (qualification, socialization, subjectivization).
Human agency	– Can assess the impact of an AI system on teacher autonomy, professional development, and educational innovation.
	– Examines sources of unacceptable bias in the data used in AI systems.
Fairness	– Considers the risks associated with emotional dependency and students' self-esteem when using interactive AI systems and learning analytics.
Humanity	– Can take into account the impact of the use of AI and data on the student community.
	– Confidently engages in discussions on the ethical dimensions of AI and their implications for technology use.
Participates in the development of educational practices that use AI.	– Can explain how ethical principles and values are incorporated and negotiated during the co-design and collaborative development of AI- and data-driven learning practices (in the context of instructional design).
Sphere 4: Assessment – the use of digital technologies and strategies to improve assessment	
Personal differences	– The realization that students respond differently to automated feedback.
Algorithmic bias	– Considers the sources of unacceptable bias in AI systems and ways to mitigate it.

Continuation of Table 3

1	2
Cognitive focus	– Recognizes that AI systems assess a student's progress based on predefined subject knowledge models.
	– Recognizes that most AI systems do not assess collaboration, social skills, or creativity.
New ways of abusing technology	– Knows common methods of manipulating AI-based assessments.
Sphere 5: Expanding student capabilities – using digital technologies to improve inclusion, personalization, and active student participation	
AI meets the diverse educational needs of students.	– Knows how personalized learning systems can adapt their behaviour (content, learning pathways, pedagogical approach).
	– Can explain how the system can benefit all learners regardless of their cognitive, cultural, socioeconomic, or physical differences.
	– Recognizes that digital learning systems may treat different student groups in different ways.
	– Can evaluate the impact on a student's self-efficacy, self-assessment, thinking, and cognitive and emotional self-regulation.
Justified choice	– Knows that AI and data use may advantage some learners more than others.
	– Can explain which evidence underpinned the decision to deploy this AI system in class.
	– Acknowledges the need for ongoing monitoring of AI outcomes and can learn from unexpected results.
Sphere 6: Promoting students' digital competence – providing students with the opportunity to creatively and responsibly use digital technologies for information, communication, content creation, well-being, and problem-solving.	
AI and the ethics of learning analytics	– Able to use AI projects and deployments to help students learn about AI ethics and the use of data in education and training.

Source: summarized by the author based on [6]

The current *European Skills Agenda* is a five-year plan designed to help individuals and businesses develop and leverage more and better skills by:

– Strengthening sustainable competitiveness;
– Ensuring social fairness;
– Building resilience [8].

The European Commission is adopting a new, dynamic EU-level skills policy approach aimed at guiding Member States and supporting the twin green and digital transitions, as well as ensuring recovery from the socio-economic impact of the COVID-19 pandemic. To succeed, lifelong learning for all must become a reality across Europe – in every Member State and region. The Recovery Plan for Europe, proposed by the Commission in May 2020 for the period 2021–2027, likewise focuses in part on measures related to skills, innovation, and digital technologies [10].

The European Skills Agenda defines targets to be met by 2025, based on quantitative indicators (Table 4).

Table 4

EU Skills Targets to Be Achieved by 2025

Naming of indicators	Goals for 2025	Current level (available last year)	Increase in percentage
Participation of adults aged 25–64 in learning over the last 12 months (%)	50 %	39.5 % (2022)	+27 %
Participation of low-skilled adults aged 25–64 in training over the last 12 months (%)	30 %	18.4 % (2022)	+63 %
The share of unemployed adults aged 25–64 with recent learning experience (%)	20 %	14.1 % (2023)	+42 %
The share of unemployed adults aged 25–64 with recent learning experience (%)	70%	55.6 % (2023)	+26%

Source: [8]

First of all, the European Commission considers it necessary to significantly increase the share of adults participating in education overall – only this guarantees an approach to lifelong learning. In addition, to ensure that recovery and the dual transition are socially fair, the Commission also proposes clear targets for the participation of low-skilled adults and the unemployed in education.

By 2025, 120 million adults in the EU should participate in learning each year. This corresponds to 50 percent of the adult population and approximately 540 million learning activities for this group over the five-year period. By 2025, 14 million low-qualified adults should engage in learning annually, equivalent to 30 percent of that cohort and roughly 60 million learning activities over five years. Monitoring this indicator alongside the actions set out in the European Skills Agenda for Sustainable Competitiveness, Social Fairness, and Resilience will also help reduce the share of low-qualified adults, which stood at 22 percent in 2019 – a figure that lags behind many global competitors.

Furthermore, by 2025, 2 million job seekers – approximately one in five – should have recent learning experience, equating to some 40 million learning activities for this group over five years. Regarding learning content, a broad spectrum of skills will be needed to support recovery and the success of the Twin Green and Digital Transitions. In particular, digital skills, strengthened by the COVID-19 context, are essential for work, education, and social interaction. Therefore, the fourth monitoring target is the share of adults who possess at least basic digital skills. By 2025, 230 million adults – 70 per cent of the EU's adult population – should have at least a basic level of digital competence [summarised from: 9].

To achieve its skills targets, the European Union is making substantial investments. Beyond contributions from businesses and Member State governments, the EU budget now prioritises investment in people and their skills (Table 5).

It is estimated that meeting the overall adult-learning participation goal will require an additional €48 billion per year. Moreover, rolling out the full Skills Agenda will necessitate further funding to support activities at the EU, national, regional, and local levels.

Table 5

EU Budget Priorities for Skills Investments

Program	**Investment (€ billion)**
Recovery and Resilience Facility (RRF)	67.7
European Social Fund Plus (ESF+)	42
Erasmus+	26.1
European Regional Development Fund (ERDF), incl. Interreg	8.7
InvestEU	2.8
Just Transition Fund (JTF)	3.1
European Globalisation Adjustment Fund	1.1
Asylum, Migration and Integration Fund (AMIF)	0.8
European Solidarity Corps	0.8
Digital Europe	0.5
Technical Support Instrument (TSI)	0.024
EU4Health	0.016
Total	153.64

Source: [8]

The EU budget in the field of skills is closely integrated with *Next Generation EU (NGEU)* – a temporary instrument for economic recovery established by the European Union in 2020 to tackle the economic and social consequences of the COVID-19 pandemic. *The main goal of NGEU* is to assist EU member states in overcoming the economic and social impacts of the COVID-19 pandemic, making their economies more resilient, environmentally friendly, and digital, as well as promoting inclusive growth.

The Commission's proposal for Next Generation EU (NGEU) includes significant resources within a large-scale budget initiative to address the economic and social consequences of the crisis. The

Commission will ensure the effective use of its tools to support and unlock investments in human capital, promoting gender equality and inclusiveness. Member states will be invited to use EU financial resources *to implement national reskilling and upskilling schemes for the workforce*.

In the short term, REACT-EU, financed under *NextGeneration EU* and the proposed adjusted 2020 EU budget, will provide €55 billion to the Cohesion Policy funds for 2020–2022. This allocation enables the European Social Fund to channel additional financing into upskilling *opportunities that accompany the green and digital transitions*.

Moreover, the *Recovery and Resilience Facility*, totalling €560 billion in grants and loans, offers Member States extensive scope to fund upskilling and reskilling measures. The European Commission's 2020 country-specific recommendations focused on urgent actions to mitigate the socio-economic impact of the pandemic, identifying *skills, education, and vocational training as a short-term priority for 22 Member States*. The national recovery and resilience plans that countries must submit to access Facility financing are required to reflect skills development as a programming priority.

During the 2021–2027 period, the *European Social Fund Plus (ESF+)*, with a proposed budget of €86 billion, will remain a key source of *financing for national upskilling and reskilling initiatives*.

In addition, the proposed €24.6 billion for *Erasmus+ will support skills development and fund several of the measures mentioned above*, such as European Universities, Centres of Vocational Excellence, and Sectoral Skills Alliances. Moreover, Erasmus+ can facilitate a significant expansion of *both physical and virtual learning mobility across the EU*, opening up new educational opportunities that may not be available domestically.

The *Horizon Europe programme* will play a pivotal role in the recovery, particularly in driving the twin green and digital transitions, by supporting industry and SMEs, as well *as universities and researchers, and by fostering brain circulation and researcher mobility*. The new Digital Europe programme will invest in the enhancement of academic offerings in digital fields and in specialised training opportunities in areas such as *data processing, cybersecurity, and artificial intelligence*, thereby addressing the current skills shortage in these critical sectors.

Other resources can directly support the *upskilling and reskilling of Europe's workforce*. Member State investments in "socially impactful infrastructure" for education and training, including digital infrastructure, can be further backed by the *European Regional Development Fund and the InvestEU programme*. Under its "Social Investment and Skills" window (with a proposed budget guarantee of €3.6 billion), Invest EU can, among other things, fund investments in *critical education and training infrastructure*.

In the context of the green transition, the Commission has made "*just transition skills*" a priority for all *27 Member States*, utilising the Just Transition Fund with its proposed €40 billion envelope. The public-sector loan facility under the Just Transition Mechanism – expected to mobilise €25–30 billion – can also invest in skills. The ceiling of the European Globalisation Adjustment Fund has been proposed for doubling in the next Multiannual Financial Framework to support upskilling and reskilling of workers and self-employed persons made redundant by large-scale industrial restructuring. Other instruments, such as the Modernisation Fund, will likewise finance upskilling and reskilling programmes to assist workers in regions and sectors affected by the green transition. [summarised from: 9].

The implementation of the Skills Agenda – including the Pact for Skills and the use of NextGenerationEU resources – encompasses a wide range of actions, for example:

– *Investments in inter-company training centres*, where firms along a value chain pool resources to deliver specialised staff training;

– *Full-scale deployment of enhanced Sectoral Skills Alliances* at national and regional levels;

– *Development and operation of skills-forecasting systems* that provide actionable intelligence on upskilling and reskilling needs at national, regional and sectoral levels – explicitly covering both the green and digital transitions – and encompassing all stages of data collection, analysis and dissemination;

– *Design and roll-out of National Skills Strategies*, developed and implemented through a cross-government approach to accompany the twin transitions, aligning efforts across a broad policy spectrum with the active involvement of stakeholders (social partners, civil society, labour-market actors, and education and training providers);

– *Reforms of vocational education and training (VET) and apprenticeship programmes*, including curriculum modernization to better match labour-market needs, integration of green and digital skills, enhanced flexibility and modularity, expansion of higher VET pathways, establishment of quality-assurance and graduate-tracking systems, up-skilling of VET teachers and trainers, support for learner, teacher and trainer mobility, and creation of Centres of Vocational Excellence linked to smart-specialisation or regional innovation and growth strategies;

– *Direct apprenticeships subsidies for SMEs*, covering trainee remuneration, hiring bonuses and temporary social-security contributions (up to 12 months), as well as instructors' salaries and social contributions, to stabilise and expand high-quality apprenticeship offers;

– *Investments in digital learning equipment and technologies*, and in advanced industrial machinery and technologies for education and training providers;

– *Incentives for the development of digital learning content and core curriculum modules* tailored to labour market needs, with a focus on digital and green skills, including online learning platforms;

– *Short-term reskilling courses* for workers transitioning to new job roles and skill requirements arising from the green and digital transitions – e.g., ICT Jump-Start and Digital Crash courses targeting SMEs to deliver intensive, rapid upskilling in ICT;

– *Master's-level programmes* to train digital experts in advanced digital competences required for digital transformation, and to prepare specialists with green-economy skills;

– *Regional and local entrepreneurial-skills hubs* supporting start-ups, employee-entrepreneurs, and innovators;

– *Investments in the quality, equity, and labour-market relevance of education and training systems* to ensure individuals acquire the key competences needed in today's workplaces and societies;

– *Support for community learning centres for adults*, where people of all ages engage in learning and knowledge exchange, fostering resilient, cohesive communities;

– *Creation, pilot implementation and operation of individual learning account schemes*;

– *Measures to encourage and facilitate learning participation*, such as adult learning credits/grants, funding for learning leave, and targeted learning support for the unemployed;

– *Support for learning initiatives accompanying reduced-working-time arrangements*, safeguarding workers and self-employed persons, especially against the risk of unemployment [summarised from: 8–9].

The European Commission will work closely with national authorities and other stakeholders to ensure adequate EU resources are allocated to support the various dimensions of the Skills Agenda. The Commission will encourage and assist Member States in prioritising skills investments under the Recovery and Resilience Facility and will monitor progress through the European Semester. This monitoring will be published in the annual Joint Employment Report and will serve as an analytical basis for more targeted country-specific recommendations on skills, education, and vocational training. Where feasible, the Commission will track achievements by gender, geographic region, and vulnerable groups, beyond low-skilled and unemployed persons, to include, for example, people with disabilities.

Delivering the Skills Agenda, particularly in digital competences and the application of AI in teaching and learning, opens new horizons for educational practice and plays a pivotal role in developing the knowledge economy, fostering its growth and qualitative transformation.

Nonetheless, *AI uptake among EU enterprises* with ten or more employees remains low: in 2023, only 8.0 % of such firms reported using any AI technologies, up marginally from 7.6 % in 2021. Considerable disparities exist across Member States. In 2023, the top ten countries exceeded 10 % AI adoption in non-financial enterprises (10+ employees): Denmark (15.2 %), Finland (15.1 %), Luxembourg (14.4 %), Belgium (13.8 %), the Netherlands (13.4 %), Malta (13.2 %), Germany (11.6 %), Slovenia (11.4 %), Austria (10.8 %), and Sweden (10.4 %). A second group ranged from 9.2 % to 5.2 %: Spain (9.2 %), Ireland (8.0 %), Croatia (7.9 %), Portugal (7.9 %), Slovakia (7.0 %), the Czech Republic (5.9 %), and Estonia (5.2 %). In the remaining Member States, adoption rates were 5 percent or lower: Italy (5.0 %), Lithuania (4.9 %), Cyprus (4.7 %), Latvia (4.5 %), Greece (4.0 %), Hungary (3.7 %), Poland (3.7 %), Bulgaria (3.6 %), and Romania (1.5 %) [11].

The use of AI and data within the knowledge economy is a critical driver of its development and transformation. A knowledge economy – grounded in the creation, dissemination, and application of information and c – derives substantial momentum from AI's capacity to process, analyse, and interpret large datasets, as well as to automate cognitive tasks.

Specifically, *the application of AI and data in the knowledge economy*:

- *Enhances the quality of human capital*. Personalised learning enabled by AI and data analytics better addresses each learner's needs and abilities. This leads to deeper mastery of content, development of essential skills, and the creation of a more qualified and competent workforce – the very foundation of a knowledge economy.
- *Improves knowledge management*. AI systems can organise, classify, and retrieve information, streamlining access to relevant knowledge for employees and facilitating experience exchange.
- *Generates new knowledge and innovation*. By detecting patterns and trends invisible to human analysts, AI fosters scientific discovery and the development of novel technologies, products, and services.
- *Stimulates innovation*. AI can identify gaps in existing knowledge and priority research areas, thereby catalysing the generation of new

ideas and technologies. Optimized learning processes then prepare specialists capable of innovative thinking and value creation in the knowledge economy.

- *Creates knowledge-based products and services*. AI underpins the development of intelligent information and expert systems, customer-support platforms, and personalized recommendation engines – high-value offerings in the knowledge economy.
- *Increases the efficiency of educational institutions*. By automating routine tasks for educators and administrators, AI frees up time for strategic activities. Data analytics likewise supports curriculum optimisation and resource allocation, boosting overall system performance.
- *Fosters lifelong learning*. AI can craft personalized learning pathways and recommend relevant resources throughout an individual's lifetime. In a rapidly evolving knowledge economy, the ability to continuously update skills and knowledge is essential for maintaining competitiveness.
- *Develops future-oriented skills*. AI and data analytics help anticipate the competencies most in demand in tomorrow's knowledge economy. Customised educational programmes that reflect these insights equip graduates for successful careers in high-tech sectors.
- *Optimises and automates R&D processes*. AI can handle repetitive tasks, analyse vast volumes of experimental data, uncover novel connections and patterns, and thus accelerate scientific breakthroughs and the knowledge-creation cycle. This boosts productivity and liberates human talent for more creative and complex work.

In summary, deploying AI and data in education is not merely a tool for improving instructional processes; it is a strategic catalyst for the knowledge economy, shaping a highly skilled workforce, driving innovation, and enhancing the efficiency of education and research.

Conclusions: The European Union demonstrates a proactive, multifaceted approach to integrating AI and data into education and the knowledge economy. Grounded in principles of ethics, safety, and human-centrism, the EU is establishing a robust legislative framework, investing in research and innovation, and rolling out concrete programmes to unlock AI's potential. Analysing these European experiences is highly valuable for Ukraine as it seeks to integrate into the European educational and economic space and develop its own capacity in these critical fields.

A key element of the European approach to AI and data in education and the knowledge economy is the creation of an enabling ecosystem. This ecosystem encompasses investments in R&D, support for innovative start-ups, the establishment of competence centres, and the promotion of interdisciplinary collaboration among academia, industry, and the public sector.

Ukraine could draw on European best practice in several ways:

- *Regulatory framework*: Studying the EU AI Act and related regulations can guide Ukraine in crafting its own legal regime for AI in education, balancing innovation with rights protection.
- *Strategic implementation*: European digital skills and AI-in-education strategies can serve as a roadmap for Ukraine's national programmes and initiatives.
- *Research and mobility*: Participation of Ukrainian universities, research centres, and EdTech firms in Horizon Europe and Erasmus+ will facilitate knowledge exchange, attract funding, and accelerate the adoption of cutting-edge European solutions.
- *EdTech adoption*: Adapting proven European AI applications – such as intelligent learning platforms, automated assessment tools, and student-support systems – can help modernise Ukraine's education system and improve learning outcomes.

Ukraine can leverage this experience by fostering public–private partnerships and directing investments toward priority AI research areas with high potential in the knowledge economy, such as natural language processing, machine learning for big-data analytics, and intelligent decision-support systems.

A cornerstone of the European strategy is *its focus on the ethical and legal dimensions of AI use*. EU regulations designed to ensure algorithmic transparency, accountability, and fairness, alongside the protection of personal data and human rights, are critical to building societal trust in AI and data technologies. In adopting European best practices, Ukraine should develop its own legal framework that both stimulates innovation and minimises the potential risks associated with AI and data use. Incorporating the EU's ethical guidelines for AI in education will be essential for earning the trust of Ukrainian teachers, learners, and parents.

In this spirit, the Ministry of Digital Transformation and the Ministry of Education and Science of Ukraine – working with the relevant Task Force and in accordance with the EU Artificial Intelligence Regulation, adopted by the European Parliament in March 2024 – have prepared the *Guidelines and Methodological Recommendations for the Introduction and Use of Artificial Intelligence Technologies in General Secondary Education Institutions (Draft)*. These guidelines are intended to establish principles for the responsible, ethical, and effective deployment of AI technologies in Ukrainian schools [12].

The document comprises the following components: "AI application domains; core principles for the responsible use of AI systems in general secondary education; organisational deployment of AI in educational institutions; professional development for teachers' AI competence; teachers' use of AI for lesson planning and delivery; typology of AI systems in education" [12]. The Guidelines also include annexes with:

– Sample provisions that can be incorporated into policies, regulations, or recommendations for the responsible use of AI;
– Risk-mitigation measures for AI deployment in education;
– Recommended student activities, with age-appropriate restrictions for AI-based services;
– Levels of AI tool integration for completing learning tasks;
– The digital-competence framework for teaching and research staff, enhanced with AI-related components;
– Guidance on prompt engineering, including sample prompts;
– Ideas for using AI tools during classroom instruction;
– Examples of generative AI tools for education [12].

In the context of the knowledge economy, European experience highlights AI and data's significant potential to enhance *educational and research processes*. AI systems can personalise learning, automate routine tasks for educators and researchers, analyse large corpora of scientific literature, uncover emerging trends and patterns, and support decision-making in R&D. Introducing these tools into Ukrainian schools, vocational institutions, universities, and research centres could substantially improve the quality of education and research.

Furthermore, AI and data increasingly underpin *innovation in the knowledge economy*. European companies deploy AI to build intelligent information systems, knowledge-management platforms, collaborative knowledge-sharing environments, and new educational and consulting services. Encouraging Ukrainian businesses to adopt similar technologies will foster high-tech job creation and increase the national economy's value added.

In summary, importing European best practices for AI and data in the knowledge economy is strategically vital for Ukraine. This endeavour demands a holistic approach – establishing an enabling ecosystem, developing ethical and legal standards, investing in education and research, and supporting innovative enterprises. By adapting successful European models, Ukraine can fully harness AI's benefits to advance its knowledge economy, enhance competitiveness, and secure a sustainable future.

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1.2. DIGITALIZATION OF FINANCES OF LOCAL GOVERNMENT OF THE ZAPORIZHIA REGION

Introduction. A state that provides a high standard of living, has the latest technological developments, implements digital finance with transparent and zero corruption at all levels is a leader of a strong digital economy and sustainable development. Therefore, the digitalization of regions and communities is a guarantee of the well-being of the population, the creation of new opportunities, the social transformation of life to the European level into modern, comfortable and safe, the reconstruction of the latest opportunities for the implementation of working capital, the development of innovative, creative and digital technologies and business, that is, the creation of a better life, work, creativity and education. The digitalization of local government finances in the Zaporizhia region has provided an opportunity to create industrial parks in communities, open new IT enterprises, digitize their services for businesses, conduct a digital campaign among doctors, educators, and municipal employees, connect settlements to fiber – optic networks and provide settlements with 4G mobile communications, implement an integrated video surveillance system, develop an electronic queue for enrolling a child in an institution, and introduce online doctor's appointments in hospitals. All of the above social, economic, and municipal services work thanks to the effective use of digital tools by local governments in the Zaporizhia region and meet modern EU requirements.

Presentation of the main material. Despite the war that has lasted for more than 3 years, Ukraine, creating innovative products, is becoming the most powerful state and leader with working digitized state and social services. Ukraine has achieved powerful changes in digital transformation and the country's digital economy guarantees a high, comfortable standard of living for its citizens, increased incomes, social support, and the introduction of barrier-free access for vulnerable segments of the population. It should be noted that Ukraine is the only European country that has sufficient human resources that can be used in the development of the digital economy [1]. It is digital tools that today decide and implement the reforms required by the status of a candidate for EU accession – these are the principles of transparency, democracy, openness, and accountability. The Cabinet of Ministers of Ukraine, by its Resolution No. 1351-r dated December 31, 2024, approved "On approval of the Strategy for the Digital Development of Innovative Activity of Ukraine for the period until 2030 and approval of the operational plan of measures for its implementation in 2025–2027". This resolution also approved the operational plan of measures for the implementation in 2025–2027 of the Strategy for the Digital Development of Innovative Activity of Ukraine for the period until 2030 [2]. The strategic digital development of Ukraine provides for the following key goals:

– "priority of developing an innovative ecosystem in educational institutions, creating conditions for in-depth study of academic subjects and integrated courses in mathematical and natural science educational fields";

– "improvement of coordination and interaction in the formation and implementation of policy in the field of innovation activity";

– "regulation of the regulatory framework for innovation, scientific, industrial and technological parks, Industry 4.0 centers, as well as the functioning and support of business accelerators, business incubators and startups";

– "stimulating research and development in conditions of limited material resources, enabling the implementation of innovative projects in priority areas";

– "ensuring the development and implementation of digital innovations in the defense sector";

– "increasing the efficiency of the agricultural sector and land management through innovative solutions";

– "ensuring the creation of conditions for the development of internal infrastructure for research, innovation and implementation of solutions in the field of artificial intelligence", etc.

The approved strategic goal of the digital development of Ukraine stipulates that all regions of Ukraine should join the Smart Platform of European Specialization (S3 PLATFORM) in order to include the regions of Ukraine and give them access to the tools of the European Platform. It also stipulates the development and implementation of processes of state financial support for regional development projects that provide for the sustainable development of types of economic activity that are extremely important for Ukraine, implemented through smart specialization and provided for in regional sustainable development strategies. However, due to the outbreak of the war in the Russian Federation, the inclusion and accession of Ukrainian regions (of Ukraine this European platform) to smart – specialization has been suspended. As of December 2024 to European platform, eleven regions of Ukraine (Volyn region, Dnipropetrovsk region, Zhytomyr region, Chernivtsi region, Sumy region, Mykolaiv region, Kherson region, Zaporizhia region, Autonomous Republic of Crimea, Kyiv city, Sevastopol city) did not join [2]. The "Ministry of Development of Communities, Territories and Infrastructure of Ukraine" together with the "Ministry of Digital Transformation of Ukraine" are developing and agreeing on the "Concept of Digital Solutions for ATC". This Concept will significantly help to implement state regional policy and implement decentralized reform. The Concept structures and prioritizes the implementation of digital technologies in regions that strengthen reforms. The Concept is a vector that guides donors who invest in digital solutions in Ukraine, and is also a guideline for sustainable development for communities and regions. The formulated directions of the Concept are concentrated and presented in Table. 1 [5].

Table 1

Key areas of the Concept

No.	Name of the direction
1	"The DREAM Single Digital Recovery Management Ecosystem"
2	"A unified geographic information system for monitoring and evaluating the development of regions and territorial communities (GIS of regional development)"
3	"Register of local government decisions"
4	"Urban planning cadastre at the state level"
5	"Digital solutions for local finance administration"
6	"Digital solutions for implementing local democracy"
7	"Register of municipal property"

Source: compiled based on [5]

Digitalization of processes, namely, monitoring, control, audit and administration of financial flows, should increase not only the cash flows of local budgets, but also contribute to the implementation of transparency, monitoring and independence of local government bodies, promote self-synchronization of strategic planning and budgeting, financial planning, and increase profitability by collecting financial resources, namely local taxes and fees. Also, digitalization of local government finances attracts and ensures the active participation of business and the concerned public in the post-war reconstruction and sustainable development of Ukraine, provides local government bodies with a new technological tool for discussing socially important issues with the public, increases the variability of opportunities by conducting surveys and voting among the localities. In addition, digital technologies expand the opportunities of the public to participate in the development and restoration of the country, offering their projects, participating in grants and distributing funding. By implementing digital tools, every citizen feels like a necessary part of society, involving their advice and opinions to improve the country, notifying local authorities about current, urgent problems regarding the improvement of the housing and communal services and infrastructure sectors, etc. The use of digital technologies improves the objectivity of monitoring, controlling, auditing, and the effectiveness of projects during their implementation. Optimization and improvement of local tax administration, the concept of which is reflected in several state legislative acts, in particular, in the "National Revenue Strategy until 2030" (CMU Order No. 1218-r dated 27.12.23) [7], "Plan of measures for reforming local self-government and territorial organization of power in Ukraine for 2024–2027" (CMU Order No. 270-r dated 26.03.2024) [8], "Budget Declaration for 2025–2027" (CMU Resolution No. 751 dated 28.06.2024) [9]. Several examples of government decisions on the implementation of digital technologies and systems can be given, for example, the "TREMBITA" system, the "PORTAL" DIYA, the "PROZORRO" system, the "SPENDING" system, etc.

To develop innovations in management, the Ministry of Digital Affairs of Ukraine uses and involves everyone in the use of an effective management system – OKR (Performance Measurement System), which is practiced by technology giants Google, Amazon, Microsoft, Intel, Samsung and others. The system provides an increase in the range of services and the implementation of unplanned projects: legal, HR, IT processes, innovative and technological, modernization of government digital technologies, digital education, smart services for citizens and businesses, 4G communications, European integration and international cooperation relations [10].

Zaporizhia region is one of the first to implement digital governance at all levels of administration and the City Council Resolution No. 117 dated February 23, 2022 approved "On Approval of the Concept "Digital Strategy of Zaporizhia-2030" [11]. Local governments of the Zaporizhia region were guided by the following legislative acts:

– The Law of Ukraine "On Local Self-Government in Ukraine";
– The Law of Ukraine "On Information";
– Resolution of the Cabinet of Ministers of Ukraine dated August 5, 2020 No. 695 "State Strategy for Regional Development for 2021–2027", in accordance with the requirements of the section "Digital Transformation of Regions";

– By decision of the Zaporizhia City Council dated December 28, 2020 No. 40, in accordance with the City Target Program "Digital Strategy of the City for 2021–2023" (as amended).

The adoption of the Concept of the Digital Strategy 2030 of the Zaporizhia region will not only ensure the implementation of the principles of digitalization of the state economy, the development of sustainable development of the region, but also increase the range of social digital services and services for the local population of territorial communities.

The concept of the Digital Strategy of the Zaporizhia region is based on important principles such as simplifying citizens' access to various services, the principle of barrier-free access , the use of artificial intelligence in solving urban problems, involving business, the public and scientists in the development of the city, digitalization of document flow in local government bodies and municipal enterprises, increasing security, improving communications between city residents, local authorities and business representatives. These are the main ideas, but, in addition, digitalization allows you to save budget funds, increase the investment attractiveness of the city and strengthen information protection. Zaporizhia local governments face some challenges, but are actively solving them, this concerns the implementation of digitalization in the field of health administration at the community level, despite the fact that all communities have Health Care Institutions "HCI" in their ownership, on the territory of the community, but there are still not enough competencies, tools and data for effective management of these institutions and control over the provision of medical services. Currently, cities are promptly resolving these issues, strengthening competencies and providing access to the necessary information for local government at the community level, and implementing reforms of electronic, municipal medical digital data systems regarding disease statistics. Local governments of the Zaporizhia region actively participate in new competitions, including the European Union program " Digital Europe ". This program with a budget from donors of more than 3.2 billion euros. The funding provides for the implementation of digital economic projects aimed at the sustainable development of the entire region:

– high-performance computing;
– AI, data and cloud technologies;
– digital skills;
– introduction of digital technologies into the economy, finance and society.

Grants foreseen in 2025 are presented in Table 2.

Table 2

Proposed Grants in 2025

No./ no.	Grant name	Competition description	Submission deadline	Budget, million Euros
1	2	3	4	5
1	Grant "Creating an Academy of Artificial Intelligence Skills"	creation of an educational center with a focus on generative AI, quantum technologies and practical training	2.09.2025	10 million euros
2	Grant "Creating a Skills Academy for Virtual Worlds"	creating educational programs with Web 4.0, metaverses, 3D modeling and simulations	2.09.2025	10 million euros
3	Grant "Creation of the Academy of Quantum Technologies"	developing courses, summer schools, and internships for acquiring quantum skills	2.09.2025	7 million euros
4	Grant "Creating an operational system for responding to disinformation threats"	creation of a European network of fact-checkers and development of tools to combat disinformation	2.09.2025	5 million euros

Continuation of Table 2

1	2	3	4	5
5	Grant “Supporting national initiatives for child safety in the online environment”	supporting a network of Safer Internet Centers in Europe	2.09.2025	42 million euros
6	Grant “Supporting Innovation in Microcircuit Production and Semiconductor Technologies “	support for the activities of the Secretariat of the Alliance for Processors and Semiconductor Technologies (Alliance on Processors and Semiconductor Technologies) to strengthen the European ecosystem in the development and production of microprocessors and semiconductors	2.09.2025	1 million euros
7	Grant “Digitalization of data exchange in agriculture “	creating AI-based tools for the agricultural sector within the European Green Deal	2.09.2025	15 million euros
8	Grant “Development and Coordination of Pan-European Data Spaces “	developing tools for sharing and securely using data	2.09.2025	10 million euros
9	Grant “Development of advanced solutions for real-time data protection and management “	development and implementation of innovative digital solutions in the fields of agriculture, healthcare, energy, ecology and production	2.09.2025	8 million euros

Continuation of Table 2

1	2	3	4	5
10	Grant "Creation and Development of European Digital Innovation Hubs "	expanding the ECIH network, services, particularly in the field of AI, to support the digital transformation of small and medium-sized enterprises (SMEs), government organizations, etc.	05/14/2025	48 million euros
11	Grant "Implementation of educational initiatives in high-performance computing "	development and implementation of a pan-European Master's degree (MSc) in High Performance Computing (HPC), building on the experience of the EUMaster4HPC pilot project	05/14/2025	10 million euros
12	Grant "Development of AI Network of European Digital Innovation Hubs "	strengthening the network of hubs in participating countries with a focus on AI	2.09.2025	9 million euros

Source: Official website of the Ministry of Digital Affairs of Ukraine [13]

Every year, the Ministry of Digital Transformation of Ukraine (Ministry of Digital Transformation) calculates the "Digital Transformation Index" of territorial communities of the regions of Ukraine. The "Digital Transformation Index" is currently one of the technological tools for establishing the level of "digitalization" in the regions of the country. Its analysis of the "Digital Transformation Index" allows not only to find out the effectiveness of the implementation of digitalization by local governments of the regions, but also to determine the requirements for digital transformation. According to the "Digital Transformation Index", in 2024 the Zaporizhia region took 22nd place out of 24 possible. According to the rating, the leaders are Lviv region – 0.850 points, Dnipropetrovsk region – 0.844 points, and Odessa region – 0.804 points.

The Digital Transformation Index identifies nine key digital indices. Zaporizhia region received the following scores:

- 0.625 points for "institutional capacity" (1 possible);
- 0.462 points for "Internet development";
- 0.249 points for "development of ASCs";
- 0.07 8 points for "implementation of the "paperless" regime;
- 0.552 points for "digital education";
- 0.202 points for "region business card";
- 0.513 points for "penetration of basic electronic services";
- 0.243 points for "industry digital transformation";
- 0.105 points for "individual CDTO projects".

This year's "Digital Transformation Index" includes another new index – "individual CDTO projects". This index allows the CDTO of the Region's administration to independently prioritize activities for digitization according to the needs of the region.

In addition, in 2023, the digital transformation index in the Zaporizhia region was 0.289 points out of 1. And in Ukraine as a whole – 0.632 [12].

Despite the challenges, the Zaporizhia region is actively participating in the digitalization of all areas of management and moving towards digital transformation, and education is one of the key areas. In particular, 10 digital educational centers were opened in the region during 2024. Children can study and develop their skills in them.

Conclusions. In the current conditions – Martial Law, and later – in the post-war recovery period, local governments of Ukraine have major obstacles to economic development – the exit from the markets of investment activity of economic donors and investors. Especially, starting from February 2022, with the beginning of the full-scale military invasion of the Russian Federation into the territory of

Ukraine, this has been sensitively reflected in the inability of regions to attract funds and their usual management, organize the budgeting process, adapt social and economic regional infrastructure in order to carry out certain works. Changes in tax revenues taking into account the reality in the economic sector of the regions and the challenges that required communities to allocate more funds to strengthen territorial defense, assist the Armed Forces of Ukraine, strengthen the defense capability of territories, and provide humanitarian assistance to the civilian population along with current expenditure items.

This has significantly caused difficulties and reduced the ability of territorial communities to direct funds to municipal, social, and cultural development, projects related to communal and infrastructure issues. However, the Zaporizhia region has made decisions on directions aimed at digitalizing all areas of management and is moving towards the digital transformation of territorial communities and local authorities [6].

Zaporizhia region, despite its proximity to the combat zone, about 25 km, and significant destruction of the utility fund, energy and transport infrastructure, cares about humanitarian assistance to its population and directs funds to education, reconstruction, medical, social, environmental reforms, support for veterans and cultural development of the region. And thanks to effective digital technologies and administrative solutions involving all existing, possible resources, their productive classification, distribution and economical targeted use of funds, it continues to compete in the Digitalization rating, also with regions that are in the rear.

Territorial communities of the Zaporizhia region, with low income – a small population and territory, do not have the opportunity and funds to implement digitalization for a comfortable, modern environment, in providing relevant social services to their residents, and this, of course, limits the population in service and reduces the effectiveness of local development and quality management. Despite all the challenges of war and destruction, the city government of the Zaporizhia region continues the digital administration of all territorial communities.

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1.3. THE ROLE OF ARTIFICIAL INTELLIGENCE IN ENSURING ECONOMIC STABILITY AND INFORMATION SECURITY IN UKRAINE

Introduction. In the context of rapid digital technology development and escalating global conflicts – especially of the hybrid type – artificial intelligence (AI) is becoming a strategic tool in ensuring national security and economic stability. AI technologies are increasingly applied both in the economic sector – for production optimization, forecasting, and process automation – and in the information space – for detecting and neutralizing fake news, manipulation, and cyberattacks. This necessitates a comprehensive study of AI's potential in two critical areas: economic development and information security.

Russia's ongoing war against Ukraine is accompanied by large-scale information aggression aimed at demoralizing society [1], discrediting state institutions, and creating artificial chaos. Under these circumstances, AI can effectively filter and analyze vast amounts of information, automatically detect disinformation, and forecast risks arising from information influence. This strengthens the relevance of exploring AI's capabilities in strategic communications and countering hybrid threats.

At the same time, a wartime economy requires an innovative approach to modernization and recovery. The implementation of AI can drive economic growth through digital business transformation, development of hightech sectors, increased labor productivity, and cost reduction. Thus, the synergy between technological development and information space protection forms a new paradigm of national resilience, highlighting the importance of studying this issue amid today's challenges.

In the context of growing hybrid warfare threats and digital transformation, the use of artificial intelligence technologies to ensure economic security and counter disinformation becomes particularly relevant. These issues are actively studied by both Ukrainian and foreign scholars. In Ukraine, researchers such as Cherep O. and Cherep A. [8] examine the impact of digital technologies on the national economy and their role as a powerful tool for environmental protection and sustainable development [14]. Prokopenko O. analyzes digital security issues, while Nesterenko O. [9] explores the informatization of public administration. Internationally, significant contributions have been made by Yoshua Bengio [10], Kate Starbird, and Karsten Geier, who study ethical, informational, and security aspects of AI use.

The purpose of this article is to systematize approaches to using artificial intelligence technologies to enhance Ukraine's economic resilience, particularly through legislative, administrative, educational, and security mechanisms, and to formulate proposals regarding the state's role in these processes. The main objective is to identify strategic directions for AI application to strengthen economic security, analyze national and international experiences in countering disinformation using intelligent technologies, and develop recommendations for cross-sectoral state policy in this field.

Presentation of Key Research Findings. Artificial intelligence is a branch of computer science focused on creating systems and algorithms capable of performing tasks that typically require human intelligence. This includes speech recognition, natural language processing, machine learning, computer vision, planning, and decision-making.

In 2024, the global AI market achieved significant financial indicators, reflecting its rapid growth and impact across various economic sectors. According to Precedence Research, the total AI market size in 2024 was approximately $638.23 billion, with forecasts projecting growth to $757.58 billion in 2025 and $3.68 trillion by 2034, representing an average annual growth rate of 19.2 %. Other sources, such as Exploding Topics, estimated the market at $621.19 billion in 2024, with projections reaching $2.74 trillion by 2032 [12].

The AIbased software market, in particular, is showing remarkable growth: in 2024, it reached $94.41 billion, with expectations to rise to $126 billion by 2025. Major tech companies like Microsoft and Alphabet (Google) reported significant revenue increases due to AI integration into their cloud services and advertising platforms. For example, Microsoft Azure saw a 33 % revenue increase, while Google's ad revenue grew by 8.5 % in the first quarter of 2024. Analysts note that to justify the current investment levels – approximately $200 billion in 2024 – revenues need to reach $600 billion, which has yet to be achieved [13].

Overall, 2024 became a turning point for the AI industry, marked by major financial achievements as well as challenges related to evaluating the real value and effectiveness of investments in this field.

The goal of AI is to develop programs that can independently learn, adapt to new conditions, and perform tasks without direct human intervention.

AI's strengths (see Table 1) include high-speed data processing, the ability to automate routine tasks, continuous learning and improvement through machine learning, high task accuracy, and the capability to operate under heavy workloads without needing breaks. However, alongside these advantages, there are also weaknesses such as dependence on data quality, limited creativity and intuitive reasoning, difficulty adapting to rapidly changing environments, and ethical and social risks – such as the threat of job displacement. These issues require careful oversight and a responsible approach to AI implementation across various fields.

Table 1

Strengths and Weaknesses of Artificial Intelligence

Strengths of AI	Weaknesses of AI
High data processing speed – can handle massive amounts of data in a short time.	High dependency on data – inaccurate or incomplete data can lead to errors.
Process automation – reduces the need for manual intervention and increases productivity.	Limited adaptability – often requires retraining when conditions change.
Continuous improvement – machine learning enables AI to constantly improve its performance.	Lack of creativity – AI cannot generate new ideas like humans can.
Increased accuracy – can achieve high precision in tasks such as image or speech recognition.	Absence of emotions and intuition – AI lacks emotional intelligence and cannot make “human-like” decisions.
Efficiency in complex and repetitive tasks – capable of executing tasks that require precision and speed.	Ethical and legal issues – AI use may raise concerns about privacy and security.
Operation under heavy workloads – can function continuously without the need for rest.	Job displacement risk – automation through AI may lead to job losses in certain sectors.

According to Figure 1, India leads in the level of AI adoption among the surveyed countries, primarily due to the development of its technology sector and the widespread implementation of innovations.

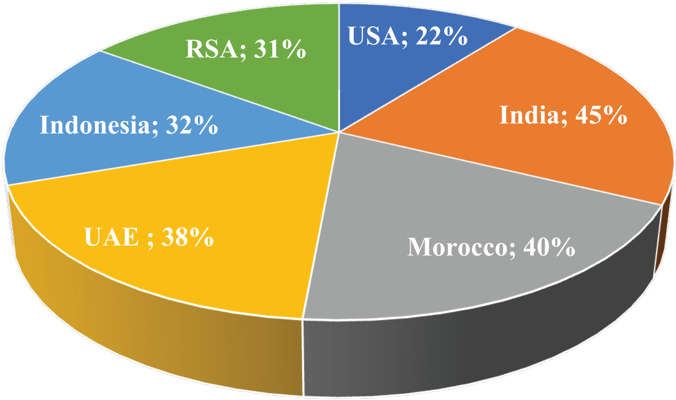

Figure 1. Countries with the Highest Use of Artificial Intelligence, According to 2024 Data

Source: compiled by the authors based on [4]

Morocco and the UAE also demonstrate high performance, indicating active digital transformation in these countries. The United States, despite substantial investments in AI, shows a lower level of usage among the general population, which may be linked to various factors, including technology accessibility and cultural characteristics.

The level of AI implementation can vary depending on the specific company and its digital transformation strategy (see Table 2).

Higher levels of AI implementation are observed in industries where automation and data analytics significantly impact the efficiency of business processes. Ukraine is actively developing AI adoption, particularly in healthcare, finance, and information technology sectors. AI technologies open new opportunities for economic growth by increasing productivity, automating routine processes, and improving the quality of management decisions. They enable enterprises to optimize production, reduce costs, and respond more quickly to market changes.

Thanks to big data analytics, AI helps forecast demand, identify risks, and develop effective development strategies. In the public

Table 2

Level of AI Implementation Across Various Industries as of 2024, Including in Ukraine and Internationally

Industry	AI Implementation Level	Main Areas of AI Usage
Financial Sector	58 %	Fraud detection, risk management, process automation, financial reporting
Healthcare	40 %	Improving treatment outcomes, medical diagnostics, personalized treatment
Retail	50 %	Inventory optimization, customer service personalization, sales analytics
Telecommunications	38 %	Network optimization, customer service, demand forecasting
Professional Services	72 %	Consulting, legal and accounting services, automation of routine tasks
Manufacturing	44 %	Automation of manufacturing processes, predictive maintenance, supply chain management
Information Technology	31.7 %	Software development, cybersecurity, data management
Logistics and Transport	47.5 %	Route optimization, inventory management, demand forecasting

Source: compiled by the authors based on [5]

sector, AI contributes to improving the efficiency of public service delivery, combating corruption, and transparent financial management. Implementing AI in key economic sectors can become a powerful driver of innovation and ensure the long-term competitiveness of countries in the global environment. Ukraine can effectively incorporate the experience of leading countries in AI adoption by adapting their strategies to its own economic and social conditions. In particular, attention should be paid to investments in education and digital skills, as India has done, which allowed it to become a leader in AI adoption among developing countries.

Equally important is the creation of a national AI ecosystem – with support for startups, research centers, and partnerships between the state and business, as seen in the USA and UAE. Additionally, regulatory frameworks for the ethical and safe use of AI should be introduced, following the example of the European Union. Such an approach will allow Ukraine not only to accelerate economic growth but also to integrate into the global technological space.

A critical analysis of Table 3 shows a variety of approaches to AI implementation in different countries, influenced by their economic potential, political will, and the level of digital infrastructure development. For example, India has focused on mass digital education in response to its large youth population and the need to ensure access to the IT market – this approach is promising for Ukraine but requires substantial funding for education, which is currently limited. The UAE and USA demonstrate government initiatives and investments in innovation, but in Ukrainian realities, the lack of a stable national AI policy may complicate adapting these models. Meanwhile, the EU's experience in forming ethical and legal norms can be directly applied in Ukraine, considering its course toward European integration. However, transferring China's model of largescale automation to Ukrainian manufacturing currently seems premature, given the technical obsolescence of many enterprises and the lack of relevant investments.

Overall, the table outlines strategically valuable guidelines, but their successful application in Ukraine requires adaptation to the local context, institutional support, and consistent government policy.

In the current conditions of hybrid warfare, where information security is as important as physical security, the state of Ukraine plays a key role in the development and implementation of artificial intelligence technologies. Primarily, this involves creating a favorable regulatory and legal framework, providing investment support for

Table 3

Countries' Experience in AI Implementation Useful for Ukraine

Country	Useful Experience	How Ukraine Can Use It
India	Mass digital skills training	Expand AI educational programs in universities
UAE	National AI development strategy	Develop a national artificial intelligence strategy
USA	Support for startups and research centers	Create innovation hubs with government support
EU	Ethical and legal AI standards	Implement AI ethics and transparency standards
China	Large-scale AI integration in industry	Apply AI for production automation

Source: compiled by the authors based on [5; 6]

innovative businesses, and initiating strategic partnerships between the public sector, science, and IT companies. The use of AI contributes to improving the efficiency of public administration, ensuring economic growth through automation, big data analytics, and the development of new products.

At the same time, AI technologies enable the rapid detection and neutralization of fake news, manipulative narratives, and information attacks, which is vital for protecting the national information space. An active position of the state (Fig. 2) in this area is a guarantee of digital sovereignty, innovative breakthrough, and strengthening national resilience against the threats of the modern world.

The distribution of actions by sectors allows for a systematic definition of priorities and the delineation of responsibilities between government authorities, scientific institutions, and businesses. A particular emphasis is placed on legislative regulation, which is intended to ensure a balance between innovation and security, as well as to create conditions for the ethical use of AI. However, the actual implementation of such initiatives requires political will, funding, skilled personnel, and broad public dialogue.

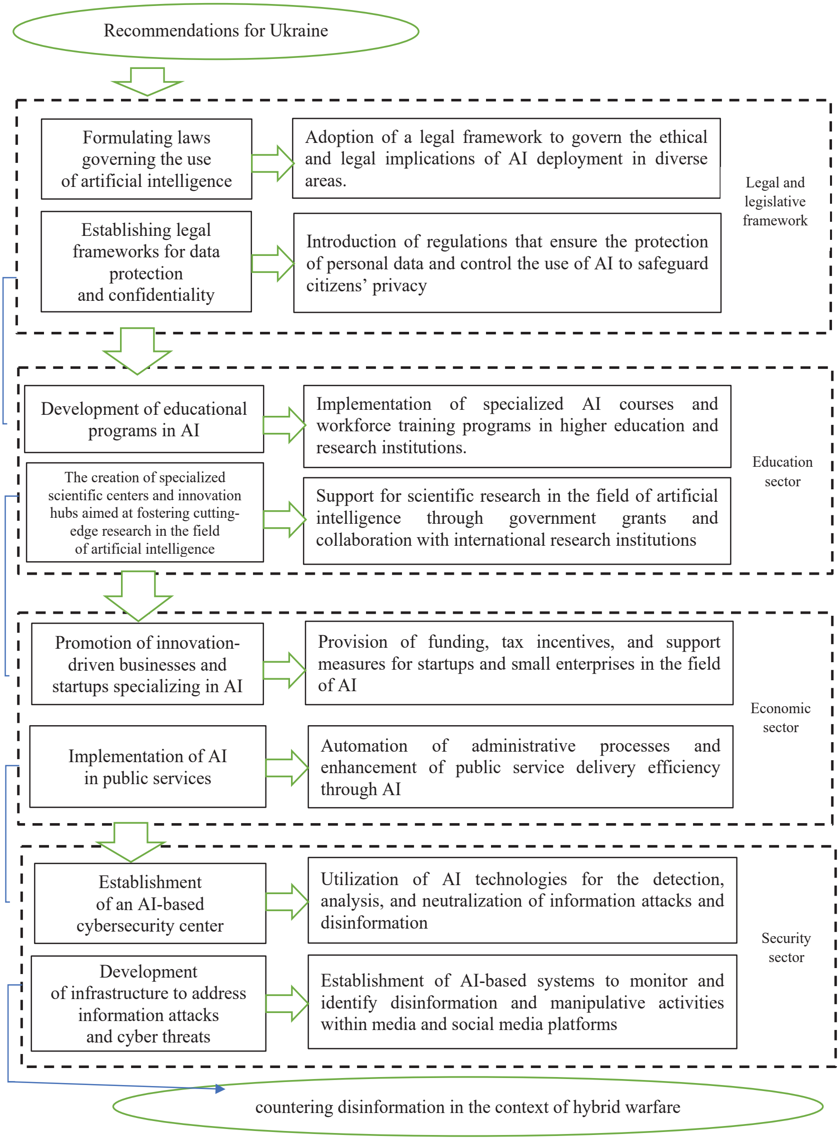

Fig. 2. Crosssectoral approach necessary for the effective implementation of artificial intelligence in Ukraine

At the same time, Fig. 2 reveals potential challenges: notably, the insufficiency of the current digital infrastructure, the brain drain of young specialists abroad, and the low level of digital literacy among part of the population. These factors may significantly slow down the practical realization of even well-planned government initiatives. Furthermore, in the security sphere, there is a need for extremely rapid response to threats, which requires flexible management mechanisms and fast policy adaptation. Therefore, to achieve strategic goals, the state must not only formulate a vision but also ensure effective tools for its implementation, relying on partnerships with the private sector and international organizations.

Ukraine has promising prospects for implementing modern approaches in government business analytics, using the experience of other countries. The introduction of business analytics systems integrated with AI will allow automatic identification of data trends, forecasting community needs, and resource planning, thereby increasing the effectiveness of management decisions. For example, the UK government actively uses business analytics to analyze open data, which promotes data-driven decision-making and increases government transparency. The Canadian experience also shows how open data platforms can engage citizens in the decisionmaking process. Additionally, automating data collection and analysis helps reduce reporting preparation time, enabling focus on strategic tasks. Citizen engagement in management processes can be enhanced by developing interactive platforms for accessing open data, which will improve transparency and legitimacy of decisions and increase trust in the government. As Canadian practice demonstrates [11], open data platforms actively facilitate citizen integration into decision-making, ensuring more effective governance. Active use of such technologies will enable Ukrainian government bodies to be more efficient, relying on factual data and citizen participation in important decisions.

Artificial intelligence is a key factor in strengthening national resilience amid hybrid warfare [15]. Its capabilities in detecting and neutralizing disinformation allow effective counteraction to information aggression accompanying modern conflicts. By analyzing large volumes of data, AI helps timely detect fake narratives, cyberattacks, and manipulations that threaten public opinion and government institution functioning. This makes AI an important component of strategic communications and digital security systems. Simultaneously, AI opens new opportunities for economic growth during a war-induced crisis. AI technologies ensure digital transformation of enterprises, increased labor productivity, optimization of production processes, and development of high-tech sectors. Combined with investments in innovation and human capital, AI can drive economic modernization and reduce dependence on external factors. Thus, integrating AI into key state development sectors creates prerequisites for strengthening the country's economic, informational, and security spheres.

Conclusions. This article reveals the role of artificial intelligence as a key factor in ensuring Ukraine's economic resilience and information security in the context of hybrid warfare. AI is an effective tool for detecting and neutralizing disinformation, allowing for rapid response to information threats and counteracting manipulative influences on public opinion. Its ability to process large amounts of data facilitates the identification of fake narratives, cyberattacks, network anomalies, and risks to critical infrastructure. This makes AI an important component of digital security and an effective tool for strategic communications against information aggression.

At the same time, AI opens new possibilities for stimulating the economy amid a prolonged crisis. AI technologies enable digital transformation of production, process automation, logistics optimization, cost reduction, and labor productivity increase. Their implementation lays the foundation for developing innovative sectors, reducing dependency on imported technologies, expanding export potential, and strengthening Ukraine's position in global markets. A cross-sectoral approach to AI implementation – coordinating actions of the state, business, academia, and the IT industry – plays a crucial role in this process.

However, alongside the advantages, AI also has several weaknesses. Ethical issues related to the use of algorithms in decisionmaking may hinder wide AI adoption. Problems of privacy and personal data protection, as well as potential new cyberthreats, require careful consideration. AI's weaknesses in some areas are also evident in its potential for incorrect or biased decisions, especially when processing and analyzing lowquality data. The article also discusses risks related to AI's impact on the labor market and social sphere.

The experience of leading countries that successfully integrate AI into public administration, defense, economy, and education is analyzed. Research shows that creating a national AI development strategy in Ukraine, considering security challenges and social needs, will ensure the country's long-term resilience, competitiveness, and independence.

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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].

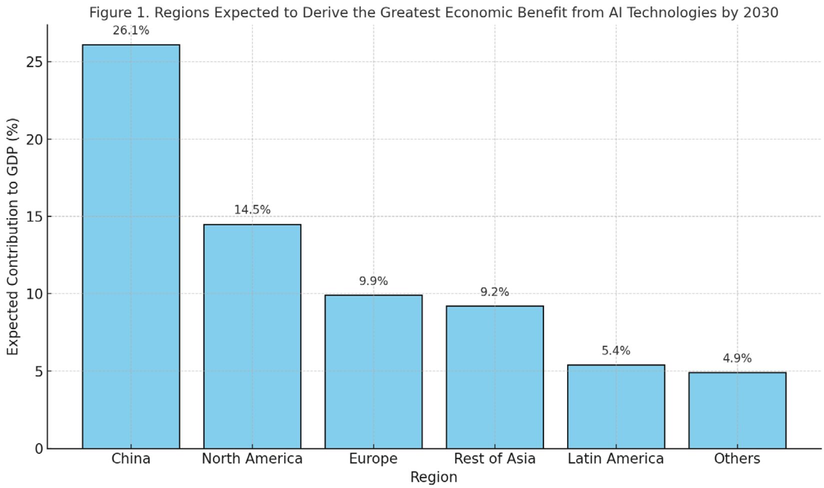

Figure 1. Regions expected to gain the greatest economic benefits from artificial intelligence technologies by 2030

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.

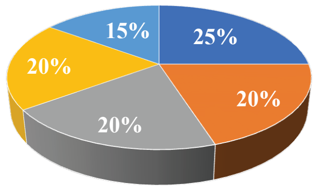

Figure 1. Areas of AI Application in the Military Sector

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.

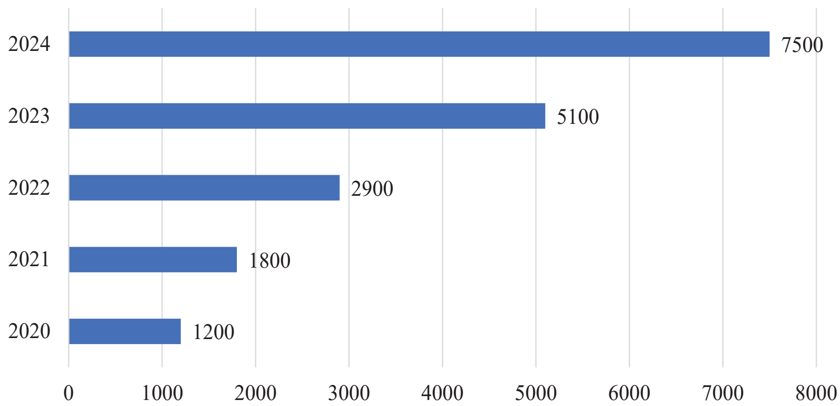

Figure 2. Dynamics of cyber threats in Ukraine (2020–2024)

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).

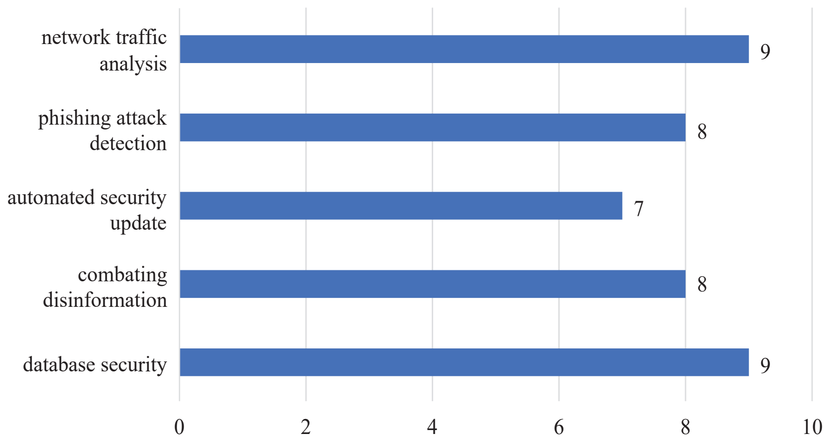

Figure 3. The Role of AI in the Cyber Defense System

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

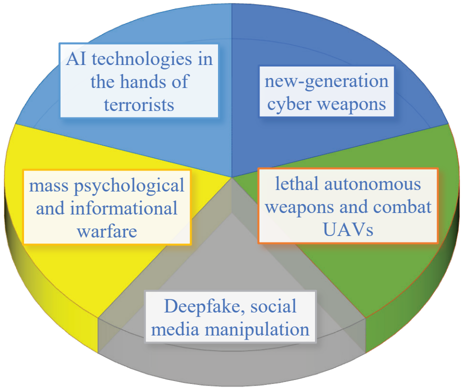

Figure 4. Main threats to national security from the misuse of AI technologies

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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SECTION 3.
Synergy of Artificial Intelligence, Digital Competence and Analytical Modeling in the Context of Economic Modernization

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3.1. THE IMPACT OF ARTIFICIAL INTELLIGENCE ON UKRAINE'S NATIONAL SECURITY

Introduction. In today's world, national security has long gone beyond military strategy alone. It encompasses political stability, cybersecurity, critical infrastructure protection, economic stability, as well as information and cultural security of the state. The impact of digitalization on the level of national security has been studied by: Voronkova V. H., Cherep A. V., Nikitenko V. O., Cherep O. H. [1], Cherep A., Voronkova V., Cherep O., Ohrenych Yu., Dashko I., Kotliarov V. [2], Zhyvtsova L. I. [3], Trofymenko O. H., Lohinova N. I., Sokolov A. V., Chykunov P. O., Akhmametieva H. V. [4], Bolkvadze N. I., Bratko O. S., Myhal O. F. [5], Chaikina A. O., Maslii O. A., Cherviak A. V. [6], Novikova N., Boiko L. [7], Nieustroiev YU. H., Yehorova-Hudkova T. I., Ostrianko V. V. [8], Cherep A. V., Voronkova V. H., Dashko I. M., Ohrenych Yu. O., Cherep O. H. [9], Cherep A. V. [10], Cherep O. H., Oleinikova L. H., Bekhter L. A., Veremieienko O. O. [11], Cherep A. V., Dashko I. M., Ohrenych Yu. O. [12].

Summary of the main results of the study. The issue of studying the impact of artificial intelligence on national security has become especially relevant for Ukraine after the start of full-scale military aggression by the Russian Federation in 2022, when both traditional and non-traditional security threats, i.e. in the field of cyberspace and information influences, became apparent. In this context, advanced digital technologies, in particular artificial intelligence (AI), have begun to play a strategic role in ensuring the state's defense capability.

Artificial intelligence is a set of methods, algorithms and technical tools capable of self-learning, data analysis, forecasting scenarios and decision-making based on a large amount of information. This technology is rapidly transforming approaches to security, from rapid threat detection and automated response to complex analysis of psychological influence in the information space. It should be noted that the potential of AI in modern warfare, which combines classical warfare with cyberattacks, fake campaigns, and cyberespionage, can significantly enhance the state's defense capabilities.

Ukraine, which is at the center of the global geopolitical struggle, has become an example of successful adaptation of the latest technologies to the challenges of war. In particular, the introduction of AI-based solutions in the defense sector (e.g., the use of enemy vehicle detection systems, drone control, and information flow analysis) has become a tool of both tactical and strategic importance. Public and private initiatives (e.g., the Brave1 technology cluster) demonstrate the potential for integrating AI into Ukraine's defense industry.

At the same time, the use of AI has not only benefits, but also challenges. These challenges include legal issues of liability for the actions of algorithms, as well as the risks of using AI by the enemy, i.e., to create disinformation campaigns or cyberattacks on critical infrastructure. Therefore, the issue of safe, controlled and ethical use of artificial intelligence in the context of national security requires a comprehensive analysis [13].

The relevance of this study lies in the need for a comprehensive understanding of how artificial intelligence is changing the security landscape of Ukraine. An important issue is to study the main areas of AI implementation in the security sector, assess its potential, and analyze risks and limitations.

In recent decades, humanity has been witnessing the rapid development of digital technologies, digital transformation processes, and the introduction of information technologies, which is bringing changes to all spheres of life. One of the most significant achievements in this area is the creation and implementation of artificial intelligence (AI) technologies. At the same time, it should be noted that AI can be viewed as an interdisciplinary phenomenon that combines computer science, mathematics, logic, neuroscience, philosophy, and ethics.

Artificial intelligence covers such areas as speech recognition, learning, planning, problem solving, big data analysis, natural language understanding, pattern detection, and even creativity.

The most general and functional definition of AI is the ability of computer systems and programs to model human cognitive functions. These can be algorithms that learn on their own based on the input data (machine learning) or complex neural networks that mimic the structure and functioning of the human brain.

Today, there are several levels of AI classification (Fig. 1):

1. Harrow AI (weak AI) – systems specializing in specific tasks (e.g., face recognition or recommendation services).

2. General AI (general AI) – hypothetical systems that can solve any intellectual task as efficiently as a human.

3. Superintelligence (superintelligence) – a concept of the future when AI exceeds human capabilities in all areas, including emotional and social [21].

The most widespread today are weak AI systems that integrate into everyday life: electronic assistants, chatbots, navigation systems, banking services, healthcare, defense, etc.

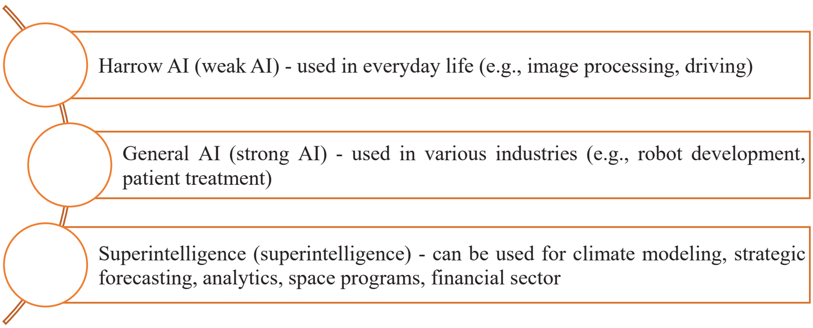

Figure 1. Levels of AI classification

Source: compiled on the basis of [21]

It should be noted that modern AI – is not a single technology, but a complex combination of several areas, in particular (Fig. 2):

- machine learning (Machine Learning, ML) – algorithms that learn from data without explicit programming [13; 22];
- deep learning (Deep Learning) – a subtype of machine learning that uses artificial neural networks of high complexity [13; 22];
- computer vision (Computer Vision) – Image and video analysis to recognize objects, people, actions, etc. [13; 22];
- natural language processing (Natural Language Processing, NLP) – technologies that allow machines to “understand” and generate human speech [13; 22];
- speech recognition (Speech Recognition) – systems that translate speech into text are used in voice assistants [13; 22].

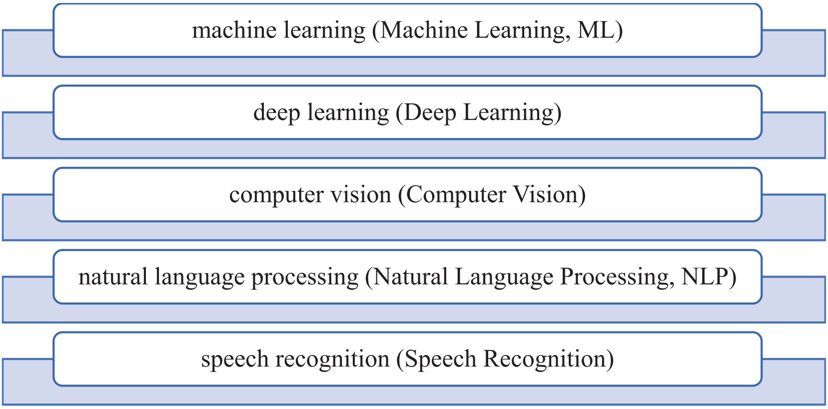

Figure 2. Areas of AI

Source: compiled on the basis of [13; 22]

In the 2020s, AI has evolved from an academic concept to a practical tool that is actively used in public administration, defense, business, medicine, and education. Its impact is so profound that some analysts are already talking about the "fourth industrial revolution" where intelligent systems will become the central technology.

In the context of national security, AI allows states to gain a competitive advantage in both defense and information space protection, which makes the study of this phenomenon extremely important for Ukraine's future [14].

Today, artificial intelligence is being actively integrated into various areas of human activity, changing approaches to management, analysis, maintenance, security, and communication. Moreover, AI ensures efficiency in solving various tasks due to its ability to predict events, self-learning, and analysis of large amounts of information. Therefore, it is advisable to analyze the main areas in which AI demonstrates the greatest potential (Fig. 3) [15].

AI plays a key role in transforming modern military strategies, as it is used in:

- autonomous combat systems (drones, robotic platforms);

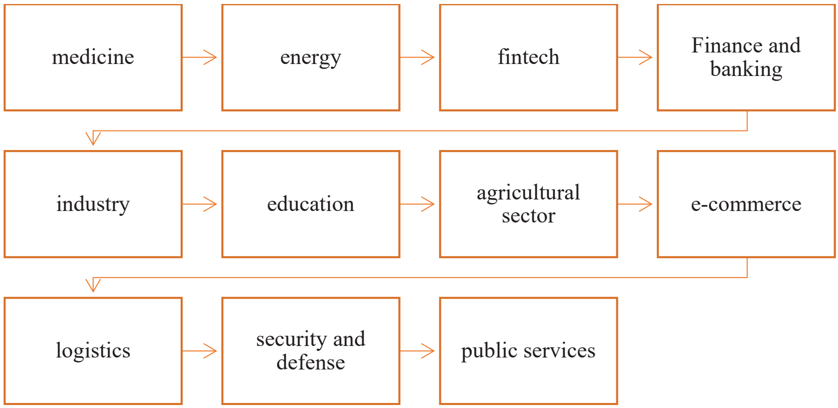

Figure 3. Areas of AI application

Source: compiled by the authors

- intelligence systems (processing of satellite images, vehicle recognition);
- analyzing data from the battlefield;
- countering cyber attacks;
- forecasting tactical scenarios.

Ukraine is actively implementing such systems, in particular through projects based on Brave1 and the Ministry of Digital Transformation of Ukraine [16].

In particular, artificial intelligence in the medical field is used to:

- Diagnostics of diseases (determination of pathologies on MRI, CT images);
- personalized medicine (analysis of genetic data);
- robotic surgery;
- epidemic forecasting;
- real-time monitoring of patients' condition.

Such systems help speed up clinical decision-making and reduce the risk of errors.

AI detects cyber threats, analyzes abnormal behavior in networks, and automates response to attacks. This is especially important in hybrid warfare, when the state is subjected to continuous cyber pressure from the aggressor. AI also allows to:

- detect phishing, malware, DDoS attacks;
- analyze risks;
- create dynamic cyber defense systems.

In the field of education, AI is used to:

- adaptive learning (platforms that adapt to the needs of the learner);
- knowledge assessment;
- creation of intelligent learning systems;
- automated support of students;
- language interpreters and assistants [17].

AI helps make education more accessible, personalized, and efficient.

In business, AI is transforming:

- process management;
- customer service (chatbots, virtual assistants);
- logistics and supply;
- financial analysis;
- risk management;
- marketing (analysis of customer behavior, personalized offers).

It is also actively used in fintech, in particular for fraud detection or automatic credit analysis.

AI ensures efficient organization of traffic flows, routes, and transportation, which reduces costs and improves the quality of service, in particular:

- autonomous driving (self-driving cars);
- smart transportation systems;
- congestion forecasting;
- optimization of warehouses and supply chains.

In the agricultural sector, AI can increase productivity, reduce environmental impact, and help:

- analyze the condition of soil and crops;
- forecast harvests;

- optimize the use of water and fertilizers;
- carry out precision farming with the help of drones and sensors.

Along with this, AI is used to:

- analysis of citizens' requests;
- management decision-making;
- automation of bureaucratic procedures;
- creation of e-governance systems;
- identification of social needs [18].

As a result, the quality of public services is improving and the level of corruption is decreasing. Thus, artificial intelligence is penetrating key areas of society, bringing benefits, efficiency, and new opportunities. Its importance will continue to grow, especially in the context of national security.

In the context of military conflict, economic instability, information pressure and cyber threats, the issue of security is of paramount importance. National security is the basis for economic stability and development of any country. The current situation in Ukraine clearly demonstrates the importance of a strategic approach to protecting the interests of the state in all spheres, from defense to social and humanitarian [19].

It should be noted that "national security is the protection of state sovereignty, territorial integrity, democratic constitutional order and other national interests of Ukraine from real and potential threats" [20]. This concept covers not only physical security (from war or terrorism), but also protection from economic pressure, cyberattacks, information aggression, environmental disasters, demographic risks, etc.

According to the Law of Ukraine "On National Security", the national security system includes the following main areas [20]:

- military security;
- political stability;
- economic security;
- cybersecurity;
- environmental security;
- energy security;

- information security;
- social and humanitarian security.

In wartime, these components are interconnected with cybersecurity breaches, which can destabilize the information space, affect the political situation and the state's defense capability. It should be noted that the main goal of national security is to create conditions under which the vital interests of the state, citizens and society will be protected from real and potential threats.

The full-scale aggression of the Russian Federation against Ukraine, which began in 2014 and entered a new phase in 2022, has changed the understanding of security. Ukraine has found itself in a hybrid war that combines classical military operations with information, cyber, economic and psychological aggression.

The key threats today include:

1. Military aggression (constant hostilities in the east and south of the country, use of high-tech weapons, drones, missiles, AI for warfare).
2. Cyber threats (attacks on state registries, banking systems, energy infrastructure, the use of viruses such as NotPetya, cyber espionage and destructive attacks on critical facilities).
3. Information warfare (large-scale dissemination of fakes, manipulative narratives, propaganda, creation of a destructive information field to undermine trust in the government, inciting panic and division in society).
4. Energy and economic instability (destruction or blocking of energy facilities, sanctions pressure, logistical difficulties, loss of investment.
5. Social vulnerability (mass migration, internal displacement, psychological trauma of society, decline in trust and social capital).
6. External interference (support of terrorist groups by other states, attempts to destabilize through subversive activities within the country).

It should be summarized that in the current conditions of war and hybrid threats, the impact of artificial intelligence on Ukraine's national security is multidimensional and it is a strategic tool that can influence changes in approaches to defense, security, resource management, and information counteraction. The main aspects of AI's impact on national security include the following (Fig. 4):

– cybersecurity – the use of AI allows for timely response to threats, detection of cyberattacks in real time (behavioral analytics, anomaly detection), and protection of critical infrastructure (energy, communications);

– military technologies – the use of AI allows for battlefield analytics (e.g., processing satellite images, video and radio intercepts for operational decision-making), threat forecasting (allows for detecting preparations for attacks, enemy logistics), automated control through the use of unmanned systems (UAVs, ground robots);

– resource management – the introduction of AI allows to improve the allocation of resources (medicine, fuel) based on forecasts, to model the logistics of humanitarian aid, to optimize the allocation of resources based on forecasts, to use intelligent risk monitoring systems (environmental, social, economic);

– information security and countering disinformation – the introduction of AI allows monitoring the information space using NLP, exposing fakes in the media and social networks;

– social stability – the use of AI allows predicting social tension by analyzing data in social networks and the media, supporting the public administration system, and providing access to quality services in a crisis;

– economic security – the introduction of AI allows protecting public finances by detecting tax evasion; predicting crises (inflation, deficit), analyzing the labor market (for example, to adapt education systems);

– state border security – AI implementation allows to improve video surveillance systems at the border (e.g., face recognition, license plates), analyze behavioral patterns to detect suspicious actions or intrusions, analyze external data flows and detect espionage activities, improve border control through automated document verification systems.

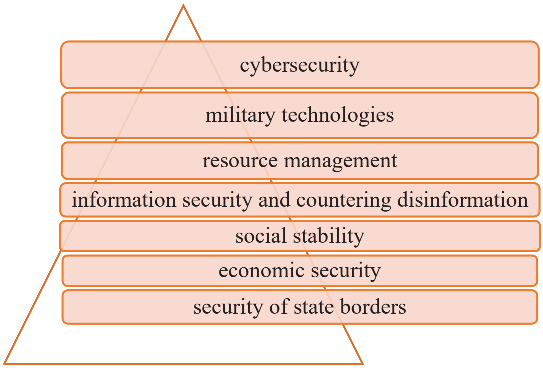

Figure 4. Key aspects of AI's impact on national security

Source: compiled by the authors

Conclusions. The introduction of artificial intelligence is becoming a strategic advantage for Ukraine in terms of automatic attack detection, analysis of large amounts of information, event forecasting, and protection of critical infrastructure. Thus, in the context of war, hybrid threats, and global instability, artificial intelligence plays an important role in strengthening Ukraine's national security. Integration of AI into the military, information, economic, and social spheres will increase the state's resilience, public administration efficiency, and ensure its competitiveness. It also helps not only to strengthen security but also to create an intellectual defense of the country's information and spatial sovereignty.

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3.2. DEVELOPING DIGITAL LANGUAGE COMPETENCE AS A FACTOR OF COMPETITIVENESS OF FUTURE MASTER'S DEGREE HOLDERS IN POWER ENGINEERING IN THE DIGITAL ECONOMY

Introduction. In the contemporary landscape of rapid technological advancement and global digitalisation, the development of high-level professional competencies among future engineers is no longer confined to technical knowledge alone. In fact, the demands of the digital economy call for a new type of specialist – one who combines deep subject-matter expertise with strong digital literacy and effective communication skills in international professional settings. For Ukrainian institutions of higher technical education, this shift requires a fundamental rethinking of pedagogical priorities, particularly in the realm of language instruction. Among the various competencies that contribute to the competitiveness of future master's degree holders in power engineering, digital language competence is emerging as a particularly vital element.

Digital language competence can be broadly defined as the ability to effectively use language – primarily English as the global language of science and technology – within digital environments to access, process, produce and communicate professional information. This competence involves not only linguistic and communicative skills, but also the confident use of digital tools and platforms to support these processes. For Ukrainian students in power engineering, whose future workplaces may range from international corporations to digitalised domestic enterprises operating within global supply chains, the ability to operate in multilingual digital contexts is a prerequisite for professional integration and success.

This chapter explores the formation of digital language competence as a key factor in enhancing the competitiveness of master's level students in the field of power engineering. In doing so, it seeks to contribute to the broader discourse on the role of digitalisation in higher education and, more specifically, on how linguistic preparation must evolve to meet the challenges of Industry 4.0 and beyond. The emphasis is placed on aligning the teaching of English for Specific Purposes (ESP) with digital educational technologies that support students' professional growth and readiness for real-world communicative situations in technical fields.

The Ukrainian context presents both unique challenges and opportunities. On the one hand, there is a strong tradition of engineering education and a growing awareness of the need for digital transformation in the academic sphere. On the other hand, the lingering effects of outdated teaching methodologies, underfunded infrastructure, and the consequences of the ongoing war have hampered the pace of educational innovation. Nevertheless, recent years have witnessed [1] an increased interest in integrating digital tools into ESP courses, with platforms such as Moodle, various learning management systems, online glossaries, technical text generators, and simulation software gaining traction. This shift has been particularly noticeable in technical universities, where the demand for relevant, industry-oriented English instruction is most acute.

The present chapter is structured into three interconnected sections. The first part analyses the role of digital language competence in preparing future power engineering professionals for the labour market. It draws attention to how digitalisation has changed communication patterns in engineering professions and emphasises the strategic importance of developing a flexible, digitally-supported command of English. The second part offers a detailed overview of digital educational technologies currently applied in ESP teaching, showcasing specific methods and tools used to enhance language instruction in technical disciplines. It highlights practical classroom solutions such as the use of Moodle for blended learning, electronic dictionaries and grammar tools for autonomous study, and project-based digital simulations for contextualised language practice. Finally, the third section presents actual recommendations for reinforcing digital language competence within master's degree programmes. These include curriculum integration strategies, examples of best practices, and proposals for fostering collaboration with European educational initiatives.

By focusing on the intersection of language, technology, and technical education, this chapter contributes to the broader effort of digitalising Ukraine's economy through the development of human capital. In particular, it underscores the role that language educators at technical universities play in shaping the communicative and digital readiness of the next generation of engineers. As Ukraine continues to move towards deeper integration with the European educational and economic space, the importance of equipping future specialists with strong digital language competencies cannot be overstated.

1. The role of digital language competence in the training of power engineering professionals

In the context of the digital economy, the competencies required of power engineering professionals are undergoing a significant transformation. Technical knowledge and hands-on skills, though still central to the profession, are no longer sufficient on their own. The globalisation of the labour market, the integration of smart technologies, and the widespread adoption of digital systems in the energy sector have brought forth new demands – particularly in the areas of communication, collaboration, and information processing within digital environments. As a result, digital language competence is becoming [2] a critical component of a modern engineer's skill set, directly influencing employability, mobility, and professional growth.

Digital language competence, especially in English, serves a dual function. On the one hand, it facilitates access to the vast body of global scientific and technical knowledge, which is predominantly published in English. On the other hand, it enables engineers to participate in international projects, communicate with colleagues from different linguistic backgrounds, and navigate technical documentation, software interfaces, and standards that are often available exclusively in English. In digitalised workplaces – be they local firms with global partners or transnational corporations – the ability to function effectively in such environments is essential.

For power engineering students in Ukraine, this competence is particularly important. The country's energy sector is actively engaging in digital modernisation, with ongoing efforts to upgrade infrastructure, implement smart grid technologies, and adopt international safety and efficiency standards. These transformations are closely tied to European integration processes, requiring not only technological but also communicative alignment with the standards and practices of European partners. Consequently, Ukrainian graduates must be prepared not only to operate the latest digital equipment and systems but also to engage with digital content, follow technical procedures, and communicate with foreign colleagues – all in English.

It is important to recognise that digital language competence is not limited to traditional language skills such as grammar, vocabulary, or pronunciation. Rather, it encompasses the ability to use language purposefully within digital environments. This includes reading and interpreting technical specifications online, composing clear and concise reports using digital templates, participating in virtual meetings and discussions, searching for technical information using appropriate keywords, and adapting messages to different audiences and communication platforms. In many ways, this competence blends language proficiency with digital literacy and professional orientation.

The role of language educators at technical universities, therefore, extends far beyond teaching English as an academic subject. In today's context, it is about equipping students with the communicative tools they need to function effectively in a digitalised professional world. This involves integrating authentic materials into the learning process – such as user manuals, software documentation, online forums, and case studies drawn from real-life engineering scenarios – as well as fostering the use of digital platforms that mirror those used in the workplace. At the same time, it requires a pedagogical shift from passive learning to active, student-centred approaches that prioritise communication, problem-solving, and the practical application of language skills.

Moreover, the development of digital language competence contributes to a broader set of XXI century skills that are valued across all sectors of the economy. These include critical thinking, adaptability, collaboration, and intercultural communication – all of which are essential for engineers working in increasingly complex and interconnected environments. For master's degree holders in power engineering, who are likely to take on leadership roles, these skills are even more important. Their ability to present technical solutions to diverse audiences, write reports for international stakeholders, and collaborate across borders is directly linked to their success and the reputation of the institutions that trained them.

In all, the role of digital language competence in the training of power engineering professionals cannot be overstated. It is a foundational element that underpins effective participation in the digital economy and supports Ukraine's broader goals of innovation, integration, and competitiveness on the global stage. As such, its systematic development within technical universities should be viewed as a strategic priority – one that bridges the gap between language education and professional engineering practice in the XX century.

The importance of English for specific purposes (ESP) in the context of digital transformation of the economy

As the global economy continues to evolve under the influence of digital technologies, the significance of English for Specific Purposes (ESP) in professional education is growing markedly. This shift is particularly evident in technical and engineering domains, where the use of English is no longer merely an academic requirement but a practical necessity for full participation in professional life. The digital transformation of the economy has intensified the need for sector-specific language training that is directly aligned with the communicative demands of rapidly changing work environments. For students of power engineering, and indeed all STEM disciplines, ESP functions as a bridge between technical knowledge and its effective application in globalised, multilingual, and technology-driven settings.

Unlike General English, ESP is tailored to the specific linguistic and communicative needs of learners operating within particular fields – whether engineering, finance, medicine, or law. In the context of digital transformation, this means equipping students with the tools to navigate domain-specific language in digital formats: reading technical manuals in PDF, following software installation instructions, participating in online engineering forums, or presenting findings during virtual conferences. These are not hypothetical situations but routine professional tasks for XX century engineers. Therefore, ESP instruction must evolve to reflect these realities, focusing not only on traditional grammar and vocabulary, but also on digital communicative functions, genre-specific writing, and cross-cultural interaction.

In recent years, the digitalisation of workplace communication has led to the emergence of new professional genres – ranging from email briefings and real-time chat support to digital maintenance logs and remote troubleshooting protocols. These forms of communication require a high level of linguistic precision, clarity, and awareness of digital etiquette. ESP instruction, when designed thoughtfully, prepares learners to function confidently in such environments. For example, in a power engineering context, students might work with authentic materials such as datasheets for photovoltaic inverters, safety regulations published by international bodies, or operational manuals for smart grid systems – all in English. Through such exposure, they develop not only language skills but also professional literacy in their future domain.

Moreover, ESP plays a vital role in ensuring that graduates are capable of engaging with international standards and regulations, many of which are available exclusively in English. As Ukrainian industries become more integrated into European and global economic systems, the ability to understand and implement such standards becomes essential. In digitalised settings, where documentation is stored and shared electronically, and where systems often operate in English by default, this linguistic competence takes on an even greater level of importance. Whether calibrating a control system, interpreting sensor data, or preparing a project proposal for an EU-funded initiative, engineers must be able to interact fluently with English-language digital content.

ESP also supports the development of lifelong learning strategies – an essential attribute in the context of digital transformation, where technologies, platforms, and tools are constantly evolving. Engineers are increasingly expected to update their skills autonomously through online learning platforms, professional webinars, and digital certification programmes, the majority of which are conducted in English. In this regard, ESP instruction helps [3] students become independent users of English-language digital resources, giving them the capacity to stay current in their field and remain competitive in the labour market.

From a pedagogical perspective, teaching ESP in the context of the digital economy requires an innovative approach. It necessitates the integration of ICT tools, real-world tasks, interdisciplinary collaboration, and learner autonomy. Platforms such as Moodle can host ESP courses that incorporate multimedia materials, interactive exercises, and project-based learning activities. Students may be tasked with simulating online meetings, preparing reports using authentic templates, or conducting research using digital engineering databases.

These activities mirror the types of communicative situations they are likely to encounter in their future professions, making the learning process both relevant and engaging. By designing ESP courses around these digital practices, educators not only enhance students' language skills but also equip them with critical competencies needed to thrive in a technology-driven professional environment.

In all, English for Specific Purposes has become a fundamental pillar of professional education in technical disciplines. In the context of the digital transformation of the economy, its relevance has only deepened. ESP enables future engineers not only to communicate effectively within their professional community but also to access, interpret, and apply the wealth of knowledge that is increasingly mediated through English and digital platforms. For Ukrainian technical universities striving to prepare students for success in the international labour market, the integration of ESP into curricula is no longer optional – it is a strategic imperative.

ESP in Ukrainian technical universities: supporting national strategies for digital transformation

The integration of English for Specific Purposes (ESP) into the curricula of Ukrainian technical universities is increasingly recognised as a vital component of the country's broader digital transformation strategy. As Ukraine positions itself more firmly within the European and global knowledge economies, the demand for specialists who are both technically competent and communicatively agile in English continues to rise. Higher education institutions, particularly those specialising in engineering and applied sciences, are thus under growing pressure to modernise their language education in line with the needs of the digital economy and the strategic goals outlined in national policy documents.

The "Digital economy and society development concept of Ukraine" (2018) and related government initiatives have emphasized [4] the importance of digital skills, international cooperation, and the development of human capital as pillars of economic competitiveness. Language proficiency in English – especially in technical contexts – is explicitly recognised as a cross-cutting competence that enables access to international research, digital platforms, and innovation networks. In this regard, ESP instruction at technical universities not only contributes to individual career readiness but also supports the national effort to foster a digitally competent workforce capable of engaging with global partners and standards.

At Vinnytsia National Technical University, as well as other leading technical institutions in Ukraine, the teaching of ESP has undergone a gradual but visible transformation. Traditional, textbook-based approaches are being replaced with blended and technology-enhanced models that simulate real-world communication tasks. For example, ESP instructors now make extensive use of platforms such as Moodle, Prometeus and Coursera where courses can include interactive quizzes, collaborative writing tasks, vocabulary training, and online presentations. These platforms allow for flexible delivery and continuous feedback, encouraging students to take ownership of their learning.

Moreover, Foreign Language Department is increasingly collaborating with subject-matter experts from engineering faculties to ensure that ESP content reflects the actual needs of the students' future professions [5]. Such interdisciplinary cooperation helps bridge the gap between language learning and professional application, making ESP instruction more meaningful and contextually relevant.

A particularly promising direction is the integration of project-based learning within ESP courses. Students may be asked to develop a prototype presentation for a smart energy solution, write a user manual for a fictional power system, or simulate an international tender process using English. These tasks not only improve language competence but also train students in digital collaboration tools, critical thinking, and cross-cultural communication – skills that are indispensable in today's digital work environment.

In addition, universities are starting to incorporate [6] open educational resources (OERs) and massive open online courses (MOOCs) into their ESP programmes. These materials, often developed by prestigious institutions and available in English, enable students to engage with up-to-date content and broaden their understanding of both language and technology. They also reflect a shift towards lifelong learning, one of the key principles of the European Higher Education Area and a cornerstone of Ukraine's integration into the European educational space.

Despite positive developments, challenges remain. The digital infrastructure in some regions is still insufficient, particularly in wartime conditions, and not all language instructors have received adequate training in the use of educational technologies or the design of ESP content. Furthermore, the lack of unified national standards for ESP instruction in technical education results in a fragmented approach across institutions. Addressing these issues will require sustained investment, policy coordination, and professional development for educators.

Nevertheless, the current trajectory is encouraging. The increasing visibility of ESP within curriculum reform, the growing engagement of language teachers in digital innovation, and the alignment of educational goals with national strategies all point to a promising future. As Ukrainian technical universities continue to evolve in response to the digital age, the role of ESP – as both a linguistic and strategic tool – will only grow in importance.

Language competence as part of professional readiness for international cooperation and smart technologies

In the era of smart technologies and interconnected global systems, professional readiness extends far beyond technical mastery. It increasingly encompasses the ability to communicate, collaborate, and solve problems across cultural, disciplinary, and linguistic boundaries. As digitalisation reshapes the landscape of engineering, energy systems, and industrial operations, language competence – particularly in English – emerges as a core element of a future professional's toolkit. This is especially relevant for students of power engineering, who are preparing to enter workplaces that are both technologically sophisticated and globally integrated.

International cooperation is no longer a peripheral aspect of engineering; it is a central reality. Power engineers routinely engage with colleagues, clients, and partners from other countries – whether through joint infrastructure projects, collaborative research, or transnational supply chains. The shift towards smart technologies, including smart grids, AI-driven monitoring systems, and Internet of Things (IoT) applications in the energy sector, further amplifies the need for precise, efficient, and adaptive communication. In such a context, language competence becomes [7] more than a communication skill – it becomes a tool for interoperability, knowledge transfer, and trust-building.

English has firmly established itself as the lingua franca of science, technology, and international business. Mastery of English allows professionals to access the latest scientific research, follow global engineering trends, and participate in professional networks. In the context of smart technologies, where innovation cycles are short and terminology evolves rapidly, the ability to engage with English-language content is vital for staying up to date. For example, understanding updates to technical standards, reading operational manuals for smart meters, or participating in international webinars requires not only technical literacy, but also strong language proficiency.

Moreover, the implementation of smart technologies in energy systems often involves working with international software solutions, digital control systems, and platforms whose user interfaces, documentation, and support services are provided exclusively in English. Without the necessary linguistic competence, the ability to effectively operate, troubleshoot, or adapt such systems is severely limited. From this perspective, language competence directly influences technical performance and operational efficiency.

Beyond technical tasks, engineers are expected to communicate their ideas clearly to non-technical stakeholders, including project managers, regulatory authorities, or international investors. This may involve writing technical reports, preparing presentations, contributing to feasibility studies, or defending proposals – all of which require fluency in both professional content and appropriate language use. For Ukrainian students entering such global arenas, the ability to articulate their knowledge and collaborate in English is essential for building credibility and fostering long-term partnerships.

At the educational level, integrating language competence into professional training is a forward-looking strategy. It supports the holistic development of future engineers who are not only experts in their field but also communicators, team members, and innovators. For example, at Ukrainian technical universities, ESP courses increasingly incorporate scenarios such as drafting a project proposal for an EU-funded energy initiative, simulating a multilingual team meeting on a smart grid rollout, or translating field-specific terms into accessible language for diverse audiences. These tasks prepare students for the kinds of international and interdisciplinary interactions they will encounter in real life.

Language competence also reinforces key soft skills that are crucial for success in the digital economy: adaptability, critical thinking, intercultural awareness, and digital communication literacy. These competencies enable professionals to navigate the dynamic, unpredictable environments characteristic of international engineering projects, where challenges are often complex, time-sensitive, and require collaboration across time zones and cultural frameworks.

In all, language competence is not a peripheral skill in the age of smart technologies – it is an integral part of professional readiness. For Ukrainian power engineering students and other future specialists in technical domains, mastering English means gaining access to the tools, communities, and innovations that drive global progress. As such, developing this competence must be seen not just as an educational goal, but as a strategic investment in the country's integration into the international digital economy.

Current demands of the labour market for digitally competent and linguistically agile engineers

The digital transformation of global industry has significantly reshaped the skillsets expected of engineering graduates, particularly in high-tech and energy sectors. The modern labour market is no longer seeking engineers who possess only technical proficiency;

rather, it increasingly demands professionals who are digitally competent, linguistically agile, and capable of functioning effectively in multicultural and multidisciplinary environments. This shift is especially evident in the field of power engineering, where digital tools, international cooperation, and innovation ecosystems define the nature of contemporary work.

Recruitment trends across Europe and internationally demonstrate a strong preference for candidates who exhibit not only domain-specific expertise but also high levels of digital literacy and communication skills in English. Employers expect future engineers to be proficient in operating digital platforms for project management, remote collaboration, data analysis, and system simulation. Tools such as SCADA systems, digital twin technologies, and cloud-based energy modelling platforms are now standard in many companies, and the ability to use them confidently is a clear hiring advantage. In parallel, English remains the dominant language for software interfaces, technical documentation, global standards, and cross-border team communication.

This dual requirement – of technological and linguistic agility – has important implications for engineering education. Language and digital skills are no longer considered “soft” or supplementary; they are core employability traits. International companies operating in Ukraine or recruiting Ukrainian graduates for positions abroad frequently list English proficiency and experience with digital tools as prerequisites in job descriptions. Furthermore, with the rise of remote and hybrid working models, engineers must often participate in international projects without leaving their home country, further intensifying the need for fluent digital communication.

Another defining characteristic of the modern labour market is the need for lifelong learners. Engineering roles today are dynamic, often involving upskilling and reskilling throughout one’s career. Digital competence is central to this, as most ongoing professional development takes place through online platforms, webinars, digital certifications, and international e-learning courses – almost all of which are delivered in English. Engineers unable to access and understand these resources risk falling behind in both knowledge and relevance.

In this context, linguistic agility refers not only to the ability to read and understand technical English but also to actively use the language in varied professional scenarios – writing emails, conducting virtual meetings, participating in collaborative design sessions, and explaining complex ideas to non-technical stakeholders. Such competence enables engineers to contribute meaningfully in international consortia, present research findings at global conferences, and even take leadership roles in multinational teams. For Ukrainian graduates seeking to enter this landscape, language proficiency significantly broadens career horizons, allowing access to employment opportunities across Europe, North America, and increasingly, Asia-Pacific regions.

Moreover, surveys of employers in the energy and engineering sectors often highlight a "skills gap" between what is taught in universities and what is required in real-world practice. One of the most cited gaps is communication in English, particularly in digital professional settings. Addressing this disconnect requires the early integration of digital and linguistic training into engineering curricula, with ESP courses playing a central role in this transformation.

Forward-thinking employers are also looking for candidates who demonstrate digital confidence – the ability to navigate new technologies, evaluate digital information critically, and adapt to emerging platforms. Combined with language skills, digital confidence creates professionals who are not only technically skilled but also versatile, innovative, and collaborative. These are the individuals who can thrive in agile project teams, contribute to sustainable energy solutions, and lead digital innovation efforts within their organisations.

In all, the labour market is sending a clear message: tomorrow's engineers must be fluent in both the languages of technology and of global communication. For Ukrainian students of power engineering, responding to this demand requires a learning environment that fosters digital literacy and robust ESP competence from the outset. Universities that invest in the development of these competencies are not only preparing students for employment – they are equipping them to shape the future of the digital economy.

The evolving expectations of the labour market underscore a pressing need for educational strategies that develop not only domain-specific expertise, but also the digital and communicative competencies that empower students to thrive in globalised, tech-driven industries. As this chapter has illustrated, digital language competence is no longer a peripheral consideration in engineering education – it is a central pillar of professional preparedness, particularly in the context of Ukraine's integration into the European and global knowledge economies.

In response to these demands, Ukrainian technical universities must adopt innovative, practice-oriented approaches to teaching English for Specific Purposes (ESP), with a strong emphasis on digital tools and platforms that reflect real-world communication practices in the energy sector. The following section of this chapter will explore how such tools – ranging from learning management systems to AI-powered writing assistants and interactive simulations – can be effectively integrated into the ESP curriculum. It will also examine specific pedagogical techniques that enhance learner engagement, foster autonomy, and bridge the gap between classroom instruction and workplace expectations.

Through a closer look at these digital methodologies, we aim to highlight practical solutions for developing the kinds of language competencies that make future engineers not only employable but truly competitive in the digital economy of Ukraine and the whole world.

2. Integrating digital educational technologies into ESP teaching for power engineering students

The effective development of digital language competence among engineering students requires not only the recognition of its importance, but also the implementation of targeted, technology-enhanced teaching practices. English for Specific Purposes courses must evolve to reflect the linguistic demands of the modern engineering workplace, which is increasingly mediated by digital tools and collaborative platforms.

In Ukrainian technical universities, this evolution is not just desirable – it is essential. By strategically incorporating digital educational technologies into the ESP classroom, educators can create immersive, practical learning environments that prepare students for authentic communication tasks in the digital economy. Such an approach ensures that graduates are not only proficient in technical English but are also confident users of the digital communication tools that define contemporary engineering practice.

One of the most versatile and widely adopted tools in this context is the Moodle learning management system. Moodle allows instructors to design flexible, blended ESP courses that combine traditional classroom instruction with independent online learning. Through Moodle, students can access technical vocabulary modules, complete interactive grammar tasks, watch instructional videos, participate in forums, and submit assignments – all within a structured, accessible digital environment. This flexibility is especially valuable in the current educational landscape, where online and hybrid formats have become the norm due to logistical, geographical, and security-related challenges faced by Ukrainian institutions.

A key advantage of Moodle lies in its capacity to host authentic, field-specific materials that reflect the language used in professional engineering contexts. For instance, power engineering students can engage with real-world documents such as electrical safety regulations, user manuals for smart grid components, and excerpts from international standards (e.g. IEC or ISO guidelines). These resources not only improve students' technical reading skills but also expose them to the terminology and discourse structures typical of their future work environments. Additionally, instructors can integrate comprehension quizzes, vocabulary lists, and writing tasks based on these materials, encouraging both passive and active language use.

Beyond structured course content, ESP teaching can also benefit from digital tools that support independent language learning and language production. For example, the use of electronic dictionaries (such as ABBYY Lingvo or Cambridge Online Dictionary) enables students to quickly look up technical terms and examples of use in real contexts. More advanced learners can also benefit from AI-based grammar and writing tools like Grammarly or QuillBot, which provide real-time feedback and encourage learners to reflect on their own language output. These tools are particularly useful for writing professional documents such as maintenance reports, incident logs, and technical summaries – genres commonly encountered in engineering workplaces.

Another promising innovation in the ESP classroom is the use of technical text generators and translation engines. Tools such as DeepL and ChatGPT can help students explore technical phrasing, sentence structuring, and genre conventions by generating model texts based on given prompts. While these tools should be used critically, under teacher guidance, they can enhance students' awareness of professional language use and offer support in developing their own written texts. For example, students can be tasked with generating a user manual section or a project description using such tools and then refining the output collaboratively, with a focus on clarity, accuracy, and register.

The table below (table 1) presents a comparative analysis of three prominent machine translation tools – DeepL, Google Translate, and ChatGPT – highlighting their strengths and limitations across key performance and usability criteria. This comparison provides insight into their suitability for different linguistic and professional contexts.

To foster communication skills in more dynamic ways, simulations and role-based scenarios offer highly effective methods. ESP instructors can design activities where students assume professional roles – such as project engineers, safety inspectors, or client representatives – and participate in simulated meetings, technical briefings, or problem-solving sessions. These scenarios can be supported by digital communication tools such as Microsoft Teams, Zoom, or Miro, which are widely used in industry and provide students with hands-on experience in navigating digital communication environments. Through such simulations, learners practise both linguistic skills and digital soft skills such as turn-taking in online discussions, presenting data via screen sharing, and negotiating meaning in intercultural teams.

Table 1

Comparative analysis of DeepL, Google Translate, and ChatGPT based on translation quality, context awareness, and usability features

Feature	DeepL	Google Translate	ChatGPT
1	2	3	4
Translation quality	Very high for European languages; natural and idiomatic	Good across many languages; sometimes literal or robotic	High-quality, context-aware translations; can adapt to tone
Context awareness	Moderate – considers sentence context	Low – often translates sentence-by-sentence	High – understands broader context (paragraphs or documents)
Supported languages	~30 languages	Over 130 languages	Over 50 languages (depending on model version)
Specialization handling	Good for business and general topics	Broad coverage, but less specialized	Can handle technical, legal, academic, and creative texts
Idioms & figurative speech	Generally good for common phrases	Often mistranslates or translates literally	Excels at interpreting idiomatic and figurative language
Customization and style control	Limited (formal/ informal in some languages)	Limited	High – can mimic specific tone, register, or user instructions
Real-time translation	Yes, via web and desktop app	Yes, in mobile and web apps	No real-time, but fast with longer inputs

Continuation of Table 1

1	2	3	4
Offline availability	Desktop app (partially offline)	Yes (mobile app downloads)	No (requires cloud access)
Text length limit	Limited (max ~5000 characters per input)	~5000 characters	Much higher (especially in Plus/ GPT-4 versions)
Document translation	Yes (supports .docx, .pptx, .pdf)	Yes (limited formatting retention)	Yes (retains structure if prompted well, but no file upload)
Cost	Free for basic, paid for Pro features	Free (ads may appear)	Free or subscription-based (ChatGPT Plus)
Best use cases	Formal documents, emails, business texts	Everyday phrases, travel, quick translations	Academic, technical, nuanced texts, content rewriting

Source: Created by authors

In addition to simulations, case-based learning provides another valuable pedagogical strategy. By working through real or hypothetical case studies related to smart technologies, renewable energy integration, or system failures, students engage with professional language in context. These tasks encourage the development of problem-solving skills, critical thinking, and the ability to articulate complex ideas in English – an essential competence for future engineers involved in strategic decision-making and international cooperation.

Project-based learning, too, has shown [8] excellent potential in combining digital and linguistic development. For instance, students might be asked to design a bilingual brochure for an energy-efficient solution, create a video presentation on the benefits of solar panels for rural areas, or prepare a technical briefing for foreign stakeholders.

These projects integrate the use of technical vocabulary, digital tools (e.g. Canva, PowerPoint, video editing platforms), and communication strategies, reflecting the authentic demands of contemporary engineering professions.

In sum, the thoughtful integration of digital educational technologies into ESP instruction creates a more responsive, realistic, and engaging learning environment. It enables students not only to acquire professional language skills, but also to practise using them in the kinds of digital contexts that they will encounter in the workplace. For Ukrainian universities committed to preparing globally competitive graduates, the implementation of such methods should be seen not as an optional enhancement, but as a core element of XX century professional education. By embracing this shift, institutions can foster a new generation of engineers who are linguistically agile, digitally competent, and fully prepared to meet the complex demands of the international labor market.

The use of moodle for blended and distance learning formats

The increasing need for flexibility in education, particularly in times of crisis and transition, has prompted higher education institutions worldwide to adopt learning management systems (LMS) as integral components of curriculum delivery. Among the various platforms available, Moodle has established itself as one of the most accessible, versatile, and pedagogically effective solutions for both blended and distance learning environments. In the context of teaching English for Specific Purposes to power engineering students, Moodle provides a structured, interactive space where language instruction can be closely aligned with professional needs and digital literacy development.

At its core, Moodle serves as a virtual classroom that enables the delivery of content, the facilitation of communication, and the monitoring of student progress – all in one platform. Its open-source nature makes it particularly suitable for Ukrainian universities operating under budget constraints, while its modular structure allows educators to design courses that reflect the specific linguistic and technical demands of their students' future professions. In ESP settings, where relevance and contextualisation are key, Moodle supports the creation of learning pathways that mirror real-world communication tasks encountered by engineers.

In blended learning formats, Moodle complements face-to-face instruction by allowing students to engage with digital content before or after in-class activities. For example, an instructor might assign a pre-lesson vocabulary module on smart grid terminology, followed by an in-class discussion on energy distribution systems. Alternatively, students may be asked to watch a video explanation of a technical process and complete a quiz on Moodle to check comprehension prior to a live seminar. This structure encourages flipped learning, where classroom time is reserved for active language use, such as collaborative problem-solving or technical debates, while individual preparation happens online at the learner’s own pace.

In fully distance-based scenarios, such as those necessitated by wartime disruptions or public health emergencies, Moodle becomes the central hub for instruction. All components of ESP teaching – reading, writing, listening, and speaking – can be adapted to the online environment using Moodle’s built-in tools. These include forums for asynchronous discussions, assignment upload features, integrated video links, quizzes, glossaries, and grading systems. Students can submit technical descriptions, respond to simulated workplace scenarios, or participate in peer-reviewed writing tasks, with timely feedback provided by instructors. This model ensures continuity of learning even when face-to-face interaction is not possible.

An important pedagogical advantage of Moodle is its support for authentic materials and task-based learning. Teachers can upload real industry documents – such as user manuals, technical specifications, or professional standards – and build exercises around them. For example, a lesson on reading technical diagrams might include an embedded PDF of a wiring schematic, followed by comprehension questions and a writing task requiring students to describe the system in English. These materials can be supplemented with digital dictionaries, video explainers, and vocabulary games, allowing for multimodal input that accommodates diverse learning preferences.

Furthermore, Moodle enables the personalisation of learning through adaptive pathways and differentiated tasks. Students with varying levels of English proficiency can be directed towards resources that match their competence, while those requiring additional support may receive individualised feedback or remedial activities. This adaptability is particularly useful in large, mixed-ability groups, which are common in Ukrainian technical universities. It also fosters learner autonomy, as students can revisit materials, track their own progress, and manage their time effectively – essential skills in both academic and professional contexts.

From an administrative perspective, Moodle offers robust tracking features that allow educators to monitor student engagement and performance over time. Attendance, activity completion, quiz scores, and assignment submissions can all be analysed to identify learning gaps or students at risk of falling behind. Such insights are valuable not only for day-to-day teaching, but also for programme evaluation and curriculum development, particularly when aiming to align language training with industry expectations.

In all, the use of Moodle in ESP teaching provides a sustainable and scalable solution for developing digital language competence among power engineering students. Whether in blended or distance formats, Moodle supports pedagogical innovation, fosters independent learning, and ensures that language instruction remains relevant, accessible, and integrated with students' professional development. For Ukrainian universities navigating the twin challenges of digital transformation and geopolitical instability, platforms like Moodle offer a path toward resilience, continuity, and educational excellence.

Application of electronic dictionaries, AI-based grammar tools, and online technical glossaries to enhance vocabulary and grammar acquisition

In the teaching of English for Specific Purposes (ESP), particularly within technical disciplines such as power engineering, the development of a precise and contextually appropriate vocabulary is essential. Equally important is the acquisition of grammatical accuracy, especially when dealing with complex sentence structures often required in technical writing. The integration of digital tools such as electronic dictionaries, AI-powered grammar assistants, and online technical glossaries into ESP instruction represents a significant advancement in language learning methodology, providing students with immediate access to linguistic support tailored to their field.

These tools not only assist in real-time correction and clarification but also foster learner autonomy by encouraging students to actively engage with authentic materials. For example, engineering students can use online corpora to analyze how specific technical terms are used in real-world academic and industrial contexts. This exposure helps bridge the gap between classroom learning and professional communication. AI-powered grammar assistants further support students in constructing syntactically complex sentences that meet the conventions of technical documentation. As a result, students gain greater confidence in producing written reports, abstracts, and project descriptions that are both linguistically accurate and professionally appropriate.

In addition, the use of digital platforms allows instructors to monitor student progress more effectively, providing targeted feedback and adaptive support based on individual learning trajectories. This level of personalization was rarely achievable with traditional methods. Importantly, the integration of technology does not replace the teacher but enhances the instructional process, allowing educators to focus on higher-order language skills such as critical reading and effective argumentation. In this context, digital tools function as an extension of the learning environment, reinforcing classroom instruction and preparing students to operate confidently in a globalized, digitally driven workforce. Ultimately, the thoughtful incorporation of these resources into ESP instruction supports not only linguistic development but also the broader goal of professional readiness.

Electronic dictionaries serve as indispensable tools for ESP learners, allowing for quick, context-sensitive look-up of unfamiliar terms.

Unlike traditional print dictionaries, digital platforms such as ABBYY Lingvo, Cambridge Dictionary Online, and Longman Dictionary of Contemporary English offer learners multiple definitions, example sentences, collocations, pronunciation guides, and sometimes even translations. For instance, a student encountering the term "*inverter*" in a text about photovoltaic systems can access not only a general definition but also sample uses within technical contexts, such as "*solar inverter*" or "*DC to AC inverter*." This deepens understanding and reinforces domain-specific usage.

Moreover, electronic dictionaries are accessible across various devices – computers, tablets, smartphones – which supports learning anytime and anywhere. Teachers can integrate dictionary tasks into ESP lessons, encouraging students to build personal glossaries, identify synonyms, and compare usage across contexts. These activities foster active vocabulary engagement and raise learners' awareness of subtle distinctions in meaning that are especially relevant in technical communication.

The table below (table 2) provides a comparative overview of three major digital language platforms – ABBYY Lingvo, Cambridge Dictionary Online, and the Longman Dictionary of Contemporary English (LDOCE). The comparison covers key aspects such as linguistic functionality, usability, and educational value, offering insights into their respective strengths for learners, translators, and educators.

In addition to dictionaries, AI-based grammar tools such as Grammarly, QuillBot, and LanguageTool have become highly effective assistants in developing grammatical competence among ESP students. These tools go beyond basic spell-checking: they analyse sentence structure, detect register mismatches, and provide suggestions for improving clarity, coherence, and tone. For example, when a student writes a sentence such as "*This system allow to reduce energy consumption*," Grammarly will immediately flag the error and suggest a corrected version: "*This system allows energy consumption to be reduced*."

Table 2

Comparison of digital language platforms: ABBYY Lingvo, Cambridge Dictionary Online, and LDOCE

Feature	ABBYY Lingvo	Cambridge Dictionary Online	LDOCE
1	2	3	4
Primary function	Translation dictionary with multiple bilingual pairs	Monolingual English learner's dictionary	Monolingual English learner's dictionary
Language support	20+ languages; strong in Russian-English / French-German	English only (with some bilingual support for learners)	English only
Pronunciation	Audio in multiple accents (e.g., UK, US)	Audio in UK and US accents	Audio + phonetic transcription using IPA
Example sentences	Varies by dictionary pack; often good for context	Rich, contextual examples from real usage	Extensive examples from real-life usage
Collocations & usage notes	Moderate; varies by dictionary used	Yes; highlights common collocations and grammar notes	Yes; includes 'Collocation boxes' and grammar patterns
Grammar & language notes	Limited (depends on dictionary pack)	Comprehensive grammar, word family, and frequency notes	Strong focus on grammar, usage, and learner-friendly features
Search features	Fast search, wildcard, morphology-aware	Instant search, search suggestions	Smart search, wildcard, integrated thesaurus
Offline availability	Yes (Windows, mobile apps)	No (online only)	Yes (premium versions)

Continuation of Table 2

1	2	3	4
Customization	Yes (user dictionaries, add own words)	No	Limited (some personalization in premium tools)
Integrated learning tools	Flashcards, quizzes, history	Word lists, quizzes, English grammar exercises	Word frequency indicators, vocabulary trainer
Audience focus	General users, professionals, translators	ESL/EFL learners, students, teachers	ESL/EFL learners, exam takers (e.g., IELTS, TOEFL)
Cost	Paid (with free basic versions available)	Free	Freemium (basic free, paid extras for LDOCE Online)
Best use cases	Fast translation, reference for multilingual users	Language learning, pronunciation, academic writing	Learning academic and spoken English, preparing for exams

Source: Created by authors

This instant feedback is especially beneficial for learners who are preparing professional texts such as reports, abstracts, or maintenance instructions, where precision and clarity are non-negotiable. Students also benefit from explanations provided by the software, which helps them understand not just what is wrong, but why – a critical feature for long-term grammar acquisition. Teachers may assign grammar improvement tasks using these tools or ask students to revise their writing based on AI suggestions and reflect on the changes made.

Another valuable resource in ESP instruction is the use of online technical glossaries, which provide field-specific terminology with definitions written for professionals or learners in the target domain. Platforms such as Electropedia (by the IEC), IEEE Glossary, and Energy Glossary by the U.S. Energy Information Administration offer reliable, up-to-date definitions of specialised terms used in the power and energy sectors. For example, a student researching "smart metering" can refer to Electropedia for the official IEC definition, which provides context and precise usage relevant to international standards. Such resources not only enhance students' understanding of domain-specific terminology but also familiarize them with the standardized language used in international technical communication, which is essential for their future professional engagement.

The following table compares (table 3) three specialized terminology platforms – Electropedia by the International Electrotechnical Commission (IEC), the IEEE Glossary, and the Energy Glossary by the U.S. Energy Information Administration (EIA). These resources are critical for ensuring consistency and clarity in technical and energy-related documentation.

Table 3

Comparison of technical glossary platforms: Electropedia, IEEE Glossary, and EIA Energy Glossary

Feature	Electropedia (IEC)	IEEE Glossary	Energy Glossary (EIA)
1	2	3	4
Publisher	International Electrotechnical Commission (IEC)	Institute of Electrical and Electronics Engineers (IEEE)	U.S. Energy Information Administration (EIA)
Scope	Electrotechnical and energy-related terms	Electrical, electronic, and computing terms	Energy production, consumption, and policy terms
Terminology depth	Highly structured and internationally standardized	Concise definitions from IEEE standards	General definitions intended for policymakers and the public

Continuation of Table 3

1	2	3	4
Audience	Engineers, standards developers, international regulators	Researchers, engineers, standards developers	General public, policymakers, educators
Search functionality	Alphabetical + thematic browsing	Search via IEEE Xplore or standards documents	Keyword search with straightforward results
Update frequency	Regularly updated as standards evolve	Updates align with standard revisions	Updated periodically with changes in energy sector
Cross-references	Yes, includes links to related terms and standards	Limited; depends on document structure	Basic internal linking within glossary entries
Access	Free online access	Access varies (some content behind paywall)	Fully free online access
Best use cases	Developing international standards, precise technical writing	Understanding IEEE standards, technical documentation	Public communication, energy education, and policymaking

Source: Created by authors

These glossaries are particularly useful when students work on reading comprehension tasks, translation exercises, or project-based writing in ESP courses. By consulting authoritative sources, students learn to recognise correct terminology, differentiate between similar technical concepts (e.g. "*current transformer*" vs. "*potential transformer*"), and avoid literal translations or incorrect usage that may arise from general-language resources.

To maximise the benefits of these tools, instructors can design integrated tasks that combine vocabulary acquisition, grammar refinement, and professional reading or writing. For example, in a lesson on renewable energy systems, students might be asked to:

- read a short excerpt from a manufacturer's datasheet on wind turbine controllers;
- use an electronic dictionary to clarify unfamiliar terms (e.g. "*yaw control*," "*anemometer*," "*cut-in speed*");
- draft a paragraph summarising the system's operation using appropriate grammar and technical vocabulary;
- run the paragraph through Grammarly or QuillBot, compare the original and revised versions, and reflect on the corrections.

Such tasks promote learner autonomy, digital literacy, and linguistic accuracy – three pillars of successful ESP education in the digital age.

In all, the application of electronic dictionaries, AI-based grammar tools, and online technical glossaries empowers engineering students to engage with technical content more confidently and accurately. These tools not only support the development of linguistic competence but also mirror the resources professionals rely on in real workplaces, thereby reinforcing the authenticity and practicality of ESP instruction. Their integration into the language curriculum is both a pedagogical necessity and a strategic enhancement of students' readiness for participation in the global digital economy.

Simulations and case-based learning as tools for developing digital communication and language skills

As the demands of the modern labour market evolve, so too must the methodologies used in English for Specific Purposes (ESP) instruction. Traditional approaches, while still useful for foundational skill-building, are often insufficient to prepare learners for the realities of XX century workplaces – particularly those shaped by globalisation, digitalisation, and interdisciplinary collaboration. To address this, simulations and case-based learning have emerged as powerful, practice-oriented strategies that mirror authentic workplace communication scenarios and foster both linguistic and digital competencies. These methods are especially relevant in the context of power engineering education, where the ability to engage in problem-solving communication is central to professional success.

Simulations offer students a structured opportunity to experience workplace-like communication tasks within a safe, educational environment. In ESP courses, this often means replicating realistic technical or professional interactions such as safety briefings, project coordination meetings, technical presentations, or maintenance report discussions. These activities are conducted using the language of the target field, and, where possible, via digital platforms that are also commonly used in industry – such as Zoom, Microsoft Teams, or Slack. By engaging in these simulations, students not only practice relevant vocabulary and discourse patterns but also develop essential soft skills like clarity, teamwork, and digital communication etiquette that are increasingly valued in modern engineering workplaces.

For example, students may be assigned roles in a simulated international engineering team tasked with evaluating the feasibility of implementing smart grid infrastructure in a rural area. Each student is given a specific function – such as system designer, environmental analyst, or financial coordinator – and must prepare and present their analysis in English. The simulation may take place entirely online, requiring students to use screen-sharing features, upload digital documents, respond to real-time queries, and collaborate in breakout rooms. Through this process, learners practise domain-specific vocabulary, improve fluency, and gain experience in managing digital tools for communication – skills directly transferable to future employment settings.

The table below (table 4) compares three widely-used collaboration platforms – Zoom, Microsoft Teams, and Slack. Each of these tools supports communication and teamwork in professional and educational settings, but they differ in features, integrations, and optimal use cases.

Table 4

Comparison of collaboration platforms: Zoom, Microsoft Teams, and Slack

Feature	Zoom	Microsoft Teams	Slack
1	2	3	4
Primary function	Video conferencing	Integrated communication and collaboration	Messaging and collaboration
Strengths	High-quality video/audio, webinars, virtual backgrounds	Strong Office 365 integration, videochat, collaboration tools	Fast and organized messaging, robust app integrations
Video conferencing	Excellent; focus on meetings and webinars	Very good; integrates with scheduling and calendar	Basic; best used with third-party plugins
Messaging & chat	Basic in-meeting chat	Full-featured persistent chat, threads, mentions	Excellent chat with threads, emojis, reactions, rich formatting
File sharing	Available during meetings	Integrated with OneDrive and SharePoint	File sharing with Slack storage or linked cloud services
Integrations	Good: Outlook, calendar, whiteboards, Zoom Apps	Excellent with Microsoft products, third-party apps	Extensive app directory: Google, Microsoft, Trello, GitHub
Breakout rooms	Yes (strong feature)	Yes (limited flexibility)	No native support (some workarounds)
Security & compliance	End-to-end encryption (E2EE) available	Enterprise-grade security, compliance features	Good security; enterprise-level compliance

Continuation of Table 4

1	2	3	4
Mobile app	Full-featured and intuitive	Robust mobile experience	Highly rated mobile chat app
Free version	Yes, limited to 40-minute meetings	Yes, with limited features	Yes, with limited integrations and storage
Best use cases	Online meetings, webinars, education	Corporate environments, team collaboration	Agile teams, project management, developer collaboration

Sourse: Created by authors

Case-based learning complements simulations by engaging students in the in-depth analysis of real or hypothetical scenarios drawn from professional contexts. These cases typically involve [9] a technical problem or decision-making challenge and require students to work collaboratively to identify solutions, justify their recommendations, and communicate their findings in English. In power engineering contexts, this might include topics such as analysing the causes of a transformer failure, evaluating competing renewable energy proposals for an industrial site, or drafting a response to a customer complaint about voltage irregularities.

A well-designed case study encourages students to read and interpret technical documents, extract relevant information, apply critical thinking, and present conclusions in written or oral form. For example, after reviewing a manufacturer's fault log and a customer's complaint email, students may be asked to write a short formal report summarising the findings and recommending preventive measures. The instructor may then guide students through a peer review process, followed by submission through Moodle, where additional feedback can be provided using AI-assisted writing tools or grading rubrics.

Both simulations and case-based activities promote communicative competence in context, which is a core aim of ESP. Importantly, they also strengthen soft skills – such as teamwork, adaptability, and digital collaboration – which are now recognised as vital components of professional readiness in engineering. In multilingual teams or international projects, engineers must frequently present their work, negotiate with stakeholders, and respond to feedback from diverse audiences. Case-based and simulation tasks provide students with a rehearsal space for these complex interactions.

Additionally, these methods support interdisciplinary integration, encouraging students to draw on their engineering knowledge while developing language and communication strategies. Teachers may collaborate with faculty from technical departments to design tasks based on current research or applied technologies in the field, thereby reinforcing the connection between language learning and students' core disciplines. Such collaboration also strengthens the authenticity of learning and increases student motivation, as learners can see a direct link between their ESP work and future professional roles.

In terms of assessment, simulations and case-based learning lend themselves well to formative and performance-based evaluation. Teachers can assess students not only on language accuracy but also on clarity, effectiveness of communication, teamwork, and professionalism. Rubrics that include language criteria alongside content and digital skills are particularly useful in capturing the multifaceted outcomes of these activities.

In all, simulations and case-based learning represent an effective response to the pedagogical challenges of preparing engineering students for global, digitally connected workplaces. They foster the development of ESP competencies in ways that are both engaging and aligned with real-world professional practices. By integrating these methods into ESP curricula, Ukrainian technical universities can ensure that their graduates are not only linguistically prepared, but also capable of navigating the digital tools and communicative demands of their future engineering careers.

Use of technical text generators and translation engines (e.g. DeepL, ChatGPT) for comprehension and production of engineering texts

The digitalisation of education and the growing presence of artificial intelligence in language processing have opened new opportunities for enhancing English for Specific Purposes (ESP) instruction in technical fields. Among the most transformative tools [10] in this area are technical text generators and translation engines, such as DeepL and ChatGPT, which enable students not only to access professional-level content but also to produce and refine their own texts in authentic formats. In the context of teaching ESP to students of power engineering, these technologies are proving to be valuable allies in supporting comprehension, vocabulary development, genre awareness, and written fluency.

DeepL, widely regarded for its high-quality machine translation capabilities, is especially useful for students working with technical documents that may be initially available in Ukrainian or another native language. Unlike earlier generations of translation software, DeepL excels in preserving terminology and syntactic clarity across complex subject matter. For example, when translating a section of an operating manual for a solar inverter system, DeepL provides not only accurate term equivalents (e.g. "*maximum power point tracking*", "*inverter efficiency*"), but also produces grammatically coherent English texts that are suitable for classroom analysis or adaptation into student reports.

In ESP instruction, teachers can leverage this tool in various ways. Students might begin with a Ukrainian-language technical document and use DeepL to generate a preliminary English version. This version can then be reviewed critically in class, allowing students to identify translation challenges, correct inaccuracies, and compare machine output with standard engineering phrasing found in original English-language manuals. This activity not only sharpens reading comprehension but also raises students' awareness of industry-specific terminology, collocations, and register.

Similarly, ChatGPT, powered by advanced natural language processing, offers [11] remarkable capabilities for generating technical texts on demand. Students and instructors can prompt the system to produce summaries, technical descriptions, formal letters, safety instructions, or product comparisons based on specific engineering topics. For instance, when asked to generate a paragraph describing the function of a synchronous generator, ChatGPT can provide a coherent, concise explanation in English, which students may then paraphrase, expand, or adapt for different purposes (e.g. a presentation slide or a maintenance instruction leaflet).

Beyond text generation, ChatGPT can also support language exploration and clarification. Students may input complex sentences or technical explanations and ask the tool to simplify them, define specific terms, or explain grammatical constructions. This promotes learner autonomy and provides immediate, tailored support for those working with unfamiliar content. Used under instructor supervision, ChatGPT can function as a digital assistant that helps students practise engineering communication in meaningful, targeted ways.

Importantly, these tools can also assist with text revision and editing. Students writing technical texts – such as system specifications, short reports, or project proposals – can use AI tools to check grammar, refine wording, and adjust tone. For instance, a student writing "*We install system for solar energy with good effectiveness*" might receive improved suggestions such as "*We install high-efficiency solar energy systems*", learning in the process about appropriate adjective use, article placement, and industry-preferred terminology.

From a pedagogical standpoint, incorporating AI-powered tools into ESP instruction supports [12] scaffolded learning. Beginners can use translation tools to understand input texts, while more advanced learners engage with generated texts as models for their own production. Tasks may include:

- comparing AI-generated texts with authentic technical manuals;
- editing or correcting AI-produced paragraphs based on grammar or factual accuracy;

- using ChatGPT to generate role-play scripts for simulations;
- analysing translation inconsistencies between DeepL and human-written equivalents.

Such tasks encourage students to think critically about language form, function, and appropriateness – core elements of communicative competence. However, it is crucial that these tools are used ethically and pedagogically, with clear guidance on their limitations. Students should be made aware that while AI tools are helpful, they are not infallible: terminology may still be used out of context, nuances can be lost, and factual errors may occasionally appear. Therefore, AI outputs must always be verified against reliable sources, especially in highly technical or safety-critical contexts.

In all, the integration of technical text generators and translation engines into ESP instruction offers significant benefits for comprehension, vocabulary acquisition, writing development, and learner engagement. For power engineering students in Ukrainian universities, these tools provide accessible, immediate support in navigating the linguistic demands of their field. When applied thoughtfully and critically, they not only accelerate language learning [13] but also familiarise students with the kinds of AI-assisted communication processes already shaping the future of engineering work worldwide.

The diverse range of digital tools explored in this section – from learning platforms like Moodle to AI-powered writing assistants and simulation-based learning – demonstrates the rich potential of technology to enhance language acquisition within technical education. These innovations not only support the development of digital language competence, but also reflect the real-world communication environments that engineering graduates will encounter in their professional lives. However, to ensure that such tools are used effectively and sustainably across institutions, broader strategic planning is required. The final section of this chapter outlines a set of practical, evidence-based recommendations for integrating digital language development into master's-level engineering programmes. These proposals aim to guide educators, administrators, and policymakers in strengthening the linguistic and communicative readiness of Ukraine's future engineers within the digital economy.

3. Practical recommendations for strengthening digital language competence in technical master's programmes

The effective integration of digital language competence into the training of future power engineers requires more than isolated classroom innovations – it demands a systematic, institution-wide approach that aligns educational objectives with the evolving needs of the digital economy. As Ukrainian technical universities continue to modernise their curricula and increase alignment with European standards, it becomes essential to embed English for Specific Purposes (ESP) instruction within a digital framework that reflects current labour market demands, technological trends, and international cooperation strategies. This section outlines practical, actionable and working recommendations aimed at strengthening and maintaining the sustainability of digital language competence in technical master's programmes in Ukrainian technical universities during full-scale russian invasion of Ukraine.

Integrate ESP and digital literacy into core curriculum design

Rather than treating ESP as an auxiliary or optional subject, universities should incorporate it as a core component of professional training. This requires a curriculum that recognises digital language competence as a cross-cutting skill, vital not only in academic settings but also in the workplace. Specifically, master's programmes in engineering should:

- include mandatory ESP modules focused on domain-specific vocabulary, documentation, and digital communication formats;
- align course content with actual workplace practices – e.g. writing system specifications, understanding technical standards in English, or participating in virtual project meetings;
- encourage interdisciplinary cooperation between language instructors and technical faculty to develop authentic tasks and assessments that blend language and subject knowledge.

Expand the use of digital tools through structured methodologies

While digital tools such as Moodle, Grammarly, ChatGPT, and DeepL are readily available, their educational impact depends on how thoughtfully they are embedded into teaching. Universities should:

- provide guidelines and training for ESP teachers on the pedagogical use of digital platforms and AI tools;
- create institutional repositories of ready-to-use tasks and lesson plans that integrate these tools in meaningful ways;
- promote the use of blended learning formats, with clear task sequencing, formative feedback, and real-world communication simulations;
- establish digital portfolios for students to document their language progress, project outputs, and AI-assisted writing samples.

Develop institutional support systems for teachers and learners

To successfully implement these innovations, support mechanisms must be put in place:

- offer continuous professional development for ESP instructors in educational technologies, curriculum development, and AI literacy;
- ensure access to updated infrastructure, including stable LMS platforms, online libraries, and AI-powered tools;
- provide technical assistance and mentoring for new staff members engaging with digital course design;
- encourage communities of practice where educators can share insights, challenges, and innovations in digital ESP teaching.

Promote collaboration with european educational and research platforms

One of the most effective ways to raise the standard of ESP instruction and digital competence is through international collaboration. Ukrainian institutions should:

- encourage student participation in MOOCs (e.g. FutureLearn, Coursera, edX) that offer content in English related to power engineering, sustainability, and innovation;
- apply for Erasmus+ mobility programmes and joint projects focusing on digital and linguistic competence development;

- engage in virtual exchanges and co-teaching opportunities with European partner universities to model real-life international communication;
- align ESP learning outcomes with CEFR descriptors and the European Framework for the Digital Competence of Educators (DigCompEdu).

Evaluate and certify digital language competence

Establishing a clear system for assessment and recognition of digital language skills reinforces the seriousness of ESP in technical education. Recommendations include:

- incorporating performance-based assessments, such as digital presentations, online report writing, and participation in virtual debates;
- offering micro-credentials or digital badges for the successful completion of ESP modules focused on digital communication;
- collaborating with industry partners to validate assessment tasks and ensure they reflect actual workplace expectations;
- encouraging students to sit for international certifications (e.g. IELTS, TOEIC, Cambridge BEC) alongside university ESP courses, with institutional support.

In summary, the development of digital language competence in technical master's programmes requires an integrated, future-oriented strategy. It is not sufficient to introduce technology into the classroom on an ad hoc basis; rather, universities must cultivate a digital learning culture that values communication as a professional tool, aligns language instruction with economic priorities, and empowers both teachers and students to engage confidently with the demands of the global labour market. By implementing the recommendations outlined above, Ukrainian technical universities can play a vital role in shaping a new generation of engineers who are not only technically proficient, but also linguistically agile and digitally fluent – ready to contribute meaningfully to the digital transformation of the economy.

Examples of successful implementation and student feedback

The effectiveness of digital tools and approaches in ESP instruction is most clearly demonstrated through real-life examples of classroom application and the experiences of students themselves. Across several Ukrainian technical universities, educators have begun systematically integrating digital platforms, AI-based tools, and task-based methodologies into ESP courses – often with highly positive outcomes. These case studies illustrate not only the pedagogical viability of such innovations, but also their perceived value by the very learners they are intended to support.

At Vinnytsia National Technical University, an ESP module for master's students in power engineering was recently redesigned to include blended instruction via Moodle, along with regular use of Grammarly and DeepL for writing support. The course focused on preparing students to communicate technical information clearly and accurately in international contexts. Assignments included writing product descriptions, composing responses to customer enquiries, and summarising technical reports using authentic data sheets and industry-standard templates.

Students were encouraged to use DeepL to translate Ukrainian-language engineering documents and then critically analyse the translation for terminology accuracy and tone. In writing tasks, Grammarly was used not only to identify surface-level grammatical errors, but also to prompt discussion about clarity, passive voice usage, and stylistic conventions in technical English. The final assessment included a simulated online presentation to international stakeholders, where students were evaluated on both linguistic clarity and digital delivery skills.

The study involved 103 students from the Faculty of Energy and Electromechanics, VNTU, all of whom participated voluntarily. In accordance with ethical research standards, informed consent was obtained from each participant, and all collected data was treated with strict confidentiality – no personal information was disclosed or published at any stage of the study.

Feedback from participants was overwhelmingly positive. In anonymous surveys, 88% of students reported increased confidence in reading and producing engineering texts in English. One student wrote:

"*Before, I was afraid to write technical reports in English because I wasn't sure of the grammar and the terms. With Grammarly and the glossary links, I could check myself and feel more secure. Also, it helped me understand the way professionals really write in English*."

Another commented on the benefits of Moodle's structured learning path:

"*I liked the combination of videos, tasks, and forums. It was like we were learning English, but with a clear purpose – for work, for communication in projects. It was not abstract*."

Similarly, ESP instructors introduced simulation-based learning activities into the master's programme in electrical systems and networks. In one project, students participated in a week-long role-play in which they were tasked with resolving a fictional blackout affecting multiple facilities. Working in teams, they had to compose internal memos, write service reports, and participate in video calls (via Zoom) with instructors posing as international consultants.

The instructors noted a marked improvement in both student engagement and language production. Many students took the initiative to use online glossaries (such as Electropedia and IEEE Glossary) to ensure accuracy in their descriptions of technical failures. AI tools like ChatGPT were allowed under supervision for drafting first versions of documents, which students then edited collaboratively using Google Docs, incorporating teacher feedback.

Student reflections following the activity indicated strong appreciation for the realistic context. As one group member shared:

"*It was like a real situation. We had to explain problems clearly, suggest solutions, and communicate formally. I learned not only new words but also how to organise my thoughts professionally in English*."

Another wrote:

"*Using Zoom and writing formal messages to 'consultants' was a new experience. It helped me think about how we will work in international teams in real jobs*."

Beyond this feedback, instructors observed increased student autonomy, improved collaborative writing skills, and greater willingness to take risks in English communication. Importantly, several students later reported applying the skills acquired in ESP courses during internship interviews and work placements, particularly in tasks involving technical correspondence or online collaboration with international colleagues.

These examples confirm that when digital tools are used purposefully – embedded in tasks that mirror authentic professional scenarios – they not only enhance language development but also contribute to the overall confidence and communicative readiness of engineering students. Moreover, student feedback reinforces the notion that ESP instruction should be practical, context-driven, and aligned with the digital realities of modern industry. These findings underscore the importance of rethinking traditional ESP methodologies in favor of dynamic, technology-enhanced approaches that better prepare students for the linguistic and professional demands of the XXI century engineering workplace.

Prospects for cooperation with European educational platforms (e.g. Coursera, FutureLearn, Erasmus+ projects)

The ongoing digitalisation of higher education, accelerated by global trends and local challenges, has opened up unprecedented opportunities for Ukrainian technical universities to engage in strategic cooperation with European educational platforms. These platforms – such as Coursera, FutureLearn, and Erasmus+ – offer not only access to high-quality, internationally recognised educational content, but also serve as catalysts for institutional development, cross-border collaboration, and the strengthening of digital and linguistic competence among both students and educators. By integrating these resources into ESP curricula, universities can better align their language education with European standards, while also fostering a more inclusive and future-ready academic environment. Such integration empowers students to participate in international academic and professional communities, enhancing their mobility, employability, and capacity to contribute meaningfully to global engineering challenges.

One of the most immediate benefits of partnering with platforms like Coursera and FutureLearn lies in their vast repositories of professionally relevant courses, many of which are offered in English and tailored to the needs of engineering and technology students. For instance, Coursera hosts courses on smart grid technologies, renewable energy systems, and data analysis for engineers, delivered by institutions such as the University of Colorado Boulder, Delft University of Technology, and Imperial College London. These modules often include authentic technical texts, English-language video lectures, interactive assignments, and automated assessments – providing an immersive language and content learning experience that supports both subject mastery and ESP development.

Integrating these courses into university ESP programmes can significantly enhance students' exposure to authentic English-language materials while also encouraging autonomous learning habits. For example, an instructor might recommend or require students to complete a FutureLearn course on *Energy Transition* as a supplement to classroom instruction, with subsequent reflective assignments or discussion tasks built around the terminology, case studies, and professional discourse encountered in the online course. Such integration not only enriches the learning process but also familiarises students with the genre conventions and rhetorical styles used by professionals in their field.

The table below (table 5) presents a comparison of three prominent educational platforms and programs – Coursera, FutureLearn, and Erasmus+. These platforms differ in their delivery models, geographic reach, and primary target audiences, yet all play significant roles in expanding access to global education and lifelong learning.

Beyond content access, cooperation with these platforms opens the door to digital credentialing, allowing students to earn verified certificates that can strengthen their CVs and LinkedIn profiles. This enhances their global employability and demonstrates initiative and language competence to potential employers. Furthermore, students gain experience working in English-language learning environments, where communication with instructors and peers from other countries develops intercultural competence alongside technical and linguistic skills.

Table 5

Comparison of educational platforms: Coursera, FutureLearn, and Erasmus+

Feature	Coursera	FutureLearn	Erasmus+
1	2	3	4
Type	Online learning platform	Online learning platform	EU-funded international education program
Provider	Private (Founded by Stanford professors)	Owned by The Open University (UK)	European Commission (EU initiative)
Delivery mode	Self-paced or instructor-led online courses	Scheduled online courses with social learning model	In-person mobility (exchange, internships) + virtual cooperation
Main focus	Professional development, university courses, degrees	Short courses, microcredentials, professional and academic skills	Student and staff exchange, institutional collaboration, capacity building
Target audience	Global learners, working professionals, students	Learners from the UK, EU, and globally	Higher education students, educators, youth workers, institutions
Certifications	Certificates, professional and university diplomas	Certificates of achievement, academic credit for some courses	Formal recognition through ECTS or learning agreements
Cost	Free audit; paid certificates, subscriptions, and degrees	Many free courses; paid upgrades for certificates	Grants and full funding for participants; free to access
Languages offered	Primarily English; some courses in Spanish, Chinese, etc.	English-focused; limited multilingual options	Multilingual (based on participating institutions)

Continuation of Table 5

1	2	3	4
Accreditation	University and industry accredited programs	Courses often from accredited universities	Official EU recognition; tied to higher education frameworks
Collaborators	Universities (e.g., Yale, Stanford), companies (e.g., Google)	Universities, British Council, professional bodies	EU universities, NGOs, vocational schools, national agencies
Best use cases	Upskilling, university degrees, career advancement	Short-term learning, professional development, academic enrichment	International study, teaching exchange, institutional development

Sourse: Created by authors

In parallel, participation in Erasmus+ projects offers [14] an invaluable avenue for building deeper institutional partnerships and fostering long-term cooperation between Ukrainian and European universities. Through Key Action 2 (Cooperation among Organisations and Institutions) and Capacity Building in Higher Education (CBHE) initiatives, Ukrainian institutions can:

- co-develop ESP and technical course content with European partners;
- implement joint digital learning programmes that blend language and subject instruction;
- train educators in CLIL (Content and Language Integrated Learning) methodologies and digital pedagogy;
- facilitate virtual exchanges and blended mobility projects, where students participate in international teamwork using English as a working language.

Such projects not only support curriculum innovation but also contribute to the internationalisation of education, a key objective for Ukraine's integration into the European Higher Education Area. Moreover, Erasmus+ fosters sustainable development by funding digital infrastructure, promoting inclusivity, and encouraging the exchange of best practices across institutions.

The prospects for future cooperation are promising, particularly as Ukrainian universities seek to align with EU digital and educational strategies. By embedding the use of European platforms into formal ESP curricula and institutional strategies, universities can:

- bridge gaps in digital and linguistic competence;
- diversify learning experiences;
- expand their academic networks;
- increase resilience in times of crisis through decentralised, cloud-based learning models.

In conclusion, collaboration with European educational platforms is not merely an option for enriching ESP instruction – it is a strategic pathway toward raising the quality, relevance, and international competitiveness of Ukraine's technical education sector. It empowers students with the tools and experiences needed to operate confidently in global digital environments and positions Ukrainian universities as active contributors to the shared European educational space.

Policy-level recommendations for aligning digital language training with national goals of economic digitalisation

As Ukraine continues its strategic transition towards a digital economy, the role of higher education – particularly in technical fields – has become central to the development of the human capital needed to support this transformation. Within this context, digital language competence should be viewed not as an isolated educational objective, but as a strategically important component of national economic resilience and international integration. Effective policy-level interventions are essential to ensure that digital language training, especially in English for Specific Purposes (ESP), is fully aligned with broader digitalisation goals and labour market demands.

To achieve this alignment, universities must collaborate closely with industry stakeholders to identify the specific digital and linguistic skills required across various sectors. Curriculum development should prioritize interdisciplinary approaches that integrate ESP with digital literacy, coding, data analysis, and critical thinking. This will not only enhance students' employability but also contribute to a more agile and innovative workforce. Policymakers must support these efforts by providing funding for educational technology, teacher training, and curriculum innovation. In addition, national standards for digital language competence should be developed to ensure consistency and quality across institutions. As digital transformation accelerates, the ability to communicate technical knowledge in English becomes a key differentiator in the global marketplace. Therefore, ESP programs should focus on real-world tasks, such as writing technical reports, engaging in virtual collaboration, and navigating international digital platforms. Universities should also foster partnerships with global institutions to offer students immersive language experiences and exposure to international best practices. Ultimately, a strategic emphasis on digital language competence will strengthen Ukraine's position in the global digital economy. By embedding ESP within a broader digital strategy, higher education can become a powerful driver of national resilience, innovation, and growth.

To further support this vision, academic institutions should leverage digital platforms and AI-powered tools to personalize ESP learning and make it more adaptive to individual needs. Emphasizing project-based learning and problem-solving in ESP courses can simulate real-world scenarios, reinforcing both linguistic and technical competencies. Government incentives for universities that demonstrate measurable progress in digital language integration could accelerate nationwide implementation. Moreover, strengthening teacher capacity through continuous professional development in digital pedagogy and ESP instruction is critical. Attention must also be paid to rural and underserved regions to prevent a digital and linguistic divide within the country. National education strategies should incorporate feedback mechanisms to continuously evaluate the effectiveness of ESP programs in meeting labour market expectations. Engagement with the tech industry can provide students with internships, mentorship, and exposure to evolving digital communication practices. Promoting multilingualism, with English as a foundational component, can enhance Ukraine's competitiveness in regional and global collaboration. Recognizing ESP as a strategic investment rather than a supplementary skill will reshape perceptions of language education. As Ukraine builds a knowledge-based economy, digitally fluent and linguistically competent graduates will be essential to driving sustainable development and innovation.

In this transformative era, embedding digital language competence into the core of higher education policy is not just beneficial but imperative for Ukraine's long-term economic sovereignty and global relevance.

Firstly, national education and innovation policies should explicitly recognise ESP and digital language competence as priority areas within the broader digital transformation agenda. Government documents such as the Digital Economy and Society Development Concept of Ukraine (2020) and subsequent implementation plans can be revised or supplemented to include specific reference to:

- the integration of digital ESP into technical and vocational education;
- the promotion of English-language proficiency in digital communication for engineers, IT professionals, and technical personnel;
- the development of educational standards that incorporate digital communication skills as a measurable graduate attribute.

Secondly, the Ministry of Education and Science of Ukraine, in collaboration with leading technical universities and employers, should develop national ESP curriculum guidelines for master's programmes in engineering and related fields. These guidelines recommend:

- the inclusion of technology-enhanced language learning (e.g. LMS, AI tools, simulations);
- the use of authentic digital content relevant to industry sectors;
- a minimum English language level (e.g. B2+) as an exit requirement for technical master's graduates;

- competency descriptors for digital communication in English, aligned with the Common European Framework of Reference (CEFR) and digital competence frameworks such as DigCompEdu.

Thirdly, it is recommended that national funding instruments be designed to support the upskilling of ESP educators in both linguistic and technological domains. This include:

- professional development grants for teacher training in AI-assisted instruction and digital pedagogy;
- institutional incentives for cross-disciplinary collaboration between language departments and engineering faculties;
- the creation of digital repositories of ESP materials, tasks, and case studies, accessible to educators across Ukraine;
- state-supported participation in international educational partnerships (e.g. Erasmus+ Capacity Building, eTwinning, European MOOCs).

In addition, industry-education cooperation mechanisms should be strengthened to ensure that digital language training remains responsive to the needs of the real economy. This can be achieved by:

- establishing sectoral advisory boards involving employers, industry experts, and ESP instructors to review and co-develop course content;
- encouraging companies to provide examples of real technical documentation, workplace communication formats, and digital language use cases;
- facilitating internship and project opportunities in which students use English in digital professional environments.

To ensure long-term sustainability, policymakers should promote the development of national certification systems that assess and recognise digital language competence within higher education. These could take the form of micro-credentials, digital badges, or part of a broader graduate profile framework, linked to both academic transcripts and the national qualification register. Such recognition would help standardise quality, increase student motivation, and provide clear signals to employers.

Aligning these certification systems with international standards would facilitate student mobility and enhance Ukraine's participation in global academic and professional networks. By embedding certified digital language competence into national education benchmarks, Ukraine can foster a future-ready workforce equipped for the demands of the digital age.

Finally, policy must acknowledge the role of digital ESP training in Ukraine's post-war recovery and reintegration into the European community. By preparing graduates to work in international settings, contribute to cross-border infrastructure projects, and access global research and innovation networks, digital language competence becomes an enabler of economic rebuilding and resilience.

In all, aligning digital language training with national economic digitalisation goals requires a coordinated policy response – one that integrates curriculum reform, teacher development, institutional innovation, and public-private cooperation. By embedding these priorities into strategic documents, funding mechanisms, and accreditation systems, Ukraine can position itself not only as a consumer of global technologies, but as an active and competitive participant in the international digital economy.

Conclusion. In the rapidly evolving landscape of the global digital economy, the importance of integrating digital language competence into the professional training of future engineers can no longer be overstated. For students of power engineering in Ukraine, the ability to operate confidently in English across digital platforms is not simply an added advantage – it is a critical component of employability, innovation, and international collaboration. This chapter has examined the multifaceted role of English for Specific Purposes (ESP) within the context of digital transformation, highlighting how language competence intersects with technological fluency to shape the modern engineering professional. Through the use of digital tools such as Moodle, AI-based writing assistants, translation engines, technical glossaries, simulations, and case-based tasks, students gain [15] not only linguistic proficiency but also valuable skills in digital communication, problem-solving, and autonomous learning.

Successful implementations at Ukrainian technical universities, backed by positive student feedback, underscore the practical relevance and transformative potential of digitally supported ESP instruction. Furthermore, prospects for cooperation with European educational platforms and the strategic alignment of digital language education with national policy objectives offer a roadmap for systemic, long-term progress. To fully realise this potential, universities must embrace a forward-looking vision supported by robust institutional policies, international partnerships, and investment in teacher development.

Ultimately, digital language competence is not merely a pedagogical goal – it is a strategic imperative for Ukraine's integration into the global knowledge economy. By embedding it within the fabric of technical education, Ukraine can empower a new generation of engineers to communicate, collaborate, and lead in an increasingly interconnected, digital world.

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3.3. MATHEMATICAL AND INFORMATION MODEL OF A SPECIAL TYPE OF TRANSPORT TASK AS A TOOL FOR INCREASING THE ECONOMIC EFFICIENCY OF FREIGHT TRANSPORTATION

Introduction. The digitalization of the country's economy includes not only the introduction of the latest technologies, but also a deep transformation of management, production and logistics processes based on data and mathematical models. In an environment where markets are becoming increasingly dynamic and the efficiency of operations is critically important, the development and implementation of mathematical and information models is a necessary tool for achieving competitiveness and sustainable development.

One of the most important application areas of such models is the organization of freight transportation.

It is here that the linear programming transport problem becomes of particular importance, which allows finding optimal cargo movement schemes based on the criterion of minimizing costs or delivery time.

In the digital economy, this task becomes the basis for creating intelligent logistics solutions that work in real time, take into account large amounts of data and adapt to changing conditions.

It is used not in isolation, but as part of digital platforms, information and analytical systems, cloud services and mobile applications that provide transparent, fast and efficient transportation management.

Such models allow to automate the processes of route planning, distribution of cargo between modes of transport, calculation of costs and delivery times.

They take into account numerous constraints – from logistics capacities and schedules to climatic conditions and road conditions. Thanks to this, state bodies and private companies can optimize cargo flows, reduce costs and improve the quality of logistics services.

The implementation of mathematical and information models of this type contributes to the digital transformation of the entire transport infrastructure, increases its sustainability, adaptability and economic efficiency. In the long term, this paves the way for building a national digital transport system that meets modern challenges and global standards of sustainable development.

The European experience in using mathematical and information models in the field of freight transportation is one of the most developed in the world, as many EU countries are actively implementing digital technologies to optimize logistics. The main goal of these approaches is to ensure effective management of transport flows, reduce costs and environmental impact, as well as increase transparency in logistics chains.

European models are based on integrated systems that combine mathematical optimization methods (linear and nonlinear programming, network planning methods, queuing theory) with modern information technologies – GPS monitoring, cloud computing, artificial intelligence systems. This allows not only to find optimal routes, but also to adapt them in real time, taking into account changes in traffic, weather conditions or infrastructure congestion.

Another important aspect of the European experience is the centralized management of logistics at the state or interregional level.

This contributes to the unification of information platforms that use common algorithms for calculating routes, pricing and delivery control. This ensures consistency of actions between private carriers, logistics companies and state authorities.

Particular attention in Europe is also paid to environmental parameters: mathematical models take into account CO_2 emissions when choosing routes, and also optimize vehicle loading to reduce "empty runs".

In general, European practice demonstrates that the use of mathematical and information models in the field of freight transportation contributes to the formation of a sustainable, efficient and high-tech logistics system, which is a benchmark for many countries around the world.

In addition to technical and organizational improvements, an important component of the European approach is the creation of a favorable legal environment for the development of mathematical information models. This not only reduces administrative costs, but also ensures the accuracy and relevance of data for the operation of mathematical models.

European logistics hubs are platforms for the implementation of innovative freight forecasting models. They use systems with machine learning elements that analyze large amounts of historical and real-world data to predict congestion, delivery times, and transportation demand. Such models not only optimize resources, but also provide flexibility in decision-making.

It is worth mentioning separately the active interaction between scientific institutions and business. In many EU countries, research consortia are being created, uniting universities, logistics companies and IT developers. Such partnerships allow creating and adapting mathematical and information models to specific market conditions, implementing pilot projects and testing the effectiveness of various algorithms in real conditions.

The analysis of sources indicates the presence of important theoretical and methodological principles and practical recommendations for the digitalization of the Ukrainian economy in the context of optimizing transport and logistics processes.

In [1; 2] contain sound theoretical approaches to the development of logistics infrastructure and procedures that form the basis for digital modeling and automation of transport tasks.

The works [6; 10; 11] offer mathematical methods and models that can be adapted to digital platforms to increase the efficiency of freight transportation.

In [3; 5; 12] consider strategic aspects of logistics development in the context of digital transformation of the economy, in particular through the integration of innovative technologies and the creation of transport and logistics clusters.

Regulatory documents [7–9] determine state policy in the field of digitalization of the transport system, in particular regarding the implementation of an electronic transit system, the development of international transport corridors and the implementation of the National Transport Strategy until 2030.

Thus, the analysis of the literature indicates the presence of agreed theoretical foundations and practical solutions that create the prerequisites for the development and implementation of digital mathematical and information models of specialized transport problems aimed at increasing the economic efficiency of freight transportation in Ukraine.

Thus, the European approach to the use of mathematical and information models in the field of freight transportation is systemic, comprehensive and high-tech. It is not limited to technical innovations, but covers managerial, regulatory and educational aspects, forming an integrated ecosystem.

The European Union also invests significantly in the development of data infrastructure, which is the basis for the effective functioning of mathematical and information models.

For example, within the framework of the CEF (Connecting Europe Facility) program, the modernization of the TEN-T transport corridors is financed, which provides not only for the physical renewal of the infrastructure, but also for its digitalization – the installation of sensors, monitoring systems, integration with logistics platforms in real time.

Another important element is the standardization of data and models. Within the framework of initiatives supported by the European Commission, common protocols for information exchange are being developed, allowing to unite the systems of different countries and operators into a single digital ecosystem.

This is especially relevant for cross-border transport, where models can take into account changing legislation, customs procedures, time zones and even language barriers.

Considerable attention is also paid to the resilience of logistics to risks – both natural (floods, snowfalls) and socio-economic (strikes, changes in legislation). European models include what-if analysis blocks, which allow simulating different scenarios and choosing the least risky or most profitable delivery strategies.

In addition, the concept of "Digital Twin" is actively used – the creation of a virtual digital twin of a transport system or a separate logistics network. This allows you to test new routes, warehousing logistics, changing modes of transport or even driver behavior in simulation mode.

Thus, mathematical and information models in Europe have long gone beyond theoretical calculations and have become a tool for strategic management of the transport industry.

Overall, the European approach demonstrates that the future of logistics is a symbiosis of intelligent mathematical algorithms, digital infrastructure and cross-sectoral cooperation. This is what allows us to maintain a balance between economic benefit, environmental responsibility and social efficiency of transport in modern logistics.

A significant feature of the European approach is the focus on personalization of logistics solutions.

Mathematical and information models increasingly take into account not only global efficiency indicators (speed, costs, volume of transportation), but also individual customer requirements – from precise delivery times to specifications for storage conditions or cargo tracking.

This "fine-tuning" is achieved by integrating models with CRM systems, e-commerce platforms, and blockchain technologies.

Another bright spot is green logistics, which is gaining more and more importance in EU strategies.

Mathematical models for route optimization include input data on energy consumption, greenhouse gas emissions, and the availability of charging stations for electric trucks. In some countries , in particular in the Netherlands and Norway – Routes for electric trucks are planned taking into account terrain, temperature fluctuations, and the rate of charge loss, which was made possible precisely thanks to deep mathematical data processing.

European experience also shows the effectiveness of interoperability: different transport management systems – for example, in Italy, Spain and Austria – can work together, exchanging data through common interfaces. This allows operators to quickly adapt to changes in traffic, customs procedures or political decisions without having to manually adjust the transportation plan.

An important trend is the active use of open data. EU governments publish real-time data on traffic, road conditions, port capacity and customs status.

This creates a favorable environment for the development of new models and services by both the state and the private sector. Such data is the basis for the development of innovative startups in the field of transport analytics and intelligent planning.

Let us consider the connection between the linear programming transportation problem and the digitalization of the country's economy.

The linear programming transportation problem is a classical mathematical model used to optimally allocate limited resources between supply and consumption points in order to minimize costs.

In the context of the digital transformation of the economy, this problem plays a key role in building efficient logistics systems, implementing automated management tools, and creating intelligent digital platforms.

1. The transportation problem as an optimization tool in the digital economy.

The transportation problem has become the basis for digital solutions in the fields of transport, logistics, manufacturing, trade and government.

It is used not only to calculate the shortest or cheapest routes, but also as a module in forecasting systems, supply chain management, and dynamic balancing of demand and supply.

In a digital economy where decisions are made based on data, the transportation task is integrated into analytical dashboards, mobile applications and government information systems. Thus, it ensures the transition from manual to automated resource management.

2. Digitalization as a catalyst for the application of transport models.

Digital technologies have radically expanded the capabilities of classical models. Now the transport problem is used not only as an abstract equation, but as an interactive part of a complex digital system:

Big Data – allows you to take into account thousands of variables: weather conditions, traffic, seasonality, consumer behavior, etc.;

IoT (Internet of Things) – connected devices (sensors, GPS, RFID) provide real-time updates of task parameters;

Cloud computing – makes it possible to process large transport models, accessible from anywhere in the world, without the need for expensive local software;

Artificial intelligence and machine learning optimize the process of finding solutions, even in non-standard or dynamic conditions.

These technologies allow for the implementation of adaptive models that automatically rebuild routes and strategies depending on changes in the system.

3. Effects on the country's economy.

The integration of the transport problem into the digital economy creates a significant socio-economic effect:

– reduction of logistics costs – optimal routes and loads reduce fuel, time, and human resources costs;

– improving infrastructure planning – models allow you to simulate various infrastructure development scenarios and determine the most appropriate investments;

– increasing business competitiveness – enterprises that implement digital logistics solutions adapt to the market faster and reduce costs;

– transparency and control in the public sector – digital models in transportation and logistics management increase the transparency of tenders, contracts and public transportation.

In addition, effective transportation management helps reduce environmental impact, as route optimization leads to a reduction in CO_2 emissions.

4. Implementation example.

As part of the digital transformation of the country's economy, the following solutions are being implemented:

– state logistics platforms: automated cargo flow control systems, such as electronic queues, transportation planning platforms, digital offices for carriers;

– private initiatives: services such as lardi-trans, zakaz.ua, uber freight integrate the transport task into their algorithms for selecting the optimal supplier or route;

– urban transport models: in megacities, the transport problem is used to plan public transport, freight transport, and optimize traffic schedules.

All this indicates the systemic penetration of mathematical modeling into all levels of the digital economy – from local enterprises to national-level public administration.

5. The role of education and science in the digital transformation of logistics.

The development of the digital economy and the active implementation of mathematical models, in particular the transport problem, require an appropriate scientific and educational base.

It is science and education that are the drivers of the integration of intelligent transport solutions into the practice of business and the state.

Universities and higher education institutions train specialists in applied mathematics, logistics, data analytics, and IT who are able to develop, adapt, and implement transportation models in digital systems.

Scientific research on optimization, modeling, and artificial intelligence allows us to improve the transport problem taking into account new parameters – stability, dynamism, and multi-criteria.

An interdisciplinary approach is becoming extremely important – today a logistics specialist must understand programming, mathematical methods, and digital technologies.

Learning platforms, simulators, and cloud laboratories allow students and young researchers to work with real data and solve problems similar to those that arise in business or the public sector.

The educational and scientific components are no less important than the technical or economic component, because without human and intellectual support, the digital transformation of the transport system will remain only at the level of ideas.

6. Integration of the transport problem into state digital platforms.

One of the key areas of digitalization of the economy is the creation of state platforms and services that automate logistics and transport processes at the national level. The transport task is used in such systems as:

- Prozorro.Sales – automated distribution of freight transportation or logistics services through tenders.
- Electronic logistics systems in the military or humanitarian sectors (e.g., delivery of humanitarian aid or military cargo).
- A unified transport system within the framework of the digital transformation of the Ministry of Infrastructure – for the coordination of rail, road, and sea transport.

The use of mathematical models in such systems allows for transparent and efficient resource management, which is especially important in conditions of limited budgets and the need for rapid response.

7. The impact of the transport problem on sustainable development and the “green” economy.

The modern digital economy is not only focused on profit, but also on environmental sustainability. Route optimization based on the transport problem allows:

- Reduce fuel consumption and emissions into the atmosphere, which is important in the context of the country's commitments to reduce its carbon footprint.

- Model environmentally friendly supply chains.
- Plan the use of alternative modes of transport (electric vehicles, rail instead of motor vehicles).

This directly contributes to the implementation of the sustainable development goals defined by the UN, and also corresponds to the concept of "green logistics", which is gaining popularity in the EU, and therefore in Ukraine.

Thus, the transport problem of linear programming, in combination with digital technologies, becomes a powerful tool for modernization of the economy.

It allows for the implementation of innovative approaches to logistics and resource management, which directly affects the efficiency of the country's economy in the context of digital transformation. Its active implementation contributes to the formation of sustainable, effective, analytically supported solutions in the field of transport, which ensures an increase in the level of digital maturity of the national economy.

Presentation of the main results of the study.

The aim of the work is to develop:

1. General approaches to modeling transport problems.

1.1. Theoretical foundations of the transport problem.

The transportation problem is considered one of the fundamental problems of linear programming.

It consists in determining the optimal way to transport goods from several points of departure to several points of destination with minimal costs. In the general case, the problem takes into account restrictions on the volume of goods, transport capabilities, delivery time, costs and other factors.

1.2. Approaches to mathematical formalization.

Mathematical modeling of the transport problem is based on the construction of an objective function of cost minimization under given constraints. Depending on the type of problem (balanced, unbalanced, multi-criteria, etc.), different formalisms are used. The work focuses on generalized structures that can be adapted to real logistics conditions.

1.3. Information support for modeling.

Effective solution of the transport problem is impossible without proper information support.

The main components of information support include databases on departure and destination points, transport costs, cargo volumes, restrictions, time frames, etc. An important direction is the integration of information systems with modern technologies for collecting, processing and analyzing data.

1.4. Optimization methods.

Traditional optimization methods include the simplex method, the potential method, and the least cost method.

However, in conditions of complex constraints and high dimensionality of the problem, heuristic and metaheuristic approaches (genetic algorithms, particle swarm algorithms, ant algorithms) become relevant.

They allow finding effective solutions in reasonable terms, even when classical methods are unsuitable.

1.5. Directions for further development.

Current trends in the development of transport problem models involve the creation of adaptive, intelligent systems that are able to independently update data, take into account unpredictable changes in conditions and make optimal decisions in real time.

Another important direction is the integration of such models with geographic information systems, cloud platforms and big data technologies.

2. Model and method for finding plans for the transportation problem when grouping suppliers.

2.1. Formulation of a transportation problem model when grouping cargo suppliers.

Transportation problems occupy a special place among linear programming problems, as they reflect typical situations that arise in logistics, transportation planning, and resource allocation optimization.

Their essence lies in the need to efficiently move a certain type of cargo or product from several points of departure, which can simultaneously be considered as production sites or warehouses, to destinations – consumers, stores, storage warehouses, etc.

The main goal of such a task is find the optimal transportation plan that meets the needs of all destinations at minimal transportation costs.

In the process of solving a transportation problem, two main types of constraints should be taken into account: supply constraints, which indicate the maximum volume of cargo that can be shipped from each supply point, and demand constraints, which determine the required amount of cargo that must arrive at each destination point. These constraints are an important component of the mathematical model, as they reflect the real physical and economic constraints that the logistics system faces.

In the classical formulation of the transport problem, the cost of transporting goods between each pair of "departure point – destination" is assumed to be known in advance and unchanging, and is assumed to be a linear function of the volume of cargo being transported.

That is, the cost of transporting one cargo unit remains constant regardless of the total volume of transportation, and the total cost is defined as the product of the cost per unit and the number of units being transported.

Despite the fact that the transport problem is a special case of the linear programming problem and, accordingly, can be solved by standard methods (for example, the simplex method), its special structure allows to significantly simplify the calculation process.

Due to this, specialized algorithms have been developed for solving transport problems, in particular the northwest corner method, the least cost method, the potential method, etc.

These methods allow to quickly find both the initial feasible solution and optimize it to the lowest possible cost.

In cases where it comes to grouping cargo suppliers, there is a need for additional analysis – for example, determining the optimal way to combine several suppliers into groups in order to reduce the number of routes or reduce transportation costs.

In such problems, the model structure can be complicated, and the solution process itself requires taking into account additional factors, such as the geographical location of suppliers, the presence of common routes, the volume of available transport and other logistical constraints.

This extends the classic transport problem to a more general model of transport network optimization with grouping, which, in turn, opens up new approaches to increasing the efficiency of freight transportation in modern conditions.

A graphical representation of the conditions of the transport problem is shown in Fig. 1.

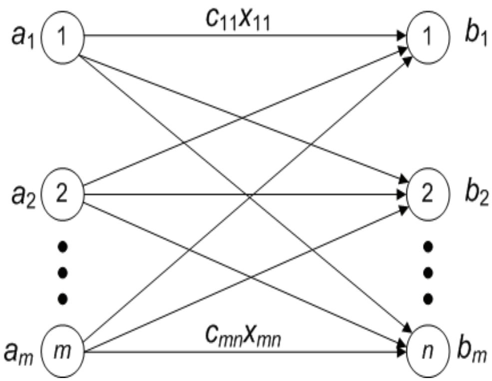

Figure 1. Schematic representation of the connections between the participants of the transportation process of the transport problem

Source: compiled by the author based on [10]

The figure shows *m* origin points and *n* destination points, which are nodes of the network.

The arcs connecting the nodes of the network correspond to the routes connecting the origin points and destinations.

Two parameters are associated with each arc (i, j) between points i and j: the transportation cost c_{ij} and the volume of goods transported x_{ij}.

The volume of goods at point i is a_i, the maximum quantity of goods at destination j is b_j. The problem is to determine the unknown quantities x_{ij}, which minimize the total transportation costs and satisfy the supply (a_i) and demand (b_j) constraints.

Within the framework of the transportation model, the problem of inventory management and the problem of distributing equipment for performing various tasks can also be considered.

The transportation problem is one of the key tools of operations research and can be presented not only in the form of a mathematical model, but also in a convenient tabular format.

In such a tabular representation, each individual row of the table corresponds to a specific departure point or source of products, that is, a supplier who has a certain amount of resources or cargo to transport.

At the same time, each column of the table corresponds to a destination, which is usually considered a consumer or a place where goods must be delivered. The value located in the cell at the intersection of the i-th row and the j-th column reflects the cost of transporting a unit of cargo from a specific departure point to the corresponding destination.

This can be, for example, a monetary amount or a conditional cost coefficient. If there is an unknown value in the cell, then it indicates the volume of transportation that must be determined in the process of solving the problem. In addition, in each row, the last cell indicates a restriction regarding the volume of supply – that is, how much product can be shipped from this source.

In turn, the last cell of each column records the amount of demand that needs to be satisfied at a specific destination. Thus, the tabular form allows you to conveniently structure the initial data of the problem, which greatly facilitates its analysis and subsequent solution.

Of particular note is the situation when cargo suppliers are grouped together. This is typical for hierarchical or multi-level logistics systems, where several lower-level suppliers are subordinate to one higher-level supplier or operator. In such a model, an additional restriction is introduced that regulates the total volume of cargo that can be exported from a certain group of suppliers.

This restriction can be significantly stricter than the simple sum of the stocks of all suppliers included in the corresponding group. The reasons for this can be technical, economic or organizational factors, for example, limited throughput of transport routes or regulated quotas for product export.

As a result of such changes, there is a need to adapt or even fundamentally redesign classical methods for solving the transport problem.

Well-known algorithms, such as the northwest corner method, the minimum element method or the potential method, may be ineffective or even unsuitable for solving problems with additional group restrictions. Therefore, modeling such problems requires the construction of specialized information and mathematical structures that allow for adequate consideration of the characteristics of supplier grouping and corresponding restrictions.

A graphical representation of the conditions of such a transport problem, taking into account the grouping of cargo suppliers and the corresponding logistical connections, is shown in Fig. 2.

It allows you to visualize the supply structure, the relationship between suppliers and recipients, and also demonstrate the effect of restrictions imposed on the movement of goods within the model.

2.2. Method for finding a reference road transportation plan when grouping cargo suppliers.

A special algorithm for solving transport problems was specially developed for fast manual calculations. Currently, most computer programs use the simplex method to solve the transport problem. However, the special algorithm is still important because it allows you to identify the features of the transport problem. Let us consider the solution of the transport problem when grouping cargo suppliers, the conditions of which are given in Table 1.

The algorithm for solving the transport problem is closely related to the classical simplex method and repeats its main stages, but is adapted to the specifics of cargo transportation. The sequence of its implementation includes the following detailed steps.

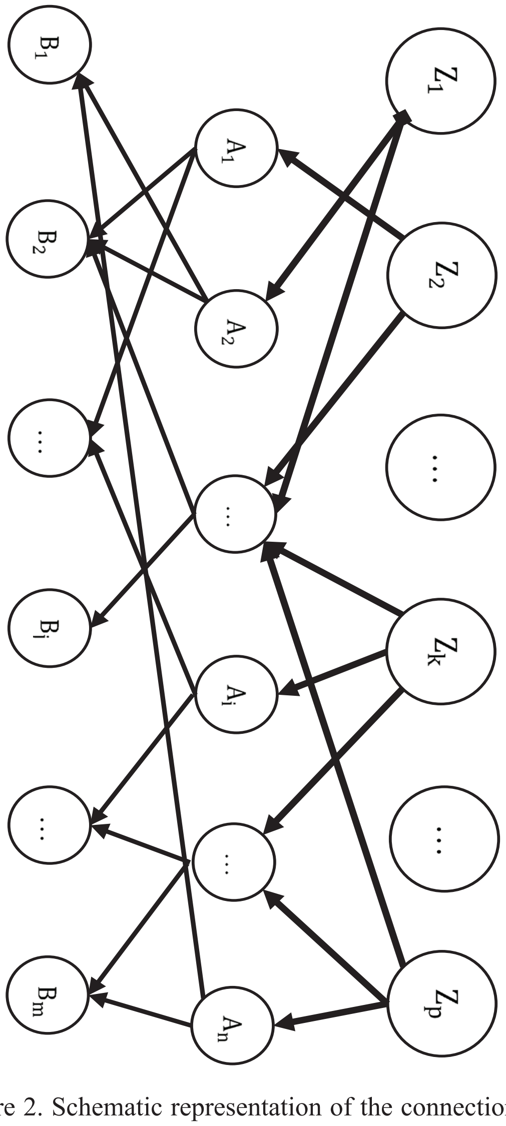

Figure 2. Schematic representation of the connections between the participants of the transport process of the transport problem provided that the cargo suppliers are grouped

Source: compiled by the author based on [10]

Table 1

Input data of the transport problem under the condition of grouping cargo suppliers

Grouping	Cargo suppliers	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
		Sp_1	Sp_2	Sp_3	…	Sp_n		
Gr_1	Ps_1	C_{11}	C_{12}	C_{13}	…	C_{1n}	b_1	g_1
	…	…	…	…	…	…	…	
	Ps_k	C_{k1}	C_{k2}	C_{k3}	…	C_{kn}	b_k	
…	…	…	…	…	…	…	…	…
Gr_u	Ps_r	C_{r1}	C_{r2}	C_{r3}	…	C_{rn}	b_r	g_u
	…	…	…	…	…	…	…	
	Ps_m	C_{m1}	C_{m2}	C_{m3}	…	C_{mn}	b_m	
Expected cargo quantity		a_1	a_2	a_3	…	a_n		

Source: compiled by the author based on [10]

1. Determination of the initial basic feasible solution.

At the first stage of solving the transport problem, it is necessary to find a reference plan, that is, an initial feasible solution that meets all the constraints of the problem: maintaining the balance between demand and supply and, if necessary, additional group or resource constraints. This solution is not necessarily optimal, but it serves as a starting point for further step-by-step improvement. It is usually built using one of the well-known methods – for example, the northwest corner method, the minimum element method or the potential method. In our case, a modified northwest corner method is used taking into account group constraints.

2. Checking the optimality of the current solution.

After constructing the initial plan, its optimality is analyzed. For this, the optimality condition is used, which is determined based on the estimates of non-basic variables. If all of them meet this condition, that is, they cannot improve the value of the objective function, then the calculation is completed – the resulting solution is considered optimal. If at least one non-basic variable allows you to reduce (or increase – depending on the goal of the problem) the value of the functional, it is selected for inclusion in the basis, which means moving to the next stage of plan correction.

3. Replacing the basic variable and forming a new solution.

In the third stage, it is determined which of the basic variables should be removed from the basis. This is done using the so-called admissibility condition – the impact of introducing a new variable on the structure of the solution is analyzed. According to the established rules, a cyclic route is found along which the values are adjusted, and the plan is updated accordingly. After this, the algorithm returns to the second stage – checking for optimality – and the cycle is repeated until an optimal solution is reached.

Building an initial plan using the northwest corner method, taking into account supplier grouping

In the case where suppliers are grouped together with restrictions on maximum transportation volumes, the classic northwest corner method is subject to appropriate modification. Its adaptation involves the inclusion of additional monitoring of the total cargo volumes in each supplier group so that they do not exceed the established values.

The process is carried out sequentially in the following detailed stages:

1. Assigning a value to cell x_{11}.

Starting from the top left cell (the so-called northwestern corner of the table), the maximum volume of cargo that can be assigned to this cell without violating the constraints on the demand of a specific consumer, the supply from a specific supplier, and the group constraints is determined. The resulting value is fixed as the initial delivery.

2. Analysis of the occupancy of rows, columns and groups.

After fixing the supply volume in the cell, it is checked whether the offer of the corresponding supplier has been fully used, the demand of the consumer has been satisfied, or the volume allowed for the group has been exhausted. If at least one of these restrictions is implemented, the corresponding row (supplier), column (consumer) or group is deleted from further consideration. If several restrictions are satisfied at the same time, a decision is made which element to delete, taking into account the logic of further construction.

3. Go to the next cell or end.

Then, move to the next matching cell: to the right if a column is crossed out, or down if a row is crossed out. The process continues in the same pattern: calculate an acceptable value for the new cell, check the constraints, cross out, and move on. If there is only one active row, column, or group left in the table, the algorithm stops because all allocation possibilities have been exhausted.

In this way, an initial reference plan is formed, which will subsequently be optimized according to the stages described above. Continuing to act similarly, we obtain the reference plan given in Table 2.

2.3. Method for finding the optimal road transportation plan when grouping cargo suppliers.

After forming an initial distribution plan that is acceptable from the point of view of the given input conditions, further processing of this solution is carried out using a special algorithm.

This algorithm is based on iterative calculations, the purpose of which is to consistently improve the existing plan until it reaches a state that can be considered optimal within the given constraints. The approach itself involves the use of a methodology that allows you to evaluate the effectiveness of the current distribution and make adjustments in accordance with the logic of the mathematical model underlying the problem.

During the implementation of the algorithm, additional constraints are introduced into the optimization process regarding the grouping of supply sources. This means that instead of analyzing each individual source individually, the model considers the combination of such sources into groups that have a common feature or function within a certain general system.

Table 2

Reference plan of the transport problem under the condition of grouping cargo suppliers

Grouping	Cargo suppliers	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
		Sp_1	Sp_2	Sp_3	…	Sp_n		
Gr_1	Ps_1	X_{11} C_{11}	X_{12} C_{12}	X_{13} C_{13}	…	X_{1n} C_{1n}	b_1	g_1
	…	…	…	…	…	…	…	
	Ps_k	X_{k1} C_{k1}	X_{k2} C_{k2}	X_{k3} C_{k3}	…	X_{kn} C_{kn}	b_k	
…	…	…	…	…	…	…	…	…
Gr_u	Ps_r	X_{r1} C_{r1}	X_{r2} C_{r2}	X_{r3} C_{r3}	…	X_{rn} C_{rn}	b_r	g_u
	…	…	…	…	…	…	…	
	Ps_m	X_{m1} C_{m1}	X_{m2} C_{m2}	X_{m3} C_{m3}	…	X_{mn} C_{mn}	b_m	
Expected cargo quantity		a_1	a_2	a_3	…	a_n		

Source: compiled by the author based on [10]

For each such group, a limit is defined on the total amount of resources that can be directed to various points of cargo consumers on the transport network.

Thus, the distribution is carried out not only in accordance with existing needs and capabilities, but also taking into account the total impact of each group on the overall transportation structure.

If, during the check of the current distribution status, it is found that the set limit for a particular group is exceeded in the corresponding direction, a change is made to the model.

The change is that part of the allocated volume is reduced in order to bring the situation into line with the introduced restrictions. Such correction is carried out in compliance with the general rules of the model, without disrupting the balance between sources and consumption points.

The process of verification and adjustment continues until a distribution is achieved that simultaneously satisfies both the initial conditions and additional constraints related to the groups.

In this approach, the very existence of a mechanism that allows you to automatically identify situations where the established limits are violated and promptly take measures to reduce the amount of resource that is distributed within the limits of the detected discrepancy is important.

This approach allows you to preserve the logic of the algorithm and ensures controllability of the optimization process even in the presence of complications in the form of additional conditions associated with grouping.

The algorithm maintains its consistency and integrity, gradually bringing the system closer to the target state without major failures or losses in the correctness of intermediate results.

As a result of the method, a plan is formed that is not only permissible, but also one that takes into account the specifics of the group structure of sources and adheres to restrictions on the level of the total impact of each of them within the overall distribution system.

After determining the initial basic solution, the potential method algorithm is applied, which allows finding the optimal solution to the transport problem.

The method adds conditions for not exceeding the total load for the established group limit at all points where this occurs.

If a violation is detected, the amount of cargo being redistributed should be reduced.

To find the optimal plan for the transportation problem when grouping cargo suppliers, we will use Table 3.

1. The variable to be introduced into the basis is determined using the simplex criterion I. If the optimal solution is achieved according to the criterion, the algorithm terminates.

2. Using simplex criterion 2, the variable to be excluded from the basis is determined. The basis is changed and the first stage is returned.

Table 3

Finding the optimal plan for the transportation problem when grouping cargo suppliers

Grouping	Cargo suppliers	Potentials	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
			Sp_1	Sp_2	Sp_3	Sp_4	Sp_n		
			Sp_1	Sp_2	Sp_3	…	Sp_n		
Gr_1	Ps_1		X_{11} C_{11}	X_{12} C_{12}	X_{13} C_{13}	…	X_{1n} C_{1n}	b_1	g_1
	…	…	…	…	…	…	…	…	
	Ps_k		X_{k1} C_{k1}	X_{k2} C_{k2}	X_{k3} C_{k3}	…	X_{kn} C_{kn}	b_k	
…	…	…	…	…	…	…	…	…	…
Gr_u	Ps_r		X_{r1} C_{r1}	X_{r2} C_{r2}	X_{r3} C_{r3}	…	X_{rn} C_{rn}	b_r	g_u
	…	…	…	…	…	…	…	…	
	Ps_m		X_{m1} C_{m1}	X_{m2} C_{m2}	X_{m3} C_{m3}	…	X_{mn} C_{mn}	b_m	
Expected cargo quantity			a_1	a_2	a_3	…	a_n		

Source: compiled by the author based on [10]

The determination of the variable introduced into the basis is carried out using the potential method, from which the coefficients of the objective function corresponding to the non-basic variables are determined. In the potential method, each row *i* and column *j* are assigned numbers (potentials) u_i and v_j that satisfy the condition:

$$u_i + v_j = c_{ij}. \qquad (1)$$

In order to find the values of the potentials from this system of equations, it is necessary to give one of them an arbitrary value (usually $u_1 = 0$), and then sequentially calculate the values of the other potentials. The potentials are determined in the table.

Using the found potential values, the following quantities are calculated for each non-basic variable:

$$u_i + v_j - c_{ij}. \quad (2)$$

The coefficients found, together with the zero coefficients for the basic variables, are the coefficients of the row of the objective function of the simplex tableau.

Since the transportation problem seeks to minimize the cost of transportation, the variable with the largest positive coefficient in the row will be entered into the basis.

The described calculations are usually performed in the transport table. And here there is no need to write out the equations for the potentials explicitly.

The calculations of the transport table begin with assigning the potential u_1 a zero value.

Then the v-potentials of all columns with basic variables in the first row are calculated. Next, based on the equation for potentials corresponding to x_{22}, the values of the potential u_2 are determined.

Knowing the value of the potential u_2, we calculate the potentials v_3 and v_4, which allows us to find the potential u_3.

Since all the potentials are determined, the values $u_i + v_j - c_{ij}$ are calculated for each non-basic variable X_{ij}.

These values are shown in the table in the lower left corner of the cells of the transport table.

Now it is necessary to determine the basic variable, which is shown in Table. 4. Let θ denote the amount of cargo transported along the route.

The maximum possible value of θ is determined by the following conditions: 1) the constraints on demand and supply and the constraints on the group of suppliers must be met; 2) no route should carry out transportation with a negative volume of cargo. Let us construct a closed cycle, which is presented in Table 5.

A cycle in this context is formed as a clearly defined sequence of moves through the table, which includes only horizontal and vertical segments.

Table 4

Basic cell of the transportation problem when grouping cargo suppliers

Grouping	Cargo suppliers	Potentials	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
			Sp_1	Sp_2	Sp_3	Sp_4	Sp_n		
			Sp_1	Sp_2	Sp_3	…	Sp_n		
			v_1	v_2	v_3	…	v_n		
Gr_1	Ps_1	u_1	X_{11} C_{11}	X_{12} C_{12}	X_{13} C_{13}	…	X_{1n} C_{1n}	b_1	g_1
	…	…	…	…	…	…	…	…	
	Ps_k	u_k	X_{k1} C_{k1}	X_{k2} C_{k2}	X_{k3} C_{k3}	…	X_{kn} C_{kn}	b_k	
…	…	…	…	…	…	…	…	…	…
Gr_u	Ps_r	u_r	X_{r1} C_{r1}	X_{r2} C_{r2}	X_{r3} C_{r3}	…	X_{rn} C_{rn}	b_r	g_u
	…	…	…	…	…	…	…	…	
	Ps_m	u_m	X_{m1} C_{m1}	X_{m2} C_{m2}	X_{m3} C_{m3}	…	X_{mn} C_{mn}	b_m	
Expected cargo quantity			a_1	a_2	a_3	…	a_n		

Source: compiled by the author based on [10]

Such segments connect the cells corresponding to the basic variables currently participating in the transportation plan, as well as the cell corresponding to the new variable being introduced into the plan.

It is worth emphasizing that construction occurs exclusively through rectilinear movements along the grid – diagonal transitions are not allowed.

This approach provides clarity in constructing the cycle structure of the potential method.

For any variable that is entered into the plan, according to the logic of the calculations, it is always possible to form only one closed loop.

Table 5

Finding the optimal plan for a transportation problem when grouping cargo suppliers

Grouping	Cargo suppliers	Potentials	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
			Sp_1	Sp_2	Sp_3	Sp_4	Sp_n		
			Sp_1	Sp_2	Sp_3	…	Sp_n		
			v_1	v_2	v_3	…	v_n		
Gr_1	Ps_1	u_1	X_{11} C_{11}	X_{12} C_{12}	X_{13} C_{13}	…	X_{1n} C_{1n}	b_1	g_1
	…	…	…	…	…	…	…	…	
	Ps_k	u_k	X_{k1} C_{k1}	X_{k2} C_{k2}	X_{k3} C_{k3}	…	X_{kn} C_{kn}	b_k	
…	…	…	…	…	…	…	…	…	…
Gr_u	Ps_r	u_r	X_{r1} C_{r1}	X_{r2} C_{r2}	X_{r3} C_{r3}	…	X_{rn} C_{rn}	b_r	g_u
	…	…	…	…	…	…	…	…	
	Ps_m	u_m	X_{m1} C_{m1}	X_{m2} C_{m2}	X_{m3} C_{m3}	…	X_{mn} C_{mn}	b_m	
Expected cargo quantity			a_1	a_2	a_3	…	a_n		

Source: compiled by the author based on [10]

This cycle has the property of being closed, that is, it begins and ends in the same cell.

This allows for further calculations that depend on the structure of such a cycle and its corner elements.

Closed loop is a key condition for applying the value redistribution mechanism in the transport table.

The next step is to find the value of the parameter θ (theta), which plays the role of the magnitude of the change.

To maintain a balance between the available supply volumes and the demand volumes, it is necessary to alternately, in accordance with the established order, add or subtract the values of θ to those basic variables that are in the corners of the constructed cycle.

This happens according to the principle of alternating addition and subtraction: one variable increases, the next decreases, and so on, until the loop is completely traversed.

This sequence of actions allows for a correct update of the baseline plan without violating the conditions of the problem.

After making such changes, it is necessary to proceed to the stage of adjusting the values of all basic variables located inside the formed cycle.

This process involves updating the quantitative indicators in the corresponding cells of the table according to the previously calculated value of θ. This is necessary in order to ensure the consistency of all elements of the plan in accordance with the logic of the cyclical method.

In the event that, during the calculations, a situation is detected that violates the restrictions on the allowable amount of cargo for a certain group operating within the task, adjustments must be made.

Such violations indicate that the group has exceeded the permitted level of supply, and therefore it is necessary to reduce the volume of cargo distributed in accordance with these restrictions. This reduction is carried out within certain limits that allow returning to the permissible level without violating other conditions of the task.

After each stage of updating the plan, it is necessary to re-perform the potential calculation procedure.

This involves recalculating the values that determine the difference between the delivery costs and the estimates of the current plan. Calculating potentials allows you to check the optimality of the newly created plan and determine whether it requires further changes.

When all coefficients of the variables included in the objective function of the problem acquire negative values or do not improve the efficiency indicator, this means that the optimality condition has been achieved.

In this case, the solution to the problem is considered complete, and no further calculations are performed.

The current plan obtained at this stage of the algorithm will be considered optimal.

3. Numerical finding of plans for the transportation problem when grouping suppliers.

3.1. Finding a reference transportation plan when grouping suppliers.

Let the conditional parameters of the problem be given in the form of a table that reflects the distribution of cargo between suppliers and consumers under grouping conditions.

The tabular form of the problem representation contains all the necessary input data.

Suppliers are conditionally divided into several groups – for example, several elements in each group.

This structure allows for additional constraints at the level of combined sources of supply, which introduces a more complex distribution logic into the model.

One of the last columns of the table shows the quantities of cargo held in warehouses or other origin points.

Another column records the quantity of cargo that each group of suppliers can provide.

The bottom row of the table shows the expected cargo volume at the final consumption points. All of these indicators must be coordinated with each other to achieve balance.

The cells of the table, which are located at the intersection of the rows and columns representing the sources and destinations, contain the values of the transportation costs or costs in the upper right corner.

These values are used for further calculations. In the central part of each cell, the desired value will be placed – that is, the amount of cargo that must be transported along the corresponding route.

These values are the basis of the reference plan, which is formed in accordance with the input data of the task.

Step-by-step iterations of searching for a reference plan for the transport problem when grouping cargo suppliers are given in table 6–14.

Table 6

Input data of the transport task when grouping cargo suppliers

Grouping	Cargo suppliers	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
		Sp_1	Sp_2	Sp_3	Sp_4	Sp_5		
Gr_1	Ps_1	16	13	18	14	15	370	810
	Ps_2	15	17	14	18	16	570	
	Ps_3	17	14	16	13	18	320	
Gr_1	Ps_4	14	15	13	16	17	420	760
	Ps_5	17	16	15	14	14	470	
	Ps_6	13	18	17	16	13	220	
Expected cargo quantity		470	220	270	520	620	2370	1620

Source: compiled by the author based on [10]

Table 7

Finding a reference plan when grouping suppliers, iteration 1

Grouping	Cargo suppliers	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
		Sp_1	Sp_2	Sp_3	Sp_4	Sp_5		
Gr_1	Ps_1	370 16	0 13	0 18	0 14	0 15	370	810
	Ps_2	0 15	0 17	0 14	0 18	0 16	570	
	Ps_3	0 17	0 14	0 16	0 13	0 18	320	
Gr_1	Ps_4	0 14	0 15	0 13	0 16	0 17	420	760
	Ps_5	0 17	0 16	0 15	0 14	0 14	470	
	Ps_6	0 13	0 18	0 17	0 16	0 13	220	
Expected cargo quantity		470	220	270	520	620	2370	1620

Source: compiled by the author based on [10]

Table 8

Finding a reference plan when grouping suppliers, iteration 2

Grouping	Cargo suppliers	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
		Sp_1	Sp_2	Sp_3	Sp_4	Sp_5		
Gr_1	Ps_1	370 (16)	0 (13)	0 (18)	0 (14)	0 (15)	370	810
	Ps_2	100 (15)	0 (17)	0 (14)	0 (18)	0 (16)	570	
	Ps_3	0 (17)	0 (14)	0 (16)	0 (13)	0 (18)	320	
Gr_1	Ps_4	0 (14)	0 (15)	0 (13)	0 (16)	0 (17)	420	760
	Ps_5	0 (17)	0 (16)	0 (15)	0 (14)	0 (14)	470	
	Ps_6	0 (13)	0 (18)	0 (17)	0 (16)	0 (13)	220	
Expected cargo quantity		470	220	270	520	620	2370	1620

Source: compiled by the author based on [10]

Table 9

Finding a reference plan when grouping suppliers, iteration 3

Grouping	Cargo suppliers	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
		Sp_1	Sp_2	Sp_3	Sp_4	Sp_5		
Gr_1	Ps_1	370 (16)	0 (13)	0 (18)	0 (14)	0 (15)	370	810
	Ps_2	100 (15)	220 (17)	0 (14)	0 (18)	0 (16)	570	
	Ps_3	0 (17)	0 (14)	0 (16)	0 (13)	0 (18)	320	
Gr_1	Ps_4	0 (14)	0 (15)	0 (13)	0 (16)	0 (17)	420	760
	Ps_5	0 (17)	0 (16)	0 (15)	0 (14)	0 (14)	470	
	Ps_6	0 (13)	0 (18)	0 (17)	0 (16)	0 (13)	220	
Expected cargo quantity		470	220	270	520	620	2370	1620

Source: compiled by the author based on [10]

Table 10

Finding a reference plan when grouping suppliers, iteration 4

Grouping	Cargo suppliers	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
		Sp_1	Sp_2	Sp_3	Sp_4	Sp_5		
Gr_1	Ps_1	370 [16]	0 [13]	0 [18]	0 [14]	0 [15]	370	810
	Ps_2	100 [15]	220 [17]	120 [14]	0 [18]	0 [16]	570	
	Ps_3	0 [17]	0 [14]	0 [16]	0 [13]	0 [18]	320	
Gr_1	Ps_4	0 [14]	0 [15]	0 [13]	0 [16]	0 [17]	420	760
	Ps_5	0 [17]	0 [16]	0 [15]	0 [14]	0 [14]	470	
	Ps_6	0 [13]	0 [18]	0 [17]	0 [16]	0 [13]	220	
Expected cargo quantity		470	220	270	520	620	2370	1620

Source: compiled by the author based on [10]

Table 11

Finding a reference plan when grouping suppliers, iteration 5

Grouping	Cargo suppliers	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
		Sp_1	Sp_2	Sp_3	Sp_4	Sp_5		
Gr_1	Ps_1	370 [16]	0 [13]	0 [18]	0 [14]	0 [15]	370	810
	Ps_2	100 [15]	220 [17]	120 [14]	0 [18]	0 [16]	570	
	Ps_3	0 [17]	0 [14]	0 [16]	0 [13]	0 [18]	320	
Gr_1	Ps_4	0 [14]	0 [15]	150 [13]	0 [16]	0 [17]	420	760
	Ps_5	0 [17]	0 [16]	0 [15]	0 [14]	0 [14]	470	
	Ps_6	0 [13]	0 [18]	0 [17]	0 [16]	0 [13]	220	
Expected cargo quantity		470	220	270	520	620	2370	1620

Source: compiled by the author based on [10]

Table 12

Finding a reference plan when grouping suppliers, iteration 6

Grouping	Cargo suppliers	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
		Sp_1	Sp_2	Sp_3	Sp_4	Sp_5		
Gr_1	Ps_1	370 [16]	0 [13]	0 [18]	0 [14]	0 [15]	370	810
	Ps_2	100 [15]	220 [17]	120 [14]	0 [18]	0 [16]	570	
	Ps_3	0 [17]	0 [14]	0 [16]	0 [13]	0 [18]	320	
Gr_1	Ps_4	0 [14]	0 [15]	150 [13]	270 [16]	0 [17]	420	760
	Ps_5	0 [17]	0 [16]	0 [15]	0 [14]	0 [14]	470	
	Ps_6	0 [13]	0 [18]	0 [17]	0 [16]	0 [13]	220	
Expected cargo quantity		470	220	270	520	620	2370	1620

Source: compiled by the author based on [10]

Table 13

Finding a reference plan when grouping suppliers, iteration 7

Grouping	Cargo suppliers	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
		Sp_1	Sp_2	Sp_3	Sp_4	Sp_5		
		$v_1 =$	$v_2 =$	$v_3 =$	$v_4 =$	$v_5 =$		
Gr_1	Ps_1	370 [16]	0 [13]	0 [18]	0 [14]	0 [15]	370	810
	Ps_2	100 [15]	220 [17]	120 [14]	0 [18]	0 [16]	570	
	Ps_3	0 [17]	0 [14]	0 [16]	0 [13]	0 [18]	320	
Gr_1	Ps_4	0 [14]	0 [15]	150 [13]	270 [16]	0 [17]	420	760
	Ps_5	0 [17]	0 [16]	0 [15]	250 [14]	0 [14]	470	
	Ps_6	0 [13]	0 [18]	0 [17]	0 [16]	0 [13]	220	
Expected cargo quantity		470	220	270	520	620	2370	1620

Source: compiled by the author based on [10]

Table 14

Finding a reference plan when grouping suppliers, iteration 8

Grouping	Cargo suppliers	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
		Sp_1	Sp_2	Sp_3	Sp_4	Sp_5		
		$v_1 =$	$v_2 =$	$v_3 =$	$v_4 =$	$v_5 =$		
Gr_1	Ps_1	370 [16]	0 [13]	0 [18]	0 [14]	0 [15]	370	810
	Ps_2	100 [15]	220 [17]	120 [14]	0 [18]	0 [16]	570	
	Ps_3	0 [17]	0 [14]	0 [16]	0 [13]	0 [18]	320	
Gr_1	Ps_4	0 [14]	0 [15]	150 [13]	270 [16]	0 [17]	420	760
	Ps_5	0 [17]	0 [16]	0 [15]	250 [14]	90 [14]	470	
	Ps_6	0 [13]	0 [18]	0 [17]	0 [16]	0 [13]	220	
Expected cargo quantity		470	220	270	520	620	2370	1620

Source: compiled by the author based on [10]

From the last table, we calculate the objective function from the found reference plan:

$$F_{Gr} = 370 \cdot 16 + 100 \cdot 15 + 220 \cdot 17 + 120 \cdot 14 + 150 \cdot 13 +$$

$$+ 270 \cdot 16 + 250 \cdot 14 + 90 \cdot 13 = 23780 \text{c.u.} \quad (3)$$

3.2.Finding the optimal road transportation plan when grouping cargo suppliers.

We compile an extended table and apply the algorithm proposed above. Step-by-step iterations of the search for the optimal plan are given in table 15–37.

From the last table, we calculate the objective function from the found optimal plan:

$$F_{Gr} = 220 \cdot 13 + 150 \cdot 14 + 440 \cdot 15 + 30 \cdot 14 + 270 \cdot 13 +$$

$$+ 120 \cdot 16 + 250 \cdot 14 + 90 \cdot 13 = 22080 \text{c.u.} \quad (4)$$

Table 15

Finding a reference plan when grouping suppliers, iteration 1

Grouping	Cargo suppliers	Potentials	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
			Sp_1	Sp_2	Sp_3	Sp_4	Sp_5		
			–	–	–	–	–		
Gr_1	Ps_1	–	^{16}	^{13}	^{18}	^{14}	^{15}	370	810
	Ps_2	–	^{15}	^{17}	^{14}	^{18}	^{16}	570	
	Ps_3	–	^{17}	^{14}	^{16}	^{13}	^{18}	320	
Gr_1	Ps_4	–	^{14}	^{15}	^{13}	^{16}	^{17}	420	760
	Ps_5	–	^{17}	^{16}	^{15}	^{14}	^{14}	470	
	Ps_6	–	^{13}	^{18}	^{17}	^{16}	^{13}	220	
Expected cargo quantity			470	220	270	520	620	2370	1620

Source: compiled by the author based on [10]

Table 16

Finding a reference plan when grouping suppliers, iteration 2

Grouping	Cargo suppliers	Potentials	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
			Sp_1	Sp_2	Sp_3	Sp_4	Sp_5		
			–	–	–	–	–		
Gr_1	Ps_1	–	370 ^{16}	0 ^{13}	0 ^{18}	0 ^{14}	0 ^{15}	370	810
	Ps_2	–	100 ^{15}	220 ^{17}	120 ^{14}	0 ^{18}	0 ^{16}	570	
	Ps_3	–	0 ^{17}	0 ^{14}	0 ^{16}	0 ^{13}	0 ^{18}	320	
Gr_1	Ps_4	–	0 ^{14}	0 ^{15}	150 ^{13}	270 ^{16}	0 ^{17}	420	760
	Ps_5	–	0 ^{17}	0 ^{16}	0 ^{15}	250 ^{14}	0 ^{14}	470	
	Ps_6	–	0 ^{13}	0 ^{18}	0 ^{17}	0 ^{16}	90 ^{13}	220	
Expected cargo quantity			470	220	270	520	620	2370	1620

Source: compiled by the author based on [10]

Table 17

Finding a reference plan when grouping suppliers, iteration 3

Grouping	Cargo suppliers	Potentials	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
			Sp_1	Sp_2	Sp_3	Sp_4	Sp_5		
			10	12	9	12	10		
Gr_1	Ps_1	6	370^{16}	0^{13}	0^{18}	0^{14}	0^{15}	370	810
	Ps_2	5	100^{15}	220^{17}	120^{14}	0^{18}	0^{16}	570	
	Ps_3	1	0^{17}	0^{14}	0^{16}	0^{13}	0^{18}	320	
Gr_1	Ps_4	4	0^{14}	0^{15}	150^{13}	270^{16}	0^{17}	420	760
	Ps_5	2	0^{17}	0^{16}	0^{15}	250^{14}	0^{14}	470	
	Ps_6	3	0^{13}	0^{18}	0^{17}	0^{16}	90^{13}	220	
Expected cargo quantity			470	220	270	520	620	2370	1620

Source: compiled by the author based on [10]

Table 18

Finding a reference plan when grouping suppliers, iteration 4

Grouping	Cargo suppliers	Potentials	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
			Sp_1	Sp_2	Sp_3	Sp_4	Sp_5		
			10	12	9	12	10		
Gr_1	Ps_1	6	370^{16}	$0 + ^{13}$	0^{18}	0^{14}	0^{15}	370	810
	Ps_2	5	100^{15}	220^{17}	120^{14}	0^{18}	0^{16}	570	
	Ps_3	1	0^{17}	0^{14}	0^{16}	0^{13}	0^{18}	320	
Gr_1	Ps_4	4	0^{14}	0^{15}	150^{13}	270^{16}	0^{17}	420	760
	Ps_5	2	0^{17}	0^{16}	0^{15}	250^{14}	0^{14}	470	
	Ps_6	3	0^{13}	0^{18}	0^{17}	0^{16}	90^{13}	220	
Expected cargo quantity			470	220	270	520	620	2370	1620

Source: compiled by the author based on [10]

Table 19

Finding a reference plan when grouping suppliers, iteration 5

Grouping	Cargo suppliers	Potentials	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
			Sp_1	Sp_2	Sp_3	Sp_4	Sp_5		
			10	12	9	12	10		
Gr_1	Ps_1	6	370 – [16]	0 + [13]	0 [18]	0 [14]	0 [15]	370	810
	Ps_2	5	100 + [15]	220 – [17]	120 [14]	0 [18]	0 [16]	570	
	Ps_3	1	0 [17]	0 [14]	0 [16]	0 [13]	0 [18]	320	
Gr_1	Ps_4	4	0 [14]	0 [15]	150 [13]	270 [16]	0 [17]	420	760
	Ps_5	2	0 [17]	0 [16]	0 [15]	250 [14]	0 [14]	470	
	Ps_6	3	0 [13]	0 [18]	0 [17]	0 [16]	90 [13]	220	
Expected cargo quantity			470	220	270	520	620	2370	1620

Source: compiled by the author based on [10]

Table 20

Finding a reference plan when grouping suppliers, iteration 6

Grouping	Cargo suppliers	Potentials	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
			Sp_1	Sp_2	Sp_3	Sp_4	Sp_5		
			10	12	9	12	10		
Gr_1	Ps_1	6	150 [16]	220 [13]	0 [18]	0 [14]	0 [15]	370	810
	Ps_2	5	320 [15]	0 [17]	120 [14]	0 [18]	0 [16]	570	
	Ps_3	1	0 [17]	0 [14]	0 [16]	0 [13]	0 [18]	320	
Gr_1	Ps_4	4	0 [14]	0 [15]	150 [13]	270 [16]	0 [17]	420	760
	Ps_5	2	0 [17]	0 [16]	0 [15]	250 [14]	0 [14]	470	
	Ps_6	3	0 [13]	0 [18]	0 [17]	0 [16]	90 [13]	220	
Expected cargo quantity			470	220	270	520	620	2370	1620

Source: compiled by the author based on [10]

Table 21

Finding a reference plan when grouping suppliers, iteration 7

Grouping	Cargo suppliers	Potentials	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
			Sp_1	Sp_2	Sp_3	Sp_4	Sp_5		
Gr_1	Ps_1		150 ^{16}	220 ^{13}	0 ^{18}	0 ^{14}	0 ^{15}	370	810
	Ps_2		320 ^{15}	0 ^{17}	120 ^{14}	0 ^{18}	0 ^{16}	570	
	Ps_3		0 ^{17}	0 ^{14}	0 ^{16}	0 ^{13}	0 ^{18}	320	
Gr_1	Ps_4		0 ^{14}	0 ^{15}	150 ^{13}	270 ^{16}	0 ^{17}	420	760
	Ps_5		0 ^{17}	0 ^{16}	0 ^{15}	250 ^{14}	0 ^{14}	470	
	Ps_6		0 ^{13}	0 ^{18}	0 ^{17}	0 ^{16}	90 ^{13}	220	
Expected cargo quantity			470	220	270	520	620	2370	1620

Source: compiled by the author based on [10]

Table 22

Finding a reference plan when grouping suppliers, iteration 8

Grouping	Cargo suppliers	Potentials	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
			Sp_1	Sp_2	Sp_3	Sp_4	Sp_5		
			11	8	10	13	11		
Gr_1	Ps_1	5	150 ^{16}	220 ^{13}	0 ^{18}	0 ^{14}	0 ^{15}	370	810
	Ps_2	4	320 ^{15}	0 ^{17}	120 ^{14}	0 ^{18}	0 ^{16}	570	
	Ps_3	0	0 ^{17}	0 ^{14}	0 ^{16}	0 ^{13}	0 ^{18}	320	
Gr_1	Ps_4	3	0 ^{14}	0 ^{15}	150 ^{13}	270 ^{16}	0 ^{17}	420	760
	Ps_5	1	0 ^{17}	0 ^{16}	0 ^{15}	250 ^{14}	0 ^{14}	470	
	Ps_6	2	0 ^{13}	0 ^{18}	0 ^{17}	0 ^{16}	90 ^{13}	220	
Expected cargo quantity			470	220	270	520	620	2370	1620

Source: compiled by the author based on [10]

Table 23

Finding a reference plan when grouping suppliers, iteration 9

Grouping	Cargo suppliers	Potentials	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
			Sp_1	Sp_2	Sp_3	Sp_4	Sp_5		
			11	8	10	13	11		
Gr_1	Ps_1	5	150 (16)	220 (13)	0 (18)	0 + (14)	0 (15)	370	810
	Ps_2	4	320 (15)	0 (17)	120 (14)	0 (18)	0 (16)	570	
	Ps_3	0	0 (17)	0 (14)	0 (16)	0 (13)	0 (18)	320	
Gr_1	Ps_4	3	0 (14)	0 (15)	150 (13)	270 (16)	0 (17)	420	760
	Ps_5	1	0 (17)	0 (16)	0 (15)	250 (14)	0 (14)	470	
	Ps_6	2	0 (13)	0 (18)	0 (17)	0 (16)	90 (13)	220	
Expected cargo quantity			470	220	270	520	620	2370	1620

Source: compiled by the author based on [10]

Table 24

Finding a reference plan when grouping suppliers, iteration 10

Grouping	Cargo suppliers	Potentials	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
			Sp_1	Sp_2	Sp_3	Sp_4	Sp_5		
			11	8	10	13	11		
Gr_1	Ps_1	5	150 + (16)	220 (13)	0 (18)	0 + (14)	0 (15)	370	810
	Ps_2	4	320 + (15)	0 (17)	120 + (14)	0 (18)	0 (16)	570	
	Ps_3	0	0 (17)	0 (14)	0 (16)	0 (13)	0 (18)	320	
Gr_1	Ps_4	3	0 (14)	0 (15)	150 + (13)	270 + (16)	0 (17)	420	760
	Ps_5	1	0 (17)	0 (16)	0 (15)	250 (14)	0 (14)	470	
	Ps_6	2	0 (13)	0 (18)	0 (17)	0 (16)	90 (13)	220	
Expected cargo quantity			470	220	270	520	620	2370	1620

Source: compiled by the author based on [10]

Table 25

Finding a reference plan when grouping suppliers, iteration 11

Grouping	Cargo suppliers	Potentials	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
			Sp_1	Sp_2	Sp_3	Sp_4	Sp_5		
			11	8	10	13	11		
Gr_1	Ps_1	5	30 [16]	220 [13]	0 [18]	120 [14]	0 [15]	370	810
	Ps_2	4	440 [15]	0 [17]	0 [14]	0 [18]	0 [16]	570	
	Ps_3	0	0 [17]	0 [14]	0 [16]	0 [13]	0 [18]	320	
Gr_1	Ps_4	3	0 [14]	0 [15]	270 [13]	150 [16]	0 [17]	420	760
	Ps_5	1	0 [17]	0 [16]	0 [15]	250 [14]	0 [14]	470	
	Ps_6	2	0 [13]	0 [18]	0 [17]	0 [16]	90 [13]	220	
Expected cargo quantity			470	220	270	520	620	2370	1620

Source: compiled by the author based on [10]

Table 26

Finding a reference plan when grouping suppliers, iteration 12

Grouping	Cargo suppliers	Potentials	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
			Sp_1	Sp_2	Sp_3	Sp_4	Sp_5		
Gr_1	Ps_1		30 [16]	220 [13]	0 [18]	120 [14]	0 [15]	370	810
	Ps_2		440 [15]	0 [17]	0 [14]	0 [18]	0 [16]	570	
	Ps_3		0 [17]	0 [14]	0 [16]	0 [13]	0 [18]	320	
Gr_1	Ps_4		0 [14]	0 [15]	270 [13]	150 [16]	0 [17]	420	760
	Ps_5		0 [17]	0 [16]	0 [15]	250 [14]	0 [14]	470	
	Ps_6		0 [13]	0 [18]	0 [17]	0 [16]	90 [13]	220	
Expected cargo quantity			470	220	270	520	620	2370	1620

Source: compiled by the author based on [10]

Table 27

Finding a reference plan when grouping suppliers, iteration 13

Grouping	Cargo suppliers	Potentials	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
			Sp_1	Sp_2	Sp_3	Sp_4	Sp_5		
			15	12	10	13	11		
Gr_1	Ps_1	1	30 (16)	220 (13)	0 (18)	120 (14)	0 (15)	370	810
	Ps_2	0	440 (15)	0 (17)	0 (14)	0 (18)	0 (16)	570	
	Ps_3	0	0 (17)	0 (14)	0 (16)	0 (13)	0 (18)	320	
Gr_1	Ps_4	3	0 (14)	0 (15)	270 (13)	150 (16)	0 (17)	420	760
	Ps_5	1	0 (17)	0 (16)	0 (15)	250 (14)	0 (14)	470	
	Ps_6	2	0 (13)	0 (18)	0 (17)	0 (16)	90 (13)	220	
Expected cargo quantity			470	220	270	520	620	2370	1620

Source: compiled by the author based on [10]

Table 28

Finding a reference plan when grouping suppliers, iteration 14

Grouping	Cargo suppliers	Potentials	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
			Sp_1	Sp_2	Sp_3	Sp_4	Sp_5		
			15	12	10	13	11		
Gr_1	Ps_1	1	30 (16)	220 (13)	0 (18)	120 (14)	0 (15)	370	810
	Ps_2	0	440 (15)	0 (17)	0 (14)	0 (18)	0 (16)	570	
	Ps_3	0	0 (17)	0 (14)	0 (16)	0 (13)	0 (18)	320	
Gr_1	Ps_4	3	0 + (14)	0 (15)	270 (13)	150 (16)	0 (17)	420	760
	Ps_5	1	0 (17)	0 (16)	0 (15)	250 (14)	0 (14)	470	
	Ps_6	2	0 (13)	0 (18)	0 (17)	0 (16)	90 (13)	220	
Expected cargo quantity			470	220	270	520	620	2370	1620

Source: compiled by the author based on [10]

Table 29

Finding a reference plan when grouping suppliers, iteration 15

Grouping	Cargo suppliers	Potentials	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
			Sp_1	Sp_2	Sp_3	Sp_4	Sp_5		
			15	12	10	13	11		
Gr_1	Ps_1	1	30 – [16]	220 [13]	0 [18]	120 + [14]	0 [15]	370	810
	Ps_2	0	440 [15]	0 [17]	0 [14]	0 [18]	0 [16]	570	
	Ps_3	0	0 [17]	0 [14]	0 [16]	0 [13]	0 [18]	320	
Gr_1	Ps_4	3	0 + [14]	0 [15]	270 [13]	150 – [16]	0 [17]	420	760
	Ps_5	1	0 [17]	0 [16]	0 [15]	250 [14]	0 [14]	470	
	Ps_6	2	0 [13]	0 [18]	0 [17]	0 [16]	90 [13]	220	
Expected cargo quantity			470	220	270	520	620	2370	1620

Source: compiled by the author based on [10]

Table 30

Finding a reference plan when grouping suppliers, iteration 16

Grouping	Cargo suppliers	Potentials	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
			Sp_1	Sp_2	Sp_3	Sp_4	Sp_5		
			15	12	10	13	11		
Gr_1	Ps_1	1	0 [16]	220 [13]	0 [18]	150 [14]	0 [15]	370	810
	Ps_2	0	440 [15]	0 [17]	0 [14]	0 [18]	0 [16]	570	
	Ps_3	0	0 [17]	0 [14]	0 [16]	0 [13]	0 [18]	320	
Gr_1	Ps_4	3	30 [14]	0 [15]	270 [13]	120 [16]	0 [17]	420	760
	Ps_5	1	0 [17]	0 [16]	0 [15]	250 [14]	0 [14]	470	
	Ps_6	2	0 [13]	0 [18]	0 [17]	0 [16]	90 [13]	220	
Expected cargo quantity			470	220	270	520	620	2370	1620

Source: compiled by the author based on [10]

Table 31

Finding a reference plan when grouping suppliers, iteration 17

Grouping	Cargo suppliers	Potentials	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
			Sp_1	Sp_2	Sp_3	Sp_4	Sp_5		
Gr_1	Ps_1		0 ^{16}	220 ^{13}	0 ^{18}	150 ^{14}	0 ^{15}	370	810
	Ps_2		440 ^{15}	0 ^{17}	0 ^{14}	0 ^{18}	0 ^{16}	570	
	Ps_3		0 ^{17}	0 ^{14}	0 ^{16}	0 ^{13}	0 ^{18}	320	
Gr_1	Ps_4		30 ^{14}	0 ^{15}	270 ^{13}	120 ^{16}	0 ^{17}	420	760
	Ps_5		0 ^{17}	0 ^{16}	0 ^{15}	250 ^{14}	0 ^{14}	470	
	Ps_6		0 ^{13}	0 ^{18}	0 ^{17}	0 ^{16}	90 ^{13}	220	
Expected cargo quantity			470	220	270	520	620	2370	1620

Source: compiled by the author based on [10]

Table 32

Finding a reference plan when grouping suppliers, iteration 18

Grouping	Cargo suppliers	Potentials	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
			Sp_1	Sp_2	Sp_3	Sp_4	Sp_5		
			15	16	14	17	11		
Gr_1	Ps_1	-3	0 ^{16}	220 ^{13}	0 ^{18}	150 ^{14}	0 ^{15}	370	810
	Ps_2	0	440 ^{15}	0 ^{17}	0 ^{14}	0 ^{18}	0 ^{16}	570	
	Ps_3	0	0 ^{17}	0 ^{14}	0 ^{16}	0 ^{13}	0 ^{18}	320	
Gr_1	Ps_4	-1	30 ^{14}	0 ^{15}	270 ^{13}	120 ^{16}	0 ^{17}	420	760
	Ps_5	-3	0 ^{17}	0 ^{16}	0 ^{15}	250 ^{14}	0 ^{14}	470	
	Ps_6	2	0 ^{13}	0 ^{18}	0 ^{17}	0 ^{16}	90 ^{13}	220	
Expected cargo quantity			470	220	270	520	620	2370	1620

Source: compiled by the author based on [10]

Table 33

Finding a reference plan when grouping suppliers, iteration 19

Grouping	Cargo suppliers	Potentials	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
			Sp_1	Sp_2	Sp_3	Sp_4	Sp_5		
			15	16	14	17	11		
Gr_1	Ps_1	-3	0 (16)	220 (13)	0 (18)	150 (14)	0 (15)	370	810
	Ps_2	0	440 (15)	0 (17)	0 (14)	0 (18)	0 (16)	570	
	Ps_3	0	0 (17)	0 (14)	0 (16)	0 (13)	0 (18)	320	
Gr_1	Ps_4	-1	30 (14)	0 (15)	270 (13)	120 (16)	0 (17)	420	760
	Ps_5	-3	0 (17)	0 (16)	0 (15)	250 (14)	0 (14)	470	
	Ps_6	2	0 + (13)	0 (18)	0 (17)	0 (16)	90 (13)	220	
Expected cargo quantity			470	220	270	520	620	2370	1620

Source: compiled by the author based on [10]

Table 34

Finding a reference plan when grouping suppliers, iteration 20

Grouping	Cargo suppliers	Potentials	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
			Sp_1	Sp_2	Sp_3	Sp_4	Sp_5		
			15	16	14	17	11		
Gr_1	Ps_1	-3	0 (16)	220 (13)	0 (18)	150 (14)	0 (15)	370	810
	Ps_2	0	440 (15)	0 (17)	0 (14)	0 (18)	0 (16)	570	
	Ps_3	0	0 (17)	0 (14)	0 (16)	0 (13)	0 (18)	320	
Gr_1	Ps_4	-1	30 + (14)	0 + (15)	270 (13)	120 (16)	0 (17)	420	760
	Ps_5	-3	0 (17)	0 (16)	0 (15)	250 (14)	0 (14)	470	
	Ps_6	2	0 + (13)	0 + (18)	0 (17)	0 (16)	90 (13)	220	
Expected cargo quantity			470	220	270	520	620	2370	1620

Source: compiled by the author based on [10]

Table 35

Finding a reference plan when grouping suppliers, iteration 21

Grouping	Cargo suppliers	Potentials	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
			Sp_1	Sp_2	Sp_3	Sp_4	Sp_5		
			15	16	14	17	11		
Gr_1	Ps_1	-3	0 ^{16}	220 ^{13}	0 ^{18}	150 ^{14}	0 ^{15}	370	810
	Ps_2	0	440 ^{15}	0 ^{17}	0 ^{14}	0 ^{18}	0 ^{16}	570	
	Ps_3	0	0 ^{17}	0 ^{14}	0 ^{16}	0 ^{13}	0 ^{18}	320	
Gr_1	Ps_4	-1	30 ^{14}	0 ^{15}	270 ^{13}	120 ^{16}	0 ^{17}	420	760
	Ps_5	-3	0 ^{17}	0 ^{16}	0 ^{15}	250 ^{14}	0 ^{14}	470	
	Ps_6	2	0 ^{13}	0 ^{18}	0 ^{17}	0 ^{16}	90 ^{13}	220	
Expected cargo quantity			470	220	270	520	620	2370	1620

Source: compiled by the author based on [10]

Table 36

Finding a reference plan when grouping suppliers, iteration 22

Grouping	Cargo suppliers	Potentials	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
			Sp_1	Sp_2	Sp_3	Sp_4	Sp_5		
Gr_1	Ps_1		0 ^{16}	220 ^{13}	0 ^{18}	150 ^{14}	0 ^{15}	370	810
	Ps_2		440 ^{15}	0 ^{17}	0 ^{14}	0 ^{18}	0 ^{16}	570	
	Ps_3		0 ^{17}	0 ^{14}	0 ^{16}	0 ^{13}	0 ^{18}	320	
Gr_1	Ps_4		30 ^{14}	0 ^{15}	270 ^{13}	120 ^{16}	0 ^{17}	420	760
	Ps_5		0 ^{17}	0 ^{16}	0 ^{15}	250 ^{14}	0 ^{14}	470	
	Ps_6		0 ^{13}	0 ^{18}	0 ^{17}	0 ^{16}	90 ^{13}	220	
Expected cargo quantity			470	220	270	520	620	2370	1620

Source: compiled by the author based on [10]

Table 37

Finding a reference plan when grouping suppliers, iteration 23

Grouping	Cargo suppliers	Potentials	Cargo consumers					Quantity of cargo in warehouses	Cargo quantity by group
			Sp_1	Sp_2	Sp_3	Sp_4	Sp_5		
			11	12	10	13	11		
Gr_1	Ps_1	1	0 ^{16}	220 ^{13}	0 ^{18}	150 ^{14}	0 ^{15}	370	810
	Ps_2	4	440 ^{15}	0 ^{17}	0 ^{14}	0 ^{18}	0 ^{16}	570	
	Ps_3	0	0 ^{17}	0 ^{14}	0 ^{16}	0 ^{13}	0 ^{18}	320	
Gr_1	Ps_4	3	30 ^{14}	0 ^{15}	270 ^{13}	120 ^{16}	0 ^{17}	420	760
	Ps_5	1	0 ^{17}	0 ^{16}	0 ^{15}	250 ^{14}	0 ^{14}	470	
	Ps_6	2	0 ^{13}	0 ^{18}	0 ^{17}	0 ^{16}	90 ^{13}	220	
Expected cargo quantity			470	220	270	520	620	2370	1620

Source: compiled by the author based on [10]

Thus, as a result of the numerical experiment conducted on the basis of specific initial data, the proposed approach to finding both the reference (i.e., the initial permissible) and the optimal road transportation plan within the modified transport problem, which takes into account the specifics of the grouping of cargo suppliers, was implemented and tested. For this, a clearly defined methodology was used, which included preliminary preparation of a tabular representation of the initial data, structuring of supply sources into groups with fixed restrictions on the total cargo, as well as step-by-step application of the adapted potential algorithm, which allowed, taking into account all the specified parameters, to form an appropriate transportation plan.

During the numerical calculation, the basic plan was sequentially constructed using classical methods (taking into account the features of the new model), with the subsequent transition to the search for an optimal solution. In this case, both classical restrictions on the volumes of supply and demand and additional restrictions imposed on the group structures of sources were taken into account. The algorithm that formed the basis of the calculation allowed adjusting the current values of transportation taking into account closed cycles, as well as determining the admissibility of each subsequent step based on the calculation of potentials and corresponding estimates.

Conclusions. Thus, the work considered the problem of optimizing transportation in the conditions of grouping of cargo suppliers, which allowed to form a new approach to building effective resource allocation plans in logistics systems. Based on the analysis of the classical formulation of the transport problem and taking into account the specifics of modern transportation processes, a model was proposed that covers the features of group organization of supply sources.

By building a model in which individual suppliers are grouped together with common constraints, it was possible to adapt traditional methods of solving transport problems to conditions that more accurately reflect real logistics processes. This approach allows not only to increase the accuracy of mathematical modeling, but also to reduce the risks of overloading individual transportation directions, ensuring the balance of the transport network.

Within the framework of the conducted research, an approach to modeling the transport problem was formulated and substantiated, taking into account the grouping of cargo suppliers, which allowed to deepen the classical formulation of the transportation problem and adapt it to more complex logistical situations encountered in practice. The main attention was paid to building a mathematical model that covers not only the relationship between sources and consumption points, but also takes into account the structure of associations of suppliers into groups, each of which has certain restrictions on the total volume of cargo that can be sent to the transport system.

Thanks to a thorough analysis of the theoretical foundations of the transport problem and modification of existing algorithms, a generalized method was created that allows for effective finding of admissible and optimal transportation plans within the new structure of the problem. In the process of work, the criteria for optimality of the plan in the presence of additional group constraints were refined, which ensured the mathematical correctness of the new approach and made it possible to preserve the integrity of the logic of the classical transport problem. The use of the potential method in combination with the introduction of mechanisms for controlling group constraints allowed adapting known algorithms to the conditions of the new formulation.

The constructed model provides an automated procedure for checking the admissibility of solutions from the point of view of not only the balance of supply and demand, but also the total limits on cargo within each group of suppliers. This significantly expands the scope of the transport problem and allows solving transportation planning problems in large logistics systems where suppliers have common resource constraints or operate within a single administrative or geographical space.

The study also implemented a numerical procedure for constructing a reference plan taking into account the structural grouping of sources, and showed how classical elements of the transport table – such as potentials, θ values, closed loops – are modified and applied in the conditions of the new model. This allowed us to demonstrate in practice the effectiveness of the developed approach and verify its operability under different configurations of the source data.

Thus, the solution of the transport problem in the context of grouping cargo suppliers is not only theoretically justified, but also practically significant. The use of such an approach allows achieving more flexible management of logistics flows, especially in cases where the supply is centrally coordinated or requires taking into account interdependencies between individual suppliers. The proposed model opens up prospects for further development in the direction of multi-criteria optimization, taking into account time intervals, as well as in the context of building dynamic adaptive transportation management systems.

It is also worth emphasizing that the use of the grouping model allows for improved transportation planning in conditions of limited vehicle resources or heterogeneity of consumer demand. This creates a basis for the application of the model in real economic conditions – both at the level of individual enterprises and at the interregional level of logistics networks. The practical implementation of such a model, taking into account modern information technologies, can serve as the basis for the creation of intelligent decision-making support systems in the field of freight transportation.

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3.4. ARTIFICIAL INTELLIGENCE AS A DRIVING FORCE FOR SMALL BUSINESS DEVELOPMENT AND A TOOL FOR TAX REPORTING

Introduction. Ukrainian small and medium-sized businesses (SMEs) are looking for ways to overcome the problem of competitiveness to enter foreign markets. And recent events in the world demonstrate significant changes in global trade, moreover, the world economy is on the verge of a major reformatting, which is associated with the policy of the new US administration. It is unlikely that globalization is threatened by anything that can be classified as collapse or destruction, but the algorithms and structure of markets will definitely change. On the one hand, these changes carry great dangers for business. On the other hand, it is during the period of great changes that you can get the same chance and be on the wave of success. Artificial intelligence (AI) can help solve such a task, with the help of which calculations are performed and solutions are simulated, which are quite difficult for a person to perform for many reasons. The main one is the lack of access to databases on the scale of the world information network. Therefore, the expertise of AI in this sense can hardly be overestimated. Another significant problem that small and medium-sized enterprises permanently solve is the management of reporting and the taxation system, which requires high competencies and efficiency. And this task should also facilitate the application of AI.

What do Ukrainian representatives of small and medium-sized businesses see as difficulties? First of all, it is an extremely complex system of regulatory relations, which is constantly changing and has signs of fiscalization, rather than stimulation and assistance in business development. The resources of SMEs are also small to attract complex technological solutions and highly professional specialists. And entrepreneurs are forced to balance between the costs of solving these problems and high penalties that can simply destroy business, and instantly. Therefore, the introduction of artificial intelligence (AI) looks like a promising solution to the problem of optimizing the regulatory system and tax reporting in SMEs. The only question is how AI will be able to comply with legal and regulatory requirements and how exactly to test its effectiveness.

Scientists are actively researching the role of AI in the formation of tax reporting and optimization of taxation of SMEs. For example, O. Bilyk and O. Panasyuk in their work prove that the integration of AI into the processes of accounting and financial reporting by automating machine learning algorithms for compliance with the legislation significantly reduced the time and effort for the formation of tax reporting, increased operational efficiency [1, p. 362]. Other scientists – A. Koshil [2, p. 341] and I. Zhiglei [3, p. 98] proved that the use of AI in work with tax reporting significantly increased the level of compliance with the legislation and reduced the number of operational errors. That is, the optimization of automated accounting systems through the integration of AI significantly increases the efficiency of SMEs in this sector. But there are also problematic issues. Some scientists have found that AI algorithms are related to a specific jurisdiction of the enterprise. And if an SME plans to work in the markets of other countries, that is, in another jurisdiction, then AI can produce erroneous data and results. The latest meta-analysis by N. Rogova revealed such discrepancies that concerned not only different jurisdictions, but also business structures [4, p. 111]. That is, this indicates a very wide scale of variability, which requires clearer and more contextual work with AI. The integration of AI into the business processes of a particular enterprise should begin with a lot of work on teaching artificial intelligence all the nuances of SME activities.

And if an SME plans to work in the markets of other countries, that is, in another jurisdiction, then AI can produce erroneous data and results. The latest meta-analysis by N. Rogova revealed such discrepancies that concerned not only different jurisdictions, but also business structures [4, p. 111]. That is, this indicates a very wide scale of variability, which requires clearer and more contextual work with AI. The integration of AI into the business processes of a particular enterprise should begin with a lot of work on teaching artificial intelligence all the nuances of SME activities.

Interestingly, there are still discussions around the ethics of using AI in the tax reporting system. For example, I. Yurieva and P. Khomin warn against the use of AI in tax activities to make decisions on the results of SMEs' activities, where algorithmic bias and interpretation of contradictory legislative norms by tax authorities may appear [5, p. 495]. And, undoubtedly, another important argument for Ukrainian small businesses is the availability of the latest digital technologies. R. Augustine's research showed that against the background of the rapid introduction of AI by large businesses, small and medium-sized businesses are lagging far behind, having a shortage of both resources and qualified personnel [6, p. 42].

Summary of the main results of the study. The purpose of this article is to identify the algorithms that AI can use to optimize the formation of tax reporting for SMEs. The main task is to understand and identify how AI can improve the operational efficiency of small and medium-sized enterprises.

Taxation of SMEs is the regular collection of taxes on the income, profits and activities of such enterprises for the benefit of the state and local communities. The business taxation system is quite complex in Ukraine. Small businesses pay a single tax for certain categories or income tax, personal income tax (PIT), social contributions, VAT, various local taxes and fees. All these taxes and fees form the basis of tax reporting, which can be monthly, quarterly and annual. Despite the fact that the volume of reporting for SMEs is much lower than for large businesses, this area of the SME's operational activities is quite complex, given the resource opportunities. And although small businesses can use outsourcing for tax reporting. Very often, entrepreneurs refuse such a decision, because these are quite expensive services, and secondly, they are very often of poor quality, which leads to fines and unpredictable costs. Work with taxes and reporting is of key importance for SMEs, which forms the basis for managerial decision-making. From the point of view of representativeness, such reporting positions the enterprise in the market and demonstrates its investment potential, which is important for those SMEs that plan foreign economic activity. Especially important in this sense is the reporting of the financial results of the enterprise. Form No. 4 – statement of financial results and equity – informs about income and expenses, demonstrates the profitability, solvency and liquidity of SMEs. That is, these are the main indicators by which the owners and managers of the enterprise control and make decisions. But there are also non-financial reports that are no less important for evaluating the company's activities. They are formed by analytical indicators on operational, marketing, personnel activities, strategic development. For example, these are sales reports, performance indicators (KPIs), inventory reports, customer portfolios and reviews, logistics maps. All this information is used to make important decisions about the development and operation of SMEs. Thanks to these reports, business owners identify trends, patterns and opportunities, and can adjust their strategy and tactics accordingly to stimulate growth and increase competitiveness [7, p. 73].

The integration of AI to optimize tax activities and generate reporting for SMEs should involve quite a lot of functions and technical solutions that should simplify and increase the efficiency of the enterprise, which is related to taxation. It makes sense to involve AI in the analysis of operational activities and all financial indicators of the enterprise. Thanks to this analysis, AI algorithms are able to form projects of managerial decisions that can become the basis for the formation of a strategy for cost saving, tax optimization, enterprise development and, tactically, its adjustment. Traditionally, these tasks were performed by personnel, whose qualifications are not always sufficient to build optimal strategies. And the question is not even in qualifications, but in the ability of a person to accurately process large amounts of information in a short period of time. It should be noted that the efficiency and effectiveness of using AI directly depends on the ability of the operational worker (working with AI algorithms) to train and form task contexts for AI. If you do not pay attention to this work, then mistakes will occur. AI is like a new employee who needs time to learn the business, its algorithms, and become effective. AI algorithms can detect trends, correlations, and anomalies in financial data, allowing small businesses to make data-driven decisions to optimize their tax outcomes, and in real time, which allows SMEs to at least minimize the risks of penalties [8].

It should be noted that developers of artificial intelligence technologies have already offered solutions specifically for small and medium-sized businesses, integrated into existing reporting platforms. These systems offer a synthesis of data analysis, voice analyzers, and forecasting systems and methods that are related to tax formation, tax planning, and expenditure formation. Accounting software platforms with integrated AI can effectively categorize enterprise expenses, analyze transactions, generate financial reports, calculate salaries and bonuses with taxes, inform about legislative changes and innovations and implement them in reporting. All this greatly facilitates the work of specialized personnel and increases the efficiency of managerial decisions [9, p. 92]. However, in addition to the advantages and advantages of AI integration, there are also certain caveats and disadvantages that should be carefully considered before starting to work with artificial intelligence. The researchers highlight one of the significant caveats, which is algorithmic biases and inaccurate calculations and conclusions of AI, which is related to the data used to train AI. This leads to erroneous conclusions, decisions, and recommendations. Such a deformation arises as a result of a large amount of information related to the complexity of the tax system itself, filled with different profiles of enterprises and contradictions in the legislative and regulatory framework. SME entrepreneurs may lack the experience and digital skills to assess the effectiveness of AI. Skepticism as a barrier to integration into their business can also be associated with significant costs for SMEs at the initial stage of applying the latest digital technologies. In addition, data privacy, security, and compliance issues may hinder the implementation of AI-based tax optimization solutions, especially for businesses operating in highly regulated industries or jurisdictions [10, p. 129]. Thus, artificial intelligence is able to optimize the work of SMEs with reporting, but it is necessary to carefully weigh all the pros and cons, even if they are temporary (table 1).

Table 1

Pros and cons of integrating AI into the reporting and taxation system for SMEs

Pros	Cons
AI can automate repetitive reporting tasks, saving time and reducing human error	AI systems can access confidential business information, raising concerns about data security among owners
Artificial intelligence algorithms are able to analyze data with high accuracy, which provides the basis for more accurate reports and insights	Implementing AI technologies involves high upfront costs for SMEs in software, training, and infrastructure
AI can quickly process large amounts of data, providing real-time information for decision-making	Overreliance on artificial intelligence in reporting processes can lead to a loss of human control and reduce data understanding
AI can tailor reports to specific business needs, providing personalized insights for better decision-making	Small businesses may lack the technical expertise or resources to effectively implement and support AI systems
AI reporting solutions can scale to meet business needs, accommodating growth without significant additional resources	Artificial intelligence algorithms may unintentionally introduce bias or discrimination into reporting processes which could lead to ethical issues
Small businesses that integrate artificial intelligence for reporting can gain a competitive advantage through the use of advanced analytics and predictive capabilities	Integrating an AI reporting system with existing infrastructure and processes can be complex and time-consuming for SMEs
Data generated through artificial intelligence can drive better decision-making by providing more detailed analysis and predictive analytics.	Employees may resist the implementation of AI technology for fear of losing their jobs or changing their role in the reporting process.

Developed by the authors based on [11]

Digitalization of SMEs should become a prerequisite for the development and formation of Ukrainian entrepreneurship that masters (or plans) foreign markets. The integration of AI into the processes of generating SME reporting is certainly a significant competitive advantage that affects the efficiency of the enterprise as a whole. Recommendations for the implementation of AI in the financial and accounting reporting system can be formed as follows:

1) each SME owner should invest in digital education, both its own and its staff, including mastering the work with artificial intelligence;

2) integrate AI into the system of analysis of tax, customs and regulatory legislation in order to timely adapt and make prompt decisions to protect businesses from penalties and useless and unpredictable costs;

3) adapt AI solutions to the needs of your own business: create user-friendly interfaces, reporting models, predictive models, and personalized chats;

4) to form a reliable data privacy protection system when generating reports using AI or algorithms for analysis and forecasts of SME development strategies – encryption, access control, backups, anonymization;

5) establish cooperation with specialized specialists of the tax and customs service, who can help in debugging the work of AI and interpreting data, results and algorithms;

6) work out the integration of reporting and taxation tools with existing platforms already used by SMEs, such as APIs for seamless data exchange and compatibility with financial systems.

Conclusions. Such modern tools as artificial intelligence, if properly used and professionally integrated into business processes, can greatly facilitate both the work of employees and decision-making by the business owner. AI as a tool for strengthening the efficiency of the enterprise and an auxiliary factor in the formation of the development strategy and presentation of SMEs in foreign markets is becoming a mandatory digital technology for small and medium-sized businesses in Ukraine.

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