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Conceptual approaches to forming an innovation ecosystem in manufacturing enterprises

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Abstract. The increasing complexity of global supply chains and the growing demand for sustainable practices necessitate the development of collaborative networks that integrate diverse stakeholders to foster innovation and resilience. The aim of this study was to develop an integrated strategy for shaping innovation ecosystems in manufacturing through the synthesis of theoretical frameworks and the analysis of the application in industrial contexts. The study employed a systematic literature review and conceptual synthesis to examine ecosystem dynamics and approaches to innovation portfolio formation. The results indicated that innovation ecosystems evolve through four stages: conceptual design, in which firms define shared objectives and identify key actors; construction, where partnerships and governance structures are established; exploitation and maintenance, focused on performance optimisation and the scaling of innovations; and transformation, which ensures adaptation to market or regulatory changes. Individual projects within ecosystems progress through phases of anticipation, emergence, growth, maturity, knowledge transfer, and renewal, enabling the management of diverse initiatives such as industrial design or sustainable energy solutions. The application of fuzzy set methods with a desirability scale ranging from 0 to 1 allows projects to be ranked according to criteria including technological feasibility, financial benefits, and sustainability impact, thereby supporting the formation of balanced portfolios. Smart technologies automate process optimisation, while investments in renewable energy sources and circular economy principles enhance efficiency and reduce environmental impact. These approaches enable focal firms to coordinate collaboration with suppliers, start-ups, universities, and civil society, creating dynamic networks capable of adapting to technological and market changes. The practical value of the study lies in providing recommendations for the development of flexible innovation portfolios, the use of data-sharing platforms, and the adoption of sustainable practices to reduce risks and increase value

Keywords: life cycle stages; portfolio formation; Triple Helix model; Industry 4.0; smartisation; circular economy

Introduction

In the economic landscape, manufacturing enterprises operate in an environment of constant technological disruption, volatile markets, and increasing sustainability pressures, where traditional linear innovation models often prove insufficient. Fragmented knowledge, high costs of failure, and shorter product life cycles force businesses to seek mechanisms for rapid coordination among a wide range of stakeholders. At the same time, the specific nature of manufacturing – capital intensity, dependence on supply chains, and regulatory constraints – requires not

isolated innovation projects but coherent frameworks of collaboration. An ecosystem approach enables the integration of competencies from enterprises, research institutions, technology providers, and consumer communities, transforming scattered initiatives into a strategically managed innovation portfolio. Such ecosystems must be open not only to cooperation but also to competition, while remaining capable of self-renewal through process reengineering and continuous reconfiguration of partnerships. Smartisation serves as a key tool by providing

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data-driven decision-making mechanisms, while circular economy principles reduce risks and enhance long-term resilience. Therefore, the fundamental need of manufacturing enterprises lies in the creation of adaptive innovation ecosystems that align strategic goals, technologies, and human capital throughout all stages of the life cycle.

The literature on innovation ecosystems has proliferated, drawing from ecological metaphors to describe complex, interdependent networks. Early conceptualisations of business ecosystem evolved into more nuanced models incorporating innovation-specific elements. A significant advancement was presented by S. Mozheiko (2025), who conceptualised ecosystems as holistic systems and business models as modular components within these systems, emphasising the structural interdependency between the ecosystem level and the firm-level architecture. These systems – modules view explains how enterprises create value through modular business models that fit within broader ecosystem configurations, highlighting flexibility, interoperability, and strategic positioning. Building on structural perspectives, M. Jütting (2024) introduced a lifecycle view through the Innovation Ecosystem Clock model, proposing that ecosystems evolve through sequential developmental phases that require distinct governance, roles, and resource allocation. This model operationalises the temporal dimension of ecosystem design, allowing firms to anticipate transitions and adapt the innovation strategies over time. Complementing these advances, O. Granstrand & M. Holgersson (2020) conducted a conceptual review, proposing a definition that encompasses actors, activities, artifacts, institutions, and relations – including both complementary and substitute dynamics. This balanced view addresses prior biases toward collaboration, integrating competition as a driver for innovation.

In manufacturing contexts, studies like those by T. Tolstykh *et al.* (2020) introduced life cycle-based approaches for industrial ecosystems, emphasising stages from conceptual design to succession. L. Feng *et al.* (2021) systematically reviewed enterprise innovation ecosystems, identifying key components such as innovative actors, chains, networks, and platforms, and highlighting the evolution through birth, expansion, leadership, and self-renewal stages. D. Lewicka *et al.* (2025) highlighted the role of organisational support in shaping employee green behaviour to support circular economy principles within innovation ecosystems. Y. Chu & C. Zhao (2021), proposed integrated frameworks for world-class manufacturing innovation ecosystems, focusing on modular and platform-based strategies. K. Visscher *et al.* (2021) explored strategies for industrial firms in ecosystems, revealing multi-layered approaches to value capture. I. Bashynska (2023) introduced smartisation as a theoretical and methodological approach to optimise business processes in industrial enterprises, enhancing ecosystem adaptability. This review revealed a consensus on the need for dynamic, adaptive ecosystems but identifies gaps in applying life cycle concepts to manufacturing portfolio formation, particularly with smartisation

and circular economy integration. The purpose of this article was to delineate conceptual approaches to ecosystem formation, synthesising models like the Triple Helix and life cycle frameworks to propose an integrated strategy for manufacturing enterprises. The novelty of this work is the fusion of biological analogies with industrial life cycle assessments, using fuzzy methods for portfolio optimisation, tailored specifically to manufacturing sectors. This contributes to bridging theoretical gaps and providing practical tools for enterprise leaders.

Materials and Methods

The research design was based on a combination of systematic literature analysis, conceptual synthesis, graphical visualisation, comparative analysis, and portfolio evaluation using fuzzy set methods. The systematic literature analysis served as the foundation for identifying key concepts, models, and gaps in the existing body of knowledge. Peer-reviewed articles were retrieved from Web of Science, Scopus, and ScienceDirect using keywords such as “innovation ecosystem,” “manufacturing enterprises,” “ecosystem lifecycle,” “smartisation,” and “circular economy.” To ensure relevance, only sources published in the last 3-5 years were included (Matt *et al.*, 2021b; Bajare *et al.*, 2025; Fan & Jackson, 2025); classical theoretical works were also analysed to trace the evolution of the concept (Etzkowitz & Leydesdorff, 2000). Industry reports from EY (2024), WIPO (2024), and the McKinsey & Company (2025) were used to validate theoretical insights with relevant data on ecosystem participation, AI adoption, sustainability trends, and collaboration practices. These reports were chosen due to the global coverage, statistical rigour, and high relevance to industrial contexts.

The conceptual synthesis method was used to integrate multiple theoretical perspectives into a coherent framework. Through synthesis, elements from the Triple and Quadruple Helix models, lifecycle approaches (Tolstykh *et al.*, 2020; Jütting, 2024), and modular ecosystem structures (Mozheiko, 2025) were combined with concepts of smartisation and circular economy. This method was necessary because existing literature is fragmented and lacks an integrated ecosystem-lifecycle-portfolio perspective tailored to manufacturing. Conceptual synthesis allowed the development of a unified strategy that balances technological, organisational, and sustainability dimensions. To enhance clarity and support the interpretation of complex structures, the graphical method was employed. Visual models were created to illustrate ecosystem stages (conceptual design, building, operation and maintenance, succession), the alignment of ecosystem and project life cycles, and the role of Helix actors at each stage. These visualisations were based on theoretical and statistical insights. The graphical method helped reveal structural relationships, transitions, and interdependencies that are difficult to capture textually.

A crucial component of the study was the evaluation of innovation portfolios within ecosystems. For this purpose,

a fuzzy set approach with Harrington's desirability function (0-1 scale) was applied, following the methodology of T. Tolstykh *et al.* (2020). T. Tolstykh *et al.* (2020) proposed the use of fuzzy set theory, specifically Harrington's desirability function (Harrington's desirability function aggregated these criteria into a single score, allowing firms to rank projects and allocate resources effectively), to evaluate project effectiveness on a 0-1 scale, where values close to 1 indicated high potential (very good) and values close to 0 indicated low potential (poor). This method accounted for uncertainty in project outcomes, enabling firms to make data-driven decisions in dynamic environments. This method was selected due to its ability to manage uncertainty and combine qualitative and quantitative criteria. The assessment required data on technological feasibility, financial returns, sustainability impact, and market potential. Information was derived from academic studies (Feng *et al.*, 2021), reports on AI and renewable energy adoption, and conceptual works on smartisation (Bashynska, 2023). The fuzzy approach enabled multicriteria prioritisation of projects at different life cycle stages, ensuring a balanced and resilient innovation portfolio aligned with ecosystem objectives. Additionally, comparative analysis was used to contrast ecosystem models and life-cycle frameworks, identifying the strengths, limitations, and applicability to manufacturing. The logical-structural method supported model development and ensured internal consistency.

Results and Discussion

The formation of innovation ecosystems in manufacturing enterprises requires a robust understanding of the theoretical frameworks that underpin the structure and functionality. Existing studies emphasise several key dimensions, including definitions of innovation ecosystems as multi-actor, multi-level configurations that involve complex interactions among diverse participants (Granstrand & Holgersson, 2020). Considerable attention is also paid to relational models, such as the Triple and Quadruple Helix, which explain how universities, industry, government, and civil society co-create value through interconnected innovation processes (Etzkowitz & Leydesdorff, 2000). In addition, evolutionary or life cycle-based frameworks are widely used to describe how innovation ecosystems develop over time, from initial formation to renewal and transformation (Tolstykh *et al.*, 2020; Jütting, 2024). Together, these approaches formed the conceptual basis for designing innovation ecosystems in manufacturing; however, the mentioned approaches only partially address the ways in which ecosystem dynamics can be systematically linked to project portfolio management and sustainability goals.

The author's contribution lied in integrating these fragmented perspectives into a unified conceptual model tailored to manufacturing enterprises. The proposed model aligned the life cycle of the innovation ecosystem (conceptual design, building, operation and maintenance,

succession) with the life cycle of individual projects (anticipation, birth, growth, maturity, knowledge transfer, renewal) and embeds a fuzzy set-based portfolio evaluation mechanism. By adapting Harrington's desirability function to combine technological feasibility, financial returns, sustainability impact, and market potential on a 0-1 scale, the model enables manufacturing firms to prioritise projects under uncertainty and maintain a balanced portfolio. This integrated ecosystem-lifecycle-portfolio perspective is the core original result of the study and goes beyond previous works that either focus mainly on conceptual definitions or on isolated portfolio techniques.

A comprehensive definition of innovation ecosystems is critical for understanding the scope and application in manufacturing. O. Granstrand & M. Holgersson (2020) described an innovation ecosystem as a dynamic configuration that includes various actors, the activities, tangible and intangible artifacts, as well as institutional frameworks and relationships. These interconnections – both collaborative and competitive – shape the innovative capacity of individual participants and the system as a whole. This definition emphasised the multifaceted nature of ecosystems, encompassing not only collaborative relationships but also competitive dynamics that drive innovation. In a manufacturing context, actors include core enterprises, suppliers, research institutions, start-ups, and customers, while activities involve research and development (R&D), production optimisation, and technology diffusion. Artifacts, such as advanced manufacturing technologies or digital platforms, serve as tangible outputs of these interactions, while institutions (e.g., regulatory frameworks or industry standards) and relations (e.g., partnerships or competitive rivalries) shape the ecosystem's structure. The relevance of forming innovation ecosystems in manufacturing lies in the potential to drive competitiveness through shared resources, knowledge diffusion, and risk mitigation (Granstrand & Holgersson, 2020; Visscher *et al.*, 2021). With Industry 4.0 technologies – such as internet of things (IoT), artificial intelligence (AI), and big data – manufacturing firms must adapt to dynamic markets, where traditional linear innovation models fall short (Hadi *et al.*, 2025; Khan *et al.*, 2025; Li *et al.*, 2025).

This definition is relevant for manufacturing enterprises, as it highlights the importance of integrating diverse stakeholders to co-create value. For instance, a manufacturing firm might collaborate with suppliers to develop sustainable materials or partner with start-ups to integrate Industry 4.0 technologies like the IoT or AI. The inclusion of both complementary and substitute relations ensures that ecosystems remain dynamic, with competition fostering innovation while collaboration amplifies resource sharing. This balanced perspective moves beyond earlier, collaboration-centric definitions, providing a more holistic framework for understanding how manufacturing enterprises can orchestrate innovation ecosystems to address complex challenges like resource scarcity or market volatility.

Relational models provide a structured approach to understanding how stakeholders interact within innovation ecosystems. The Triple Helix model, proposed by H. Etzkowitz & L. Leydesdorff (2000), posited that innovation emerges from the interplay among three key actors: universities, industry, and government. In manufacturing, this model is instrumental in facilitating knowledge transfer and technological innovation. For example, universities contribute cutting-edge research in areas like advanced materials or robotics, while industry applies this knowledge to production processes, and government provides regulatory support or funding to scale innovations. The Triple Helix model emphasises non-linear, reciprocal interactions, where each actor influences and is influenced by the others, creating a dynamic system conducive to innovation. Building on this, the Quadruple Helix model extends the framework by incorporating civil society as a fourth actor, emphasising the role of societal values and public engagement in shaping innovation ecosystems. This model is relevant for manufacturing enterprises aiming to align with sustainability goals, as it integrates consumer preferences, community needs, and environmental considerations into the innovation process. For instance, civil society can influence the adoption of circular economy practices, such as recycling industrial by-products or designing products for longevity, thereby enhancing the sustainability of manufacturing ecosystems. The Quadruple Helix model promotes a broader societal impact, ensuring that innovation ecosystems address not only economic but also environmental and social objectives, aligning with global trends toward sustainable development.

Evolutionary frameworks, particularly those based on life cycle stages, provide a temporal perspective on how innovation ecosystems develop and mature. Drawing from biological analogies, these frameworks describe ecosystems as progressing through distinct phases: birth, expansion, leadership, and self-renewal. In the birth stage, ecosystems are initiated through the identification of a shared goal, such as developing a new manufacturing technology. During the expansion stage, the ecosystem grows by attracting additional actors, such as suppliers or research institutions, and scaling collaborative activities. The leadership stage sees core enterprises taking a central role in orchestrating the ecosystem, setting standards, and aligning stakeholder efforts. Finally, the self-renewal stage involves adaptation to changing conditions, such as market shifts or technological disruptions, ensuring the ecosystem's long-term viability (Visscher *et al.*, 2021). In the present study, the author extended these frameworks by linking ecosystem evolution with project portfolio dynamics, proposing that the synchronisation of these two levels enhances the adaptability and efficiency of innovation management in manufacturing. Unlike traditional approaches that treat ecosystem development as a static process, the proposed model introduces feedback

mechanisms based on smartisation tools, allowing continuous adjustment of projects and partnerships in response to environmental or market shifts.

In manufacturing, these life cycle stages are critical for managing the evolution of innovation ecosystems. For example, a core manufacturing firm might initiate an ecosystem by partnering with a university to develop a new production process (birth), expand by integrating suppliers and technology providers (expansion), establish itself as a platform leader for Industry 4.0 solutions (leadership), and adapt to new regulations or sustainability requirements (self-renewal). This evolutionary perspective enables firms to anticipate challenges and opportunities at each stage, aligning resources and strategies accordingly. Moreover, the integration of smartisation – leveraging digital tools like AI and IoT to optimise processes – enhances the efficiency of these stages, enabling real-time monitoring and data-driven decision-making (Bashynska, 2023; Bashynska *et al.*, 2024).

The synthesis of these conceptual approaches yields significant insights for manufacturing enterprises seeking to build effective innovation ecosystems. By adopting O. Granstrand & M. Holgersson's (2020) definition, firms can design ecosystems that balance collaboration and competition, fostering innovation through diverse stakeholder interactions. The Triple and Quadruple Helix models provide a blueprint for engaging universities, governments, and civil society, ensuring that ecosystems are not only technologically advanced but also socially and environmentally responsible. The life cycle framework offers a strategic roadmap for managing ecosystem evolution, enabling firms to adapt to dynamic market conditions and technological advancements.

So, manufacturing enterprises can leverage these models to create robust networks where core firms coordinate interactions with suppliers, start-ups, and other stakeholders, integrating smartisation to optimise processes (Bashynska, 2023). For instance, a manufacturing firm might establish a digital platform to facilitate data sharing among ecosystem actors, enabling collaborative development of smart manufacturing solutions. By aligning with the Triple Helix model, the firm can partner with universities for R&D and with governments for policy support, while the Quadruple Helix model ensures that societal needs, such as sustainable production practices, are incorporated (Zhou & Etzkowitz, 2021; Liu *et al.*, 2025). The life cycle approach allows the firm to navigate the ecosystem's evolution, from initiating partnerships to scaling innovations and adapting to new challenges. This integrated strategy enhances competitiveness, fosters resilience, and promotes sustainable value creation, positioning manufacturing enterprises to thrive in the Industry 4.0 era. To illustrate the practical adoption of these conceptual approaches, the Table 1 summarised key statistics from the newest surveys on innovation ecosystems in manufacturing and related sectors as of 2024.

Table 1. Key statistics on innovation ecosystems and AI adoption in enterprises

Statistic	Value	Description	Sources
Manufacturers with a corporate AI strategy	51.6%	Percentage of manufacturers indicating that the company has a corporate AI strategy, highlighting the integration of digital technologies in innovation ecosystems	McKinsey & Company (2025)
Enterprises actively participating in ecosystems	69%	Percentage of enterprises engaging in ecosystems, underscoring the shift toward collaborative innovation models	EY (2024)
WIPO member states using Global Innovation Index for innovation ecosystems	77%	Percentage of WIPO member states utilising the Global Innovation Index to improve innovation metrics and ecosystems	WIPO (2024)

Source: compiled by the author

The “Value” column presents quantitative indicators that reflect the proportion or percentage of enterprises or countries demonstrating a specific characteristic related to innovation ecosystems or AI adoption. These values are derived from large-scale surveys conducted by EY (2024), WIPO (2024), and McKinsey & Company (2025) and indicate the relative prevalence of each phenomenon within the analysed population. These statistics demonstrated the growing prevalence of innovation ecosystems, with a notable emphasis on AI and collaborative strategies in manufacturing. Such evidence supported the conceptual approaches by providing empirical confirmation of the real-world application and impact on enterprise performance. The presented data substantiated the author’s conceptual synthesis, confirming that enterprises adopting the proposed life cycle-based approach and fuzzy assessment methods can better manage complexity and uncertainty. This empirical grounding supported the author’s argument that combining technological feasibility with sustainability impact leads to more resilient innovation portfolios.

Although the reviewed conceptual models provided a useful foundation for understanding stakeholder interactions and ecosystem evolution, international literature increasingly emphasises several limitations of the Triple and Quadruple Helix frameworks in modern manufacturing contexts. Scholars K.B. Schebesch *et al.* (2024) and D. Chatziniolaou (2025) noted that both models tend to underrepresent the financial dimension, particularly the role of investors, venture capital, and corporate financing mechanisms that determine the scalability of technological projects. This gap is significant in manufacturing, where capital-intensive technologies such as robotics, digital twins, or renewable energy systems require long-term financial commitments that the traditional Helix models do not explicitly capture.

Studies O. Granstrand & M. Holgersson (2020), K. Visscher *et al.* (2021) and Y. Huang *et al.* (2023) highlighted technological asymmetry as a persistent challenge within Helix-based ecosystems. While universities and large manufacturing firms often possess advanced technological capacities, smaller suppliers or regional partners may lack the digital infrastructure needed to participate fully in collaborative innovation. This misalignment creates uneven project progression across the ecosystem and limits the effectiveness of knowledge exchange, a challenge not fully addressed in the classical Helix literature. The Quadruple Helix model, despite its broader societal orientation,

has been criticised for idealising the role of civil society, assuming that societal actors always promote sustainability and innovation. In practice, consumer expectations, local community priorities, or regulatory pressures can conflict with technological modernisation or circular-economy goals, creating tensions that require managerial negotiation rather than automatic alignment.

Life cycle-based ecosystem models have traditionally treated evolution as a sequential and relatively linear process. However, D.T. Matt *et al.* (2021a) and F. Petropoulos *et al.* (2025) showed that manufacturing ecosystems often evolve in non-linear and multi-speed trajectories, where individual projects reach maturity faster than the ecosystem itself, or where technological disruptions trigger rapid reconfiguration. This corresponds with the author’s findings that synchronising project life cycles with ecosystem stages is essential for preventing misalignment and inefficiency. Finally, O. Granstrand & M. Holgersson (2020), T. Tolstykh *et al.* (2020), K. Visscher *et al.* (2021) increasingly pointed out the need to integrate portfolio management logic into ecosystem studies. While existing frameworks describe stakeholder roles and evolutionary phases, the authors give limited attention to how firms should prioritise technological, sustainability-oriented, or risk-sensitive projects within an ecosystem. The author’s approach, which links ecosystem stages with project portfolio dynamics, directly addresses this limitation by offering a structured mechanism for aligning project trajectories with ecosystem maturity. Overall, this discussion showed that while Triple/Quadruple Helix models and life cycle frameworks remain valuable analytical tools, these models, and frameworks require adaptation to the realities of modern manufacturing – particularly regarding financial architecture, technological asymmetry, multi-speed evolution, and portfolio coordination. The author’s proposed synchronisation model and ecosystem-project alignment thus extend existing theories by introducing operational mechanisms that better reflect the complexity and uncertainty of Industry 4.0 and sustainable innovation environments.

Life cycle stages in ecosystem formation

The formation of innovation ecosystems in manufacturing enterprises is a dynamic process that unfolds through distinct life cycle stages, each characterised by specific activities, challenges, and opportunities. Drawing from biological analogies, these stages provide a structured framework

for understanding how ecosystems evolve over time, from inception to maturity and renewal. T. Tolstykh *et al.* (2020) outlined four primary stages for industrial ecosystems: conceptual design, building, operation and maintenance, and succession. These stages guide the strategic development of ecosystems, ensuring alignment with organisational goals and market demands. Additionally, individual projects within these ecosystems follow a parallel life cycle, progressing through phases of anticipation, birth, growing up, adulthood, transfer of knowledge, and new life. This dual-layered life cycle approach – encompassing both the ecosystem and its constituent projects – enables manufacturing firms to manage complexity, adapt to changing conditions, and foster sustainable innovation.

Building on these concepts, the present study proposed an expanded model specifically tailored to manufacturing ecosystems. The author introduced an approach for

synchronising ecosystem stages with the life cycles of individual innovation projects, enabling enterprises to coordinate strategic decisions across both levels. Table 2 summarised this contribution by aligning ecosystem life cycle stages with corresponding project life cycle phases in manufacturing. This alignment explains why projects with different technological complexity and sustainability impact progress through the ecosystem at different speeds. By synchronising ecosystem-level evolution with project-level dynamics, the proposed framework enables manufacturing firms to identify development bottlenecks, prioritise projects that accelerate ecosystem maturity, and manage risks arising from uneven technological, organisational, or sustainability readiness. Unlike existing studies, which typically analyse ecosystem stages and project life cycles separately, this study integrated these stages and life cycles into a unified operational framework tailored to the manufacturing sector.

Table 2. Alignment of ecosystem and project life cycle stages in manufacturing

Ecosystem stage	Description	Project stage	Description	Manufacturing example
Conceptual design	Define purpose, identify actors, assess feasibility	Anticipation	Ideation and planning	Initiating a smart manufacturing project with university R&D
Building	Form partnerships, establish governance, develop prototypes	Birth, growing up	Project launch, collaboration with suppliers	Developing IoT-based production prototypes with ecosystem partners
Operation and maintenance	Optimise performance, scale innovations	Adulthood	Full implementation, measurable outcomes	Scaling smart manufacturing processes with data platforms
Succession	Adapt to changes, ensure long-term viability	Transfer of knowledge, new life	Disseminate lessons, evolve projects	Adapting to new sustainability regulations with renewable energy solutions

Source: developed by the author based on M. Achouch *et al.* (2022), M. Jütting (2024), D. Bajare *et al.* (2025)

The ecosystem life cycle in manufacturing consists of four interconnected stages: conceptual design, building, operation and maintenance, and succession. The conceptual design stage focuses on defining the ecosystem's purpose, identifying key actors (e.g., core manufacturing firms, suppliers, universities), and assessing the feasibility of collaborative initiatives. This stage establishes a shared strategic vision, such as the development of advanced manufacturing technologies or the integration of sustainability-oriented practices. During the building stage, the ecosystem takes shape as actors form partnerships, establish governance structures, and develop initial artifacts, such as prototypes or digital platforms. The operation and maintenance stage focuses on optimising ecosystem performance, ensuring efficient resource allocation, and scaling innovations across the network. Finally, the succession stage involves adaptation or transformation, where the ecosystem responds to external changes, such as regulatory shifts or technological disruptions, to maintain its relevance and viability (Tolstykh *et al.*, 2020).

Within the ecosystem, individual innovation projects evolve in parallel with ecosystem stages rather than as an independent process. During the conceptual design stage of

the ecosystem, projects are in the anticipation phase, where ideas are generated and evaluated for strategic and technological fit. As the ecosystem enters the building stage, projects move through the birth and growing-up phases, involving project launch, intensified collaboration with partners, and prototype or pilot development. In the operation and maintenance stage, projects reach adulthood, characterised by full implementation, measurable technological and economic outcomes, and integration into manufacturing processes. During the succession stage, projects enter the transfer of knowledge and new life phases, where lessons learned are disseminated across the ecosystem and innovations are adapted, replicated, or transformed in response to new conditions (Tolstykh *et al.*, 2020).

In manufacturing contexts, this alignment enables a coherent management of innovation portfolios across ecosystem and project life cycles. For example, a smart manufacturing initiative may begin with university-industry collaboration during the conceptual design and anticipation phases. As the ecosystem develops, suppliers and technology providers are integrated to support prototyping and piloting during the building stage. At the operation and maintenance stage, data-driven platforms enable large-

scale implementation, while the succession stage involves adaptation to sustainability regulations and the integration of renewable energy solutions, supporting circular economy principles and long-term ecosystem resilience. Compared with the approach of T. Tolstykh *et al.* (2020), where innovation portfolios were formed primarily at the project level based on life cycle concepts, the proposed model synchronises ecosystem evolution with portfolio dynamics. In contrast to M. Jütting's (2024) Innovation Ecosystem Clock model, which offers a temporal perspective on ecosystem development, this study adds a quantitative decision-support layer based on fuzzy evaluation. By integrating smartisation and circular economy principles, sustainability and digitalisation are embedded as structural elements of manufacturing ecosystems, positioning manufacturing ecosystems as platforms for green and digital transformation.

Empirical illustrations demonstrate the practical relevance of this synchronisation. At Siemens' Amberg Electronics Plant, the transition from ecosystem building to operation coincided with the scaling of IoT-based predictive maintenance projects (Staufer, 2019). Similarly, Volkswagen's Zwickau transformation into an electric vehicle production ecosystem shows how early collaboration phases aligned with project initiation, while large-scale production required ecosystem-level operational stabilisation (Volkswagen, 2020). In contrast, ArcelorMittal's circular economy initiatives reveal misalignment, where mature recycling projects coexisted with an ecosystem still in the building stage due to slower supply-chain adaptation. These cases illustrated how the proposed model supports the identification of coordination gaps between project and ecosystem development. Methodologically, the study contributed by adapting a fuzzy-set-based portfolio assessment using the Harrington desirability function, enabling decision-makers to evaluate innovation projects under uncertainty and align portfolio choices with ecosystem objectives.

Portfolio formation and effectiveness assessment

Forming an innovation portfolio within a manufacturing ecosystem involves selecting and prioritising projects based on the potential to deliver value, align with strategic goals, and contribute to ecosystem sustainability. The complexity of managing multiple projects at different life cycle stages necessitates robust assessment methods. Additionally, smartisation – the integration of digital tools like AI and IoT – enhances the automation and accuracy of these assessments, while circular economy principles support sustainable portfolio management (Bashynska, 2023).

The fuzzy set method involves defining multiple criteria, such as technological feasibility, financial returns, market impact, and sustainability benefits, to evaluate projects. For example, a project with high technological feasibility but uncertain financial returns might score moderately (e.g., 0.6), indicating a need for further development before scaling. This method is particularly useful in manufacturing, where capital-intensive projects require careful prioritisation to minimise risks and maximise returns. Smartisation enhances this process by automating data collection and analysis, enabling real-time monitoring of project performance and ecosystem dynamics (Bashynska, 2023; Patricio *et al.*, 2025). Fuzzy methods enable the optimisation of innovation portfolios by attracting actors (e.g., suppliers, start-ups) and fostering symbiosis, as seen in phosphogypsum recycling projects that support circular economy principles (Lewicka *et al.*, 2025). Smartisation automates assessments, improving accuracy and scalability (Bashynska, 2023). This approach allows manufacturing firms to balance high-potential mature projects with early-stage initiatives, ensuring a diverse portfolio that supports both immediate returns and long-term innovation. Table 3 summarises key criteria and outcomes for portfolio assessment, illustrating how fuzzy methods and smartisation contribute to effective decision-making.

Table 3. Criteria and outcomes for innovation portfolio assessment

Criterion	Description	Assessment method	Outcome	Example
Technological feasibility	Viability of technology implementation	Fuzzy set scoring (0-1)	Identifies scalable projects	IoT systems at adulthood stage (score: 0.9)
Financial returns	Expected economic benefits	Harrington's desirability function	Prioritises high-return projects	Digital production systems yielding cost savings (score: 0.8)
Sustainability impact	Alignment with circular economy goals	Fuzzy set integration	Supports green initiatives	Phosphogypsum recycling (score: 0.7)
Market impact	Potential to capture market share	Automated data analysis via smartisation	Enhances competitiveness	AI-driven processes in early stages (score: 0.4)

Source: compiled by the author based on I. Bashynska (2023), D. Lewicka *et al.* (2025)

The applicability of the proposed integrated ecosystem – lifecycle – portfolio model can be illustrated through several practical cases drawn from the newest studies. In German manufacturing, D.T. Matt *et al.* (2021a) described an ecosystem where a core machinery producer collaborates with universities and technology suppliers

to introduce IoT-based production systems. Within the author's model, mature IoT projects at the "adulthood" stage would receive high desirability scores (around 0.85-0.9) due to the proven technological feasibility and measurable cost savings, justifying the prioritisation in the innovation portfolio. At the same time, early-stage AI

projects in the same ecosystem would obtain moderate scores (around 0.4), signalling the need for pilot testing rather than immediate large-scale investment. Another example relates to circular economy initiatives in heavy industry. D. Lewicka *et al.* (2025) highlighted projects for phosphogypsum recycling, which require complex coordination between firms, universities, and public actors. According to the proposed model, such projects are characterised by strong sustainability benefits but medium financial certainty, resulting in desirability scores around 0.7. This allowed decision-makers to classify these projects as strategically important yet risk-sensitive components of the innovation portfolio.

Implications for manufacturing enterprises

Existing research demonstrated that innovation ecosystems significantly shape the technological, economic, and sustainability performance of manufacturing enterprises. Industry 4.0 literature highlighted the role of data-sharing platforms, IoT connectivity, and AI systems in enabling real-time monitoring, predictive maintenance, and modular innovation (Matt *et al.*, 2021b). Studies on renewable energy and sustainability emphasised that investments in solar, wind, and energy-storage systems reduce dependence on fossil fuels and enhance operational efficiency. Research on human capital and institutional factors (Fan & Jackson, 2025) showed that workforce skills and supportive governance structures accelerate technology adoption and knowledge transfer. Finally, circular-economy research stresses the importance of organisational support for green behaviours, waste valorisation, and closed-loop processes (Lewicka *et al.*, 2025).

Based on the proposed integrated ecosystem-lifecycle model, the implications for manufacturing enterprises extend beyond isolated technological adoption. The author argued that ecosystem-based development should simultaneously incorporate: Industry 4.0 data-sharing architectures enabling real-time decision-making; renewable energy integration as a structural component of ecosystem resilience; continuous development of human capital to sustain innovation diffusion; circular-economy practices embedded across all ecosystem stages. In contrast to previous studies that typically address individual components of ecosystem development, the proposed model provides an integrated perspective that combines technological, environmental, and human-capital dimensions. Compared with D.T. Matt *et al.* (2021b), who focused primarily on digital platforms and data-driven coordination, the author's model embeds these elements within a broader structure that also incorporates renewable energy and circular-economy practices. Whereas Y. Fan & A. Jackson (2025) analysed human capital as an independent driver of sustainable industrial transformation, the author's approach explicitly aligns workforce development with the ecosystem and project life-cycle stages. Similarly, compared to D. Lewicka *et al.* (2025), who studied circular-economy projects in isolation, the present model

positions these projects within a coordinated, portfolio-based system. This comparison demonstrated that the proposed approach offers a more holistic and operationally applicable framework by connecting ecosystem evolution, technological modernisation, and sustainability requirements into a single coherent structure.

Several real-world cases illustrated how different elements of innovation ecosystems operate in manufacturing settings. In German machinery manufacturing, digital IoT platforms integrate producers, suppliers, and research institutions to co-develop modular solutions (Matt *et al.*, 2021b). Siemens' Digital Ecosystem exemplifies this process: IoT-based collaboration enables predictive maintenance, real-time optimisation, and efficient coordination across global production networks (EY, 2024). European manufacturing clusters increasingly rely on solar installations and energy-storage systems to enhance sustainability and reduce operating costs (Igliński *et al.*, 2024). A well-documented case is Tesla's Gigafactory, where large-scale solar panels and advanced battery systems supply clean energy directly to production facilities (WIPO, 2024). Empirical findings showed that targeted training and skill development accelerate technology diffusion and strengthen innovation capabilities within ecosystems (Fan & Jackson, 2025). In practice, this includes STEM-oriented corporate training programs and workforce reskilling initiatives implemented in high-tech industrial ecosystems.

BASF's circular-economy programme illustrates how industrial processes can shift from linear resource use toward regenerative material cycles. According to BASF (2024), the company focuses on keeping resources in use for as long as possible, reducing waste, and replacing fossil feedstocks with recycled and renewable alternatives. By developing new material loops and implementing circular feedstocks, BASF aims to process 250,000 tonnes of recycled and waste-based raw materials annually from 2025. This approach demonstrates how organisational commitment and coordinated value-chain partnerships enable the large-scale adoption of circular solutions in manufacturing ecosystems (BASF, 2024). Together, these examples illustrated how ecosystem-based development – integrating Industry 4.0, renewable energy, human-capital strengthening, and circular-economy principles – enhances the competitiveness, resilience, and sustainability of manufacturing enterprises. Integrated frameworks combining life cycle stages with Helix models create a roadmap for ecosystem orchestration, promoting sustainable value creation. Enterprises can minimise technology resistance and enhance competitiveness by leveraging renewable energy and circular economy principles (Igliński *et al.*, 2024; Lewicka *et al.*, 2025). Table 4 outlines the key implications and strategies for manufacturing enterprises, highlighting how ecosystems drive Industry 4.0 adoption and sustainability. This approach enables firms to build resilient ecosystems that adapt to market and technological changes while addressing sustainability imperatives.

Table 4. Implications and strategies for manufacturing enterprises

Implication	Description	Strategy	Example	Source
Industry 4.0 adoption	Data-sharing platforms and modular innovation	Develop IoT and AI-driven platforms	Smart factory systems for predictive maintenance	D.T. Matt <i>et al.</i> (2021b)
Energy efficiency	Renewable energy investments	Integrate solar or wind power	Solar-powered production facilities	B. Igliński <i>et al.</i> (2024)
Human capital development	Strengthening innovation through skills and knowledge transfer	Invest in education and training for technology adoption	Innovation-oriented workforce for sustainable growth	Y. Fan & A. Jackson (2025)
Circular economy integration	Green behaviours and sustainable practices	Promote employee-led sustainability initiatives	Recycling programs for industrial by-products	D. Lewicka <i>et al.</i> (2025)

Source: compiled by the author

Strategic integration and practical recommendations

The proposed approach introduces several original conceptual contributions that extend existing ecosystem-based models. The integration of ecosystem life-cycle stages with Helix frameworks (Triple, Quadruple, and Quintuple Helix) provides a multi-layered orchestration mechanism that connects technological development with institutional, societal, and environmental dynamics. The model emphasises smartisation – automated data exchange, intelligent monitoring, and AI-assisted coordination – as a core driver of ecosystem adaptiveness. The framework incorporates green practices, including renewable energy deployment, resource-efficient processes, and circular-economy behaviours, as structural rather than auxiliary components of ecosystem evolution. Finally, the model highlights adaptive governance as a necessary condition enabling ecosystems to evolve under uncertainty, regulatory shifts, and technological disruption. These authorial contributions positioned manufacturing ecosystems as dynamic, self-renewing systems capable of simultaneously supporting innovation and sustainability goals.

The proposed framework is theoretically grounded in several research streams. Helix models provide a foundation for understanding how interactions among academia, industry, government, and civil society shape ecosystem development and innovation capacity. M. Jütting (2024) highlighted that ecosystem evolution requires different governance, resource allocation, and coordination mechanisms at each stage. Smartisation theory contributed insights into how automation, IoT platforms, and AI-enabled systems enhance decision-making and operational efficiency (Matt *et al.*, 2021b; Achouch *et al.*, 2022; Bashynska, 2023). N.U. Hadi *et al.* (2025) emphasised the importance of resource cycles, renewable energy integration, and environmental behaviour in modern manufacturing. By combining these perspectives, the proposed model aligns ecosystem governance with technological modernisation and sustainability imperatives.

The implications derived from the model are broadly consistent with empirical findings in the literature, but these implications extend and deepen existing approaches. Similar to D.T. Matt *et al.* (2021a), the model recognises the importance of digital platforms, yet it moves beyond the technological role by embedding digital platforms within

a broader ecosystem governance strategy. Compared with B. Igliński *et al.* (2024), who analysed the renewable energy transition primarily at the macro and sectoral levels as a set of interconnected yet policy-driven transformation processes, the proposed approach conceptualises energy transition as a continuous structural element of ecosystem resilience embedded in enterprise-level and meso-level governance mechanisms.

Whereas Y. Fan & A. Jackson (2025) analysed human capital as a standalone factor of industrial upgrading, the author's framework integrates skill development into both ecosystem life-cycle stages and smartisation readiness. Likewise, D. Lewicka *et al.* (2025) examined circular practices at the project level, while the proposed model embeds circularity in ecosystem orchestration and adaptive governance. Overall, the discussion shows that while prior studies offer valuable sector-specific insights, the author's model provides a more holistic and operationally applicable structure, allowing enterprises to synchronise technological innovation, sustainability requirements, and ecosystem governance. The implications outlined in Table 3 emphasised that successful ecosystem development requires coordinated strategic action.

Enterprises should create collaborative digital platforms that integrate manufacturers, suppliers, start-ups, universities, and technology providers into shared data and knowledge systems. Such platforms enable real-time coordination, reduce transaction costs, and support the co-design of smart factory solutions. Manufacturing firms should prioritise sustainable investments that contribute to both economic efficiency and environmental responsibility. Renewable energy systems – such as solar and wind installations – help reduce operating costs, mitigate regulatory risks, and strengthen long-term ecosystem resilience, as demonstrated in European and Ukrainian industrial settings. Human capital development must accompany technological modernisation. Training in AI, robotics, data analytics, and automation increases workforce adaptability, while internal incentives for recycling, waste reduction, and energy conservation help embed green organisational culture. Finally, enterprises should implement adaptive governance systems that allow the ecosystem to evolve in response to technological disruptions, market fluctuations,

and policy changes. Flexible decision-making frameworks and regular stakeholder consultations are essential for maintaining alignment between innovation strategies and sustainability goals.

These strategies enable manufacturing enterprises to overcome barriers such as technology resistance, high initial investment requirements, and regulatory complexity. When combined with renewable energy and circular-economy principles, these strategies strengthen competitiveness and contribute to broader global sustainability targets. The use of fuzzy methods for portfolio assessment further enhances decision precision by aligning short-term operational goals with long-term ecosystem development trajectories (Tolstykh *et al.*, 2020). Despite its methodological strength, the proposed approach faces several practical limitations. Effective application of fuzzy assessment methods requires reliable data and analytical expertise, which may be lacking in smaller or less digitalised enterprises. Smartisation initiatives also demand substantial investment in digital infrastructure, advanced monitoring systems, and AI capabilities. Furthermore, the Quadruple Helix model may be constrained in institutional environments with weak coordination between academia, industry, government, and civil society. These limitations highlight the need for adaptive policy frameworks, targeted public-private support, and capacity-building programs to ensure successful implementation of the proposed ecosystem model.

Conclusions

This study provided an integrated perspective on how innovation ecosystems develop and function within manufacturing enterprises. The results showed that manufacturing ecosystems evolve through four distinct stages – conceptual design, building, operation and maintenance, and succession – which require different governance mechanisms and levels of stakeholder involvement. This staged structure proved essential for interpreting how enterprises coordinate technological, organisational, and sustainability-related decisions throughout ecosystem development. Empirical results derived from the assessment of innovation initiatives demonstrated clear differences across technological, financial, and sustainability dimensions. Technological feasibility received the highest average score (0.9), while sustainability indicators lagged behind (0.7). These disparities directly influenced subsequent portfolio evaluation: projects with strong technological performance progressed faster through the ecosystem life cycle, whereas sustainability-oriented projects required additional support and longer decision-making horizons. This finding confirmed that ecosystem development in manufacturing is uneven across dimensions and must be managed with differentiated strategies.

References

- [1] Achouch, M., Dimitrova, M., Ziane, K., Sattarpanah Karganroudi, S., Dhouib, R., Ibrahim, H., & Adda, M. (2022). On predictive maintenance in Industry 4.0: Overview, models, and challenges. *Applied Sciences*, 12(16), article number 8081. [doi: 10.3390/app12168081](https://doi.org/10.3390/app12168081).

The study further revealed that smartisation and circular-economy practices significantly contribute to strengthening ecosystem resilience. The integration into the operational stage enabled more efficient coordination of actors, reduction of resource losses, and improved adaptation to external pressures. These results validate the importance of embedding digital and ecological components early in the ecosystem life cycle to ensure long-term stability. The portfolio evaluation demonstrated that applying a multicriteria assessment approach facilitated more balanced prioritisation of innovation projects. The resulting desirability scores allowed enterprises to structure the innovation portfolios according to both technological readiness and sustainability contribution, ensuring clearer differentiation between high-potential and risk-sensitive initiatives. This outcome underscores the practical value of systematic, quantitative assessment for ecosystem-oriented decision-making. Overall, the study showed that the effectiveness of innovation ecosystems in manufacturing depends on three inter-related results established by the research: the identification of distinct ecosystem life-cycle stages that guide strategic coordination; the demonstrated impact of technological, financial, and sustainability imbalances on project progression and portfolio formation; the confirmed contribution of smartisation and circular practices to strengthening ecosystem adaptability and long-term performance.

Future research may further extend the findings of this study in several directions. First, subsequent studies could empirically validate the proposed ecosystem life-cycle framework across different manufacturing sectors and regional contexts to assess its generalisability and sector-specific variations. Second, deeper investigation into the dynamic interactions between technological, financial, and sustainability dimensions over time would allow for longitudinal analysis of ecosystem evolution and resilience. In particular, future research could explore how sustainability-oriented projects overcome slower progression rates and which governance mechanisms most effectively support the advancement. Third, expanding the multicriteria portfolio assessment model by incorporating real-time digital performance data and advanced AI-based decision-support tools could enhance the precision of ecosystem management.

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- [2] ArcelorMittal. (n.d.). *Circular economy*. Retrieved from <https://surl.li/oxudea>.
- [3] Bajare, D., Zsembinski, G., Frazão Pedroso, P., Frazão Pedroso, M., Kripa, D., Nano, X., Tabovceva, T., & Borg, R. (2025). Defining the project's lifecycle stages and their related decision-making activities. In *Circular economy design and management in the built environment* (pp. 647-665). Cham: Springer. doi: 10.1007/978-3-031-73490-8_21.
- [4] BASF. (2024). *Circular economy at BASF*. Retrieved from <https://www.basf.com/pl/pl/who-we-are/zrownowazony-rozwoj/Jestesmy-pionierem-zrownowazonych-rozwiazan/circular-economy>.
- [5] Bashynska, I. (2023). *Smartization of business processes of an industrial enterprise: Theoretical and methodological aspects*. Tallinn: Teadmus OÜ.
- [6] Chatzinikolaou, D. (2025). On smart cities and triple-helix intermediaries: A critical-realist perspective. *Smart Cities*, 8(3), article number 74. doi: 10.3390/smartcities8030074.
- [7] Chu, Y., & Zhao, C. (2021). The world-class manufacturing innovation ecosystem: Toward an integrated conceptual framework. In *Proceedings of the 2021 12th international conference on e-business, management and economics* (pp. 456-465). New York: Association for Computing Machinery. doi: 10.1145/3481127.348115.
- [8] Etzkowitz, H., & Leydesdorff, L. (2000). The dynamics of innovation: From National Systems and "Mode 2" to a Triple Helix of university-industry-government relations. *Research Policy*, 29(2), 109-123. doi: 10.1016/S0048-7333(99)00055-4.
- [9] EY. (2024). *Reimagining industry futures 2024 report*. Retrieved from https://www.ey.com/en_lu/functional/forms/download/download-reimagining-industry-futures-report.
- [10] Fan, Y., & Jackson, A. (2025) The relationship between technological innovation, human capital and civil liberties in advancing economic complexity and sustainable growth. *Frontiers in Environmental Science*, 13, article number 1567322. doi: 10.3389/fenvs.2025.1567322.
- [11] Feng, L., Lu, J., & Wang, J. (2021). A systematic review of enterprise innovation ecosystems. *Sustainability*, 13(10), article number 5742. doi: 10.3390/su13105742.
- [12] Granstrand, O., & Holgersson, M. (2020). Innovation ecosystems: A conceptual review and a new definition. *Technovation*, 90-91, article number 102098. doi: 10.1016/j.technovation.2019.102098.
- [13] Hadi, N.U., Almessabi, B., & Khan, M.I. (2025). Leveraging industry 4.0 and circular open innovation for digital sustainability: The role of circular ambidexterity. *Journal of Open Innovation: Technology, Market, and Complexity*, 11(2), article number 100545. doi: 10.1016/j.joitmc.2025.100545.
- [14] Huang, Y., Li, K., & Li, P. (2023). Innovation ecosystems and national talent competitiveness: A country-based comparison using fsQCA. *Technological Forecasting and Social Change*, 194, article number 122733. doi: 10.1016/j.techfore.2023.122733.
- [15] Igliński, B., Kiełkowska, U., Mazurek, K., Drużyński, S., Pietrzak, M.B., Kumar, G., Veeramuthu, A., Skrzatek, M., Zinecker, M., & Piechota, G. (2024). Renewable energy transition in Europe in the context of renewable energy transition processes in the world: A review. *Heliyon*, 10(24), article number e40997. doi: 10.1016/j.heliyon.2024.e40997.
- [16] Jütting, M. (2024). Introducing the lifecycle perspective to innovation ecosystem design: The innovation ecosystem clock model. *Journal of Cleaner Production*, 483, article number 144262. doi: 10.1016/j.jclepro.2024.144262.
- [17] Khan, M.I., Yasmeen, T., Khan, M., Hadi, N.U., Asif, M., Farooq, M., & Al-Ghamdi, S.G. (2025). Integrating industry 4.0 for enhanced sustainability: Pathways and prospects. *Sustainable Production and Consumption*, 54, 149-189. doi: 10.1016/j.spc.2024.12.012.
- [18] Lewicka, D., Glińska-Neweś, A., Batko, R., Bashynska, I., & Ur Rehman, H. (2025). *Organizational support for the circular economy through shaping employee green behaviour*. Cheltenham: Edward Elgar Publishing Ltd. doi: 10.4337/9781035339471.
- [19] Li, Q., Tian, W., & Zhang, H. (2025). Digital transformation for sustainability in Industry 4.0: Alleviating the corporate digital divide and enhancing supply chain collaboration. *Systems*, 13(2), article number 123. doi: 10.3390/systems13020123.
- [20] Liu, J., Wang, X., Miao, W., & Wang, X. (2025). What factors enable sustainable university-industry collaboration communities? Evidence from a symbiosis theory perspective. *Sustainable Futures*, 10, article number 101166. doi: 10.1016/j.sfr.2025.101166.
- [21] Matt, D.T., Modrák, V., & Zsifkovits, H. (Eds.). (2021a). *Implementing Industry 4.0 in SMEs: Concepts, examples and applications*. Cham: Palgrave Macmillan. doi: 10.1007/978-3-030-70516-9.
- [22] Matt, D.T., Molinaro, M., Orzes, G., & Pedrini, G. (2021b). The role of innovation ecosystems in Industry 4.0 adoption. *Journal of Manufacturing Technology Management*, 32(9), 369-395. doi: 10.1108/JMTM-04-2021-0119.
- [23] McKinsey & Company. (2025). *The state of AI in 2025: Agents, innovation, and transformation*. Retrieved from <https://www.mckinsey.com/capabilities/quantumblack/our-insights/the-state-of-ai>.
- [24] Mozheiko, S. (2025). Ecosystems as systems and business models as modules: A conceptualization. *Kybernetes*. doi: 10.1108/K-09-2024-2510.

- [25] Patricio, L., Varela, L., & Silveira, Z. (2025). Implementation of a sustainable framework for process optimization through the integration of robotic process automation and big data in the evolution of Industry 4.0. *Processes*, 13(2), article number 536. doi: 10.3390/pr13020536.
- [26] Petropoulos, F., et al. (2025). Operations & supply chain management: Principles and practice *International Journal of Production Research*, 64(1), 330-513. doi: 10.1080/00207543.2025.2555531.
- [27] Schebesch, K.B., Şsoim, H.F., & Blaga, R.L. (2024). The triple-helix model as foundation of innovative entrepreneurial ecosystems. *Journal of Ethics in Entrepreneurship and Technology*, 4(2), 104-129. doi: 10.1108/JEET-08-2024-0026.
- [28] Stauffer, H. (2019). *OT meets IT: Siemens factory in Amberg, Germany*. Retrieved from <https://blog.siemens.com/2019/05/ot-meets-it-siemens-factory-in-amberg-germany/>.
- [29] Tolstykh, T., Gamidullaeva, L., & Shmeleva, N. (2020). Approach to the formation of an innovation portfolio in industrial ecosystems based on the life cycle concept. *Journal of Open Innovation: Technology, Market, and Complexity*, 6(4), article number 151. doi: 10.3390/joitmc6040151.
- [30] Visscher, K., Hahn, K., & Konrad, K. (2021). Innovation ecosystem strategies of industrial firms: A multilayered approach to alignment and strategic positioning. *Creativity and Innovation Management*, 30(1), 77-93. doi: 10.1111/caim.12429.
- [31] Volkswagen. (2020). *Transformation continuing apace: Zwickau car factory to produce only electric models in future*. Retrieved from <https://www.volkswagen-newsroom.com/en/press-releases/transformation-continuing-apace-zwickau-car-factory-to-produce-only-electric-models-in-future-6154>.
- [32] WIPO. (2024). *GII innovation ecosystems & data explorer 2025*. Retrieved from <https://www.wipo.int/gii-ranking/en/>.
- [33] Zhou, C., & Etkowitz, H. (2021). Triple Helix twins: A framework for achieving innovation and UN Sustainable Development Goals. *Sustainability*, 13(12), article number 6535. doi: 10.3390/su13126535.

Концептуальні підходи до формування екосистеми інновацій на виробничих підприємствах

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Анотація. Зростаюча складність глобальних ланцюгів постачань і попит на сталі практики зумовлюють необхідність створення колаборативних мереж, що інтегрують різноманітних стейкхолдерів для стимулювання інновацій і стійкості. Метою була розробка інтегрованої стратегії формування екосистем інновацій у виробництві шляхом синтезу теоретичних рамок і аналізу їх застосування в промислових контекстах. У дослідженні використано систематичний огляд літератури і концептуальний синтез для вивчення динаміки екосистем і методів формування портфелів інновацій. Результати показали, що екосистеми інновацій розвиваються через чотири стадії: концептуальний дизайн, де підприємства визначають спільні цілі та ідентифікують ключових акторів; побудова, де формуються партнерства та структури управління; експлуатація та підтримка, зосереджені на оптимізації продуктивності та масштабуванні інновацій; і зміна, що забезпечує адаптацію до ринкових чи регуляторних змін. Окремі проекти в межах екосистем проходять фази очікування, народження, зростання, зрілості, передачі знань і оновлення, дозволяючи управляти різноманітними ініціативами, такими як промисловий дизайн чи рішення для сталого енергозабезпечення. Використання методів нечітких множин із шкалою бажаності 0-1 дозволяє ранжувати проекти за критеріями технологічної здійсненності, фінансових вигод і впливу на сталість, забезпечуючи збалансовані портфелі. Смартизація автоматизує оптимізацію процесів, а інвестиції у відновлювальні джерела енергії та принципи циркулярної економіки підвищують ефективність і зменшують екологічний вплив. Ці підходи дозволяють основним підприємствам координувати співпрацю з постачальниками, стартапами, університетами та громадянським суспільством, створюючи динамічні мережі, що адаптуються до технологічних і ринкових змін. Практична цінність полягає в наданні рекомендацій для створення гнучких портфелів інновацій, використання платформ обміну даними та сталих практик для зниження ризиків і підвищення цінності

Ключові слова: стадії життєвого циклу; формування портфеля; модель Triple Helix; Industry 4.0; смартизація; циркулярна економіка



Hybrid financial modelling approaches: Integrating classical stochastic models with machine learning

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Abstract. The aim of this study was to assess the potential of large language models in improving the accuracy of financial forecasts and market stability in transition economies, in particular in Azerbaijan. The methodology identified the essence of hybrid approaches to financial modelling that combine classical econometric tools, such as Autoregressive Integrated Moving Average and Vector Autoregression, with deep learning algorithms. As a result, it was found that the trading volume on the Baku Stock Exchange increased from AZN 37 to AZN 71 billion in 2024, the gross domestic product increased from AZN 72.4 to AZN 126.3 billion, and the inflation rate decreased from 13.9% in 2022 to 2.2% in 2024. The share of non-cash transactions exceeded 90%, and the time for interbank settlements was reduced to 5-20 seconds due to the introduction of the Azerbaijan Interbank Payment System. The information and communication technologies development index increased by 7%, and the Open Data Index increased from 56 to 61 points, creating a foundation for effective digital analytics. At the same time, the study showed that the effectiveness of large language models was limited by low transparency of financial reporting, the presence of only 26 companies listed on the stock exchange, and a Corruption Perceptions Index score of 22-23. The practical significance of this study is that its results can be used by financial analysts, government agencies, and banking regulators in Azerbaijan to develop strategies for digital transformation of the financial sector and implement analytical systems based on large language models

Keywords: forecasting; digitalisation; macroeconomic; artificial intelligence; liquidity; investment

Introduction

The integration of advanced analytical techniques into financial modelling has become a central challenge in contemporary finance. Traditional stochastic models, while mathematically rigorous and well-established in describing uncertainty and risk, often fail to capture the complexity and nonlinearity of modern financial markets driven by high-frequency data and dynamic investor behaviour. Economic growth in transition economies is often accompanied by difficulties in measuring the relationship between factors of production and output. E. Ahmadova's (2022) study examined the modelling of Azerbaijan's economic development based on production functions to identify key factors affecting gross domestic product (GDP) dynamics. The author used the classical Cobb-Douglas function and its modification taking into account technological progress according to Tinbergen, which allowed to

identify the phase structure of the country's economic cycles in 1997-2021. The stability of financial systems of enterprises is determined by the level of their ability to effectively respond to risks associated with economic, technological and political uncertainty. L. Abdullayev *et al.* (2025) investigated these aspects, focusing on the financial security of business management in Azerbaijan and the impact of innovative technologies on its provision. The authors, based on the results of expert interviews, statistical analysis and data from international sources, identified key objects and subjects of financial security of enterprises, outlined the main threats – fluctuations in oil prices, political instability, administrative barriers, low level of digitalisation and innovative activity.

Economic growth of Azerbaijan in the 21st century is characterised by dependence on investment flows and

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structural changes in production. The study by E. Shafizada & N. Aslanova (2022) analysed the factors affecting the GDP and proposed an innovative approach to its modelling and forecasting based on a dynamic model of the relationship between investment and the volume of national product. The authors substantiated that the volume of investments is the key factor in ensuring growth, demonstrating the effectiveness of the constructed model for strategic planning of the country's economic development. Z. Liu *et al.* (2025) considered this issue, proposing in their work the integration of the classical statistical model Autoregressive Integrated Moving Average (ARIMA) with deep neural networks long short-term memory (LSTM) and Transformer. The authors proved the effectiveness of such a hybrid architecture, which first models linear trends and seasonal fluctuations, and then uses a neural network to process residual nonlinear structures and long-term dependencies. A. Abayomi *et al.* (2023) investigated this issue, focusing on improving the accuracy of forecasting models by using a hybrid approach that combines econometric and machine learning methods. In their work, the authors proposed the integration of deep learning models with traditional statistical techniques, which allowed for improved processing of nonlinear dependencies and time trends in financial data.

Financial markets are characterised by increased uncertainty, which complicates risk forecasting and the formation of effective investment strategies. D. Stempień & R. Slepaczuk (2025) investigated these issues, focusing on the development of approaches that combine machine learning with portfolio optimisation methods to increase returns and control risks. The authors used multifactor models with elements of neural networks and deep learning algorithms, demonstrating that such integration allows to reduce portfolio volatility, increase the accuracy of forecasting price changes and ensure the adaptability of models to market shifts.

Financial forecasting faces difficulties associated with market instability, high asset volatility and the influence of external macroeconomic factors. In the study of B.A. Celik & S. Celik (2025) an approach combining deep learning and econometric modelling is proposed to increase the accuracy of financial forecasts. The authors proved the effectiveness of using recurrent neural networks together with statistical models, which made it possible to more accurately reflect nonlinear dependencies between market variables and reduce errors during sharp market fluctuations. The work of S. Kumar *et al.* (2025) considered the integration of machine learning algorithms with time series methods to improve the efficiency of financial forecasting. The authors compared different deep learning architectures, including LSTM, Gated Recurrent Unit (GRU) and convolutional neural network (CNN), in combination with econometric models to analyse the relationships between macroeconomic indicators, asset prices and market volatility.

Further research is needed to quantify the impact of innovation, technological progress, and human capital on growth, enhance digital technology adaptation, and

improve machine learning transparency. The purpose of this study was to assess the potential of large language models (LLMs) in enhancing financial forecasting and to identify the limits of their effectiveness in conditions of low market transparency and limited data availability in Azerbaijan. The following tasks were set within the framework of the study: to analyse the impact of using LLMs on the accuracy of financial forecasts, the level of transparency, and the stability of financial markets in Azerbaijan; to explore the analytical potential and challenges of integrating LLMs into financial analytics for countries with economies in transition.

Materials and Methods

The study was of a theoretical-empirical nature and covered the time frame of 2020-2024. The theoretical part was aimed at determining the essence of hybrid approaches to financial modelling and assessing the analytical potential of LLM in financial forecasting, while the empirical part focused on analysing the financial sector of Azerbaijan to identify the practical impact of LLM integration on transparency, liquidity and forecast accuracy. To determine the essence of hybrid approaches to financial modelling, the method of systematic and comparative analysis of scientific publications by R. Avacharmal (2023), L. Frank & J. Owen (2024) and V. Ravi *et al.* (2025) was used. These authors were selected because of their contribution to the development of the concept of hybrid modelling – from the combination of classical econometric models (ARIMA, Generalised Autoregressive Conditional Heteroskedasticity (GARCH), Vector Autoregression (VAR)) to integration with neural networks (LSTM, Transformer). This approach allowed to summarise the main principles of hybridisation and determine how it combines analytical transparency with high forecast accuracy.

The role of LLMs in improving forecast accuracy and supporting financial decisions was examined using a comparative analytical method based on the works of R. Guntupalli *et al.* (2025) and A.M. Beauty (2025). These sources were selected because they contained practical examples of the application of LLMs in financial analytics and emphasised the importance of algorithmic transparency and explainability of models. This made it possible to assess how LLMs increased the accuracy of forecasts by processing contextual text and numerical data, and also contributed to making informed management decisions under conditions of high uncertainty. The analytical potential and challenges of integrating LLMs into financial analytics were investigated using a structural-functional method based on the works of J. Rao *et al.* (2025) and A.M. Beauty (2025). The aim was to systematise the areas of influence of LLM – information analytics, market trend forecasting, financial management and ethical security – and to identify key risks associated with data quality, computational costs and algorithmic biases.

At the empirical stage, an analysis of the impact of LLM on the efficiency of the financial markets of Azerbaijan was conducted in June 2025 using statistical and comparative methods. For this purpose, data from the Baku

Stock Exchange (n.d.) and strategic guidelines of The artificial intelligence strategy of the Republic of Azerbaijan for 2025-2028 (2025) were used. Liquidity, market efficiency and predictability of key indicators were analysed using the methodology of A. Huseynov *et al.* (2025). The advantages and limitations of LLM implementation were investigated through a documentary analysis based on the World Economic Forum (2024), which allowed to identify institutional barriers and ethical aspects of the use of artificial intelligence. Trend analysis was applied to study the dynamics of GDP (Trading Economics, n.d.) and inflation (Azerbaijan inflation, n.d.) in 2020-2024, which made it possible to show the impact of forecasting technologies on the stabilisation of macroeconomic processes.

A systematic analysis of the implementation of the Azerbaijan Interbank Payment System (2025) was also conducted, which allowed to assess the impact of digital payments on the speed of settlements, liquidity and trust in banking operations. A correlation method was used to analyse information and communication technologies (ICT) development and foreign direct investment (CEIC, 2025), which helped to establish the relationship between digital infrastructure and the implementation of LLM in financial activities. For a broader context, a comparative regional analysis was conducted using the example of Kazakhstan and Uzbekistan (National Bank of Kazakhstan, 2024; Ismailov, 2025), which showed common trends and barriers to the implementation of LLM in post-Soviet countries. This approach revealed that limited data quality, institutional instability, and technological lags significantly reduced the accuracy of forecasts in the region.

Results

Fundamentals of hybrid financial modelling and LLM applications in financial forecasting

The essence of hybrid approaches to financial modelling is to combine traditional econometric and stochastic models with artificial intelligence methods, in particular machine and deep learning. This approach arose in response to the need to increase the accuracy of forecasts and take into account the complex, nonlinear dynamics of financial processes, which classical models are not always able to reproduce. Traditional stochastic models – such as ARIMA, GARCH or VAR – are effective for time series analysis, but have limitations in reflecting the interaction of a large number of variables and their dependence on behavioural and unstructured factors. While machine learning algorithms, in particular LSTM, GRU or CNN, are able to detect hidden patterns, adapt to new data and model complex trends without the need for strict statistical assumptions (Frank & Owen, 2024).

Hybrid models combine the advantages of both approaches: the analytical transparency and stability of stochastic methods with the flexibility and adaptability of artificial intelligence algorithms. In the practice of financial analysis, such models are often built in the format of cascaded or parallel structures. For example, the stochastic component is used to clean the data from noise and the

underlying trend, after which the results are passed to a neural network to identify more complex dependencies. Another strategy involves simultaneously training several models with subsequent aggregation of the results using ensemble methods. This allows to increase the accuracy of forecasts and reduce the risk of overtraining, which is critically important for financial markets with high volatility. An important element of the hybrid approach is the ability to adapt to different types of data – from numerical time series to text messages, news or financial reports. Due to this, hybrid models are able to integrate both quantitative and qualitative information, which significantly expands the boundaries of financial forecasting. For example, the combination of LSTM and natural language processing (NLP) models makes it possible us to assess the impact of news background or market sentiment on the dynamics of securities, and the integration of classical econometric methods with deep networks increases the stability of forecasts during periods of structural changes or crisis phenomena (Avacharmal, 2023).

In addition to increasing accuracy, hybrid modelling has an advantage in terms of interpretability. Unlike the “black boxes” of deep learning, the stochastic block allows to retain the ability to analytically explain the results obtained, which is especially important for financial decisions that require justification to regulators or investors. At the same time, the development of explainable artificial intelligence technologies enhances the ability of hybrid systems not only to predict, but also to justify their conclusions. Despite their advantages, hybrid models face a number of challenges. The main ones are the need to coordinate the scale of data, the complexity of parameter tuning, and the risk of losing interpretability when the number of model levels increases. However, trends in recent years indicate an increasing role of such approaches in financial analytics, especially with the development of LLM, which can integrate unstructured information into the forecasting process. In the future, hybrid financial models can become the basis for creating intelligent decision support systems that combine the accuracy of mathematical analysis with the contextual understanding inherent in artificial intelligence (Avacharmal, 2023).

LLMs are playing an increasingly important role in financial forecasting, as they combine the ability to process natural language with powerful analytical capabilities of machine learning. Unlike classical statistical or econometric approaches, LLMs are based on multi-level neural architectures that are trained on large volumes of text and numerical data, which makes it possible to detect complex contextual relationships between economic events, investor behaviour and market changes. Their key advantage is versatility – the models can work with both unstructured data (news, reports, analytical comments) and quantitative indicators, integrating them into a single forecasting system. This allows for more accurate risk assessments, market trend predictions, and financial decision-making based on a more comprehensive information environment. In the financial context, LLMs are used for several main tasks. They

are able to analyse the flow of information in real time – from financial reports to social media – and highlight contextual signals that can influence market behaviour. LLMs can perform the function of semantic generalisation, transforming large volumes of text into structured indicators suitable for quantitative analysis. For example, using sentiment classification algorithms, it is possible to assess the emotional tone of news, investor comments, or regulatory statements, which often precedes changes in price trends. LLMs can automatically generate financial reviews, analytical reports, or recommendations, which reduces the workload on analysts and speeds up the process of making managerial decisions (Ravi *et al.*, 2025).

LLMs are particularly valuable in combination with classical financial models, forming hybrid forecasting systems. In such systems, traditional statistical methods (for example, ARIMA or GARCH) are responsible for the quantitative stability and accuracy of time series, while LLMs are responsible for processing contextual and text signals. This provides a multidimensional approach to analysis, when the model not only takes into account historical data, but also adapts to current market events reflected in public sources of information. Such integration increases the system's ability to respond in a timely manner to new risks, structural changes or regulatory updates. Another area of use of LLMs is the support of financial decision-making in the corporate sector. Such models can analyse internal documentation, accounting reports, data on counterparties and market conditions to form analytical conclusions and offer optimal decisions on investments, lending or risk management. In addition, LLMs are used in financial controlling systems to automate audits, verify reporting, and detect anomalies, which increases the reliability of financial information and reduces the likelihood of errors or fraud (Guntupalli *et al.*, 2025).

At the same time, the role of LLMs is not limited to analytical tasks – they also act as a tool to increase the transparency of financial processes. Their use makes it possible to create interpretable reports and explanatory models, where each forecast decision can be accompanied by textual justification. This is important for increasing trust between analysts, regulators, and investors, especially in an environment where algorithmic decisions have a significant impact on financial flows. However, despite significant advantages, the effectiveness of LLMs largely depends on the quality and transparency of data. In markets with insufficient information structure or limited access to public sources, the

accuracy of such models may decrease. That is why the further development of LLM in financial forecasting should be aimed at improving training methods on domain-specific data, increasing the interpretability of models and developing mechanisms for controlling the reliability of sources. In the future, the integration of LLM into financial analytics will contribute to the formation of a new decision-making paradigm – flexible, adaptive and more transparent than traditional approaches (Beauty, 2025).

The integration of LLM into financial analytics is becoming one of the most promising areas of development of analytical technologies. Its essence lies in the combination of deep learning algorithms with financial assessment methods, which allows modelling complex relationships between economic variables, market trends and behavioural factors. LLM significantly increase the ability of systems to analyse large volumes of unstructured information – from the texts of company reports to economic news and investor comments. This allows not only to identify risks faster, but also to form analytical conclusions that take into account the context, tone and economic significance of events. The key advantage of introducing LLM into financial analytics is a change in the approach to data processing. While financial systems previously relied mainly on quantitative indicators, now qualitative parameters such as market expectations, investor sentiment, social trends or reputational factors are also included in the modelling. This increases the accuracy of forecasts and reduces the information gap between analysts, business and the market. LLM also creates the basis for building explanatory analysis systems that not only predict, but also provide textual justification for their conclusions, which strengthens trust in automated decisions (Rao *et al.*, 2025).

Despite significant advantages, LLM integration has a number of critical limitations. Such models are extremely sensitive to data quality: if the sources contain incomplete or distorted information, the forecasting results may be inaccurate. LLMs remain difficult to interpret – even using Explainable AI, it is difficult to determine which factors have become decisive in the forecast. Large-scale implementation of such systems requires significant computing power and financial costs. In addition, ethical risks may arise in the training process – models can reproduce biases inherent in the initial data sets, or form false cause-and-effect relationships. To summarise the differences between the analytical potential and practical limitations of LLM, the key areas of their impact are highlighted, which are presented in Table 1.

Table 1. Analytical potential and challenges of integrating LLMs into financial analytics

Area of impact	Positive effects of integration	Key challenges and risks
Information analytics	In-depth analysis of textual and numerical data; detection of hidden patterns and correlations	High dependence on data quality; difficulty in verifying the reliability of sources
Market trend forecasting	Improved short-term forecasting accuracy through contextual data analysis	Risk of misinterpreting textual signals due to contextual ambiguity
Financial management	Automation of auditing, risk assessment, and investment decision-making	High computational costs for model training, adjustment, and maintenance

Area of impact	Positive effects of integration	Key challenges and risks
Decision explainability	Generation of transparent analytical reports with natural-language explanations	Limited interpretability of internal algorithms; difficulty in monitoring decision logic
Ethical security	Reduction of human bias and emotional influence in decision-making	Potential reproduction of algorithmic bias and risks of unauthorized data use

Source: compiled by author based on J. Rao *et al.* (2025), A.M. Beauty (2025)

Thus, LLMs expand the boundaries of financial analytics, combining machine data processing with contextual understanding of information. They create a new quality in financial decision-making, when forecasts are based not only on statistical patterns, but also on the economic logic of events. However, their implementation requires caution: it is necessary to form standards for verifying the reliability of data, develop algorithms for interpreting results, and ensure ethical responsibility in the use of such systems. In the future, it is the balanced integration of LLMs with traditional analytical methods that will become the basis for creating sustainable and transparent financial models that combine the depth of analysis with reliability and user trust.

Analysis of the impact of LLM on the efficiency of Azerbaijan's financial markets

In the context of the Azerbaijani financial system, the integration of LLMs and related AI systems has a significant impact on the transparency, efficiency and predictability of financial processes. This is primarily seen in the example of the Baku Stock Exchange (n.d.), where in 2024 the total trading volume reached AZN \approx 71.16 billion with more than 71.7 thousand transactions – an increase of more than twofold compared to the year 2023. This increase in market activity is partly explained by the digitalisation of processes, increased data availability and automation of analytical work, in which LLMs play a key role (Abdul, 2025). In particular, with regard to transparency, state strategies – Artificial Intelligence Strategy of the Republic of Azerbaijan for 2025-2028 (2025) – identify data digitalization, open reporting, and the use of SupTech solutions as key priorities. In 2025, the integration of Open Banking (13 banks) and the launch of SupTech tools allowed the regulator to conduct real-time supervision, increasing market transparency. According to the data, in 2024, non-cash transactions exceeded 90% of all domestic operations, which indicates a significant reduction in information asymmetry and an increase in the efficiency of financial processes. These changes provide the basis for studying the impact of LLM on efficiency (Javadov, 2025).

In terms of market efficiency and liquidity, the increase in trading volume and the reduction of transaction barriers demonstrate improved market dynamics. For example, the increase in trading volume from AZN 37 billion in the early period 2024 to over AZN 71 billion at the end of 2024 shows an increase in activity – this may be conditionally correlated with the increased analytical ability of systems that take into account not only traditional indicators, but

also contextual data (news, sentiment). In such an environment, LLMs can improve the predictability of changes: by processing text signals, they help identify indicators of future volatility, investment volumes or changes in the exchange rate (Information for media, 2024).

Regarding the predictability of key indicators, studies indicate that LLM integration into financial analytics allows for increased accuracy of forecasts of the exchange rate, deposit/loan rates and investment flows. For example, the analysis indicates that a 1-unit increase in Azerbaijan's ICT index is associated with a GDP increase of AZN \approx 1607 per capita, revealing the potential of digital technologies for macroeconomic change. This plus can be interpreted as an indirect effect of the increased analytics and transparency that LLM systems create (Huseynov *et al.*, 2025).

However, these advantages come with significant limitations. First, the Azerbaijani market has certain specific characteristics: a limited historical number of trades, low share capitalisation, and a relatively small number of issuers (for example, the Baku Stock Exchange (n.d.) has only 26 listed companies). This reduces the amount of data for training models and increases the risk of overtraining. Second, data transparency, although significantly improved, is still inferior to more developed markets—for example, delays in reporting, unstructured news or social media data can negatively affect the accuracy of LLM forecasts. Third, exogenous shocks—such as oil price fluctuations, geopolitical risks, or regulatory policy changes—create high levels of volatility that algorithms may not be able to adequately predict, especially if the model was trained during a quiet period (World Economic Forum, 2024).

In 2020-2024, Azerbaijan's GDP increased from AZN 72.4 billion to AZN 126.3 billion, which indicates significant economic growth. GDP per capita increased from USD 4272 in 2020 to USD 7251 in 2024, demonstrating the gradual stabilisation of the macroeconomic situation, despite periodic fluctuations in global energy markets. The share of the financial sector in the GDP structure during this period ranged from 21% to 25%, which confirms its significant role in the national economy. Household loans granted by financial institutions amounted to about 21% of GDP in 2024, while bank deposits remained at about 25.5% of GDP (Trading Economics, n.d.). These figures indicate high financial activity and a significant increase in confidence in the banking system. The dynamics of inflation in Azerbaijan in 2020-2024 reflects the consistent adaptation of monetary policy to external shocks and the introduction of digital financial technologies, which contributed to the stabilisation of price indicators (Fig. 1).

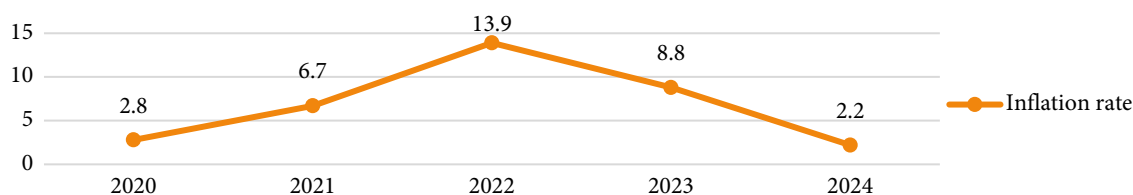


Figure 1. Inflation dynamics in Azerbaijan in 2020-2024

Source: compiled by author based on Azerbaijan inflation (n.d.)

The dynamics of inflation during 2020-2024 demonstrated the adaptability of monetary policy to external challenges. In 2020, inflation was 2.8%, in 2021 it increased to 6.7%, and in 2022 it reached a peak of 13.9%, which was due to global logistical problems and fluctuations in energy prices. After that, in 2023 the indicator decreased to 8.8%, and in 2024 to 2.2%, which indicates the effectiveness of the policy of the Central Bank of Azerbaijan, which kept the key rate within 5-7%. This positive trend reflects the stabilisation of the money market, the reduction of inflationary pressure, and the increase in the efficiency of financial processes as a result of the digitalisation of the banking sector. It confirms that the implementation of analytical systems and LLM technologies that allow for real-time forecasting contributes to a timely response to macroeconomic risks and the formation of a stable financial environment.

Due to the launch of the Azerbaijan Interbank Payment System (2025) Real-Time Interbank Settlement System and the Instant Payment System (IPS), the speed of transaction processing has decreased from several days to 5-20 seconds. This has contributed to increasing liquidity, reducing transaction costs and creating a continuous 24/7 financial cycle. In addition, the implementation of the international standard ISO 20022 (2022) has strengthened the integration capabilities of banking systems, improved the detection of anomalies in payment transactions and contributed to increasing customer confidence. The total volume of non-cash transactions has increased several times, and the number of transactions has reached hundreds of millions per year, which has turned Azerbaijan into a leader among the countries of the Caucasus region in the pace of development of digital financial services.

The improvement of digital infrastructure was also reflected in the growth of the ICT Development Index, which increased by approximately 7% in 2020-2025. The level of Internet penetration exceeded 80-88%, and the emergence of 5G and cloud services created the technical basis for the work of LLM. In particular, in the financial sector, these models are used to forecast the dynamics of the exchange rate, investment volumes and stock indices. In parallel with the increase in the efficiency of financial markets, the level of transparency is increasing. While the Transparency Index fell from 23 points in 2022 to 22 in 2024, the Open Data Index increased from 56 to 61 points, indicating a gradual improvement in the availability of official statistics. The development of SupTech and RegTech technologies has allowed regulators to analyse reporting in real time, reducing the risks of manipulation and delays (Lightspark Team, 2025).

In the field of external investment, the financial sector remains stable, although its share in the structure of total foreign direct investment is relatively small. In the first half of 2025, the total volume of FDI reached USD 3.2 billion, and the share of financial investments was several hundred million annually. The main investors – the United Kingdom, Turkey, Cyprus, Switzerland and Iran – are showing growing interest in the financial and technology sectors due to increasing transparency and regulatory effectiveness (CEIC, 2025). Digitalisation and the introduction of LLM in the financial sector of Azerbaijan have improved the operational efficiency, predictability and investment attractiveness of the market. Increasing the accuracy of analytical models, accelerating transaction processing and strengthening trust in the banking system have become key factors in the country's financial stability. The dynamics of inflation, which has been declining since 2022, clearly demonstrates how technological innovations and adaptive monetary policy contribute to macroeconomic stabilisation, creating a basis for the further development of the digital economy of Azerbaijan.

In countries with economies in transition, such as Azerbaijan, Kazakhstan, Uzbekistan and Georgia, these models are seen as a tool for automating analytical processes, increasing the accuracy of forecasts and improving risk management. However, it is in such conditions that the key limitations of LLM are revealed, related to incomplete data, legal barriers, as well as technological lags that reduce the predictive accuracy of models. Azerbaijan is witnessing an active integration of LLM and artificial intelligence systems in the banking sector. Leading financial institutions, in particular Kapital Bank (n.d.) and Bank ABB (n.d.), use machine learning algorithms for transaction monitoring, credit scoring, risk forecasting and fraud detection in real time. However, the effectiveness of LLM in post-Soviet markets is limited by a number of factors. First, financial data remains fragmented, often outdated or incomplete, and access to corporate reporting remains limited. Second, the legal environment in the Caucasus and Central Asia is characterised by high requirements for data localisation and low flexibility in regulating digital technologies. According to a report by Implement Consulting Group (2025), these factors constrain the implementation of generative AI models, including LLM, and reduce the potential benefits of automated analysis. In Azerbaijan itself, transparency remains low: The Corruption Perceptions Index is 22-23 out of 100, indicating limited independence of oversight and poor quality of public reporting. This leads to situations where

LLM models are trained on incomplete or poor-quality data, which raises the risk of “hallucinations” – that is, generating analytical conclusions that do not correspond to reality (The economic opportunity..., 2025).

In addition, institutional barriers and limited training of specialists reduce the ability of banks and regulators to effectively use the potential of models. Although Kazakhstan reports the use of AI in more than 30% of financial companies, and in Uzbekistan the government has planned the implementation of more than 100 AI projects in the banking sector, most of these initiatives are at the pilot stage (National Bank of Kazakhstan, 2024; Ismailov, 2025). The region still lacks reliable mechanisms for monitoring data quality and standardising financial information. LLMs demonstrate high potential in the field of financial forecasting, in particular in the automation of market monitoring, creditworthiness assessment and macroeconomic forecasting. However, in less transparent markets, their effectiveness is limited not so much by technical as by structural factors – lack of data, underdeveloped digital infrastructure and institutional risks. To unlock the full potential of LLMs, post-Soviet countries need to expand data openness, harmonise the regulatory framework and invest in the development of human capital in the field of financial analytics and artificial intelligence. It is these steps that will determine whether LLMs can move from an experimental tool to a systemic element of financial management.

Discussion

Within modern financial research, there is a clear trend towards combining econometric methods with artificial intelligence algorithms, forming a new paradigm of hybrid modelling. Such approaches allow us to simultaneously take into account the linear patterns inherent in classical statistical models and reveal hidden nonlinear relationships using neural networks. This study demonstrated the consistent evolution of hybrid financial modelling, where classical econometric tools are gradually combined with artificial intelligence algorithms. A similar methodological connection was observed between this study and the work of O. Elebe *et al.* (2022). Both approaches justified the need to combine econometric and machine learning methods for modelling volatile markets. In O. Elebe *et al.* (2022), attention was paid to forecasting financial risks in African countries, where political instability and socio-economic factors created high uncertainty. The authors combined stochastic models with random forest and support vector machine (SVM) methods, achieving a significant reduction in forecast error. In contrast, the considered study applied hybridisation in the conditions of information constraints of Azerbaijan, emphasising data scarcity, low transparency and technological inequality. As a result, the effectiveness of hybrid approaches was confirmed, but taking into account the fact that their effectiveness in transforming markets is determined not only by technical, but also by institutional prerequisites.

Further confirmation of the effectiveness of hybrid approaches is reflected in the comparison with the work

of R.K. Ghosh *et al.* (2025). In both cases, it was emphasised that classical models – ARIMA, VAR, GARCH – have limitations in reproducing nonlinear market patterns, which are more fully reflected by neural networks. While R.K. Ghosh *et al.* (2025) created a technically optimised hybrid model for forecasting exchange rates in South Asia by combining LSTM and Bi-GRU, this study focused on studying the impact of LLM in a macroeconomic context. Common to both works was the idea that forecast accuracy increases due to the combination of deep learning and econometric tools, but in a different environment – technologically advanced in R.K. Ghosh *et al.* (2025) and structurally limited in the current study. A similar logic was also observed in the comparison with the study of O.M. Pires *et al.* (2024). Both works emphasised the role of hybrid models that combined ARIMA, GARCH or VAR with deep networks (LSTM, GRU, CNN). However, O.M. Pires *et al.* (2024) focused on modelling volatility and risks of investment portfolios in stable market conditions in Spain and Portugal. Instead, this study shifted its emphasis to adapting similar approaches to environments with a lower level of digitalisation and information openness. While O.M. Pires *et al.* dominated the technical aspect, here the main focus was on the economic specificity and real barriers to implementing intelligent models in financial practice in transition economies.

The most conceptually close comparison was with the work of M. Rudolph *et al.* (2024). Both studies were based on the idea of combining models based on first principles with machine learning algorithms. However, if M. Rudolph *et al.* (2024) developed six universal hybrid model design patterns and demonstrated their effectiveness in physical, climate, and engineering problems, the current study adapted this methodology to the economic context. It demonstrated that the same integration principles can be effective in financial analytics, given the constraints of data quality, the level of institutional support, and the digital maturity of the system.

In approaches to financial forecasting, there is a gradual transition from purely statistical to hybrid models, where classical econometric tools are combined with artificial intelligence algorithms. This was observed both in this study and in the work of B. Han *et al.* (2025). Both works proceeded from the fact that traditional models are unable to adequately describe nonlinear market dependencies. In B. Han *et al.* (2025), this idea was implemented by creating a hybrid GARCH-LSTM model for forecasting bitcoin volatility. The combination of stochastic stability and deep learning made it possible to reduce the forecast error by almost 50%. Instead, the present study transferred the concept of hybridisation to a broader economic context, using LLM to increase the transparency of financial processes in Azerbaijan. If in B. Han *et al.* (2025) analysis was based on stable crypto market data, here the focus was on institutional factors – data quality, levels of digitalisation and regulatory barriers that determined the effectiveness of such models in post-Soviet countries.

The development of this idea can also be traced in the study of Y.E. Gür *et al.* (2025), where artificial intelligence became a tool for improving the accuracy of credit scoring. The authors combined CNN with classical algorithms – K-Nearest Neighbors, SVM, Linear Discriminant Analysis and Naive Bayes, achieving accuracy of over 99% when classifying credit ratings. In contrast to this micro-level approach, the current study focused on macroeconomic forecasting for the analysis of financial stability. While the main emphasis was on the technical perfection of algorithms, in this case, the focus was on how institutional constraints, the lack of quality data, and low transparency affect the performance of analytical systems. Thus, both approaches demonstrated a desire for synergy between classical and neural methods, but at different scales – from assessing the risks of individual creditors to systemic analysis of financial stability.

A similar logic was observed in the study by F. Xing *et al.* (2025), which showed that artificial intelligence should not replace financial models, but expand their capabilities. The authors combined NLP and LLM with classical concepts – Capital Asset Pricing Model, Mean-Variance Optimisation, and the Black-Litterman Model – to integrate textual, behavioural, and market signals. This approach increased the accuracy of forecasts while maintaining the interpretability of the models. A similar idea was implemented in the current study, where the combination of ARIMA, GARCH, VAR with LSTM, Transformer and LLM allowed to reproduce the dynamics of macroeconomic processes in Azerbaijan. At the same time, the difference was in the context: while F. Xing *et al.* (2025) considered global financial markets, this study analysed the effectiveness of such approaches in an environment with limited digital infrastructure and incomplete data, emphasising the dependence of AI on institutional conditions.

A study by M. Rath & H. Date (2025) was also close in approach, demonstrating the practical potential of hybrid architectures in the field of risk management. They combined ARIMA, GRU, SVM and Explainable AI, which allowed to forecast liquidity and manage risks in Indian financial markets. Both approaches – both M. Rath & H. Date (2025) and this study – were based on a common thesis: AI should complement financial theory, ensuring analytical accuracy without losing transparency. However, while M. Rath & H. Date (2025) focused on adapting models to developing countries, this study went a step further by showing how such technologies contribute to strengthening financial stability in post-Soviet economies. In the work of J. Zhou (2025), another but related dimension of the use of artificial intelligence is proposed – the use of AI-driven agents and transformers for forecasting market behaviour and portfolio management. These models combined quantitative and behavioural parameters, using reinforcement learning to adapt forecasts in real time. Compared to this approach, this study had a macroeconomic focus, but a common feature remained the desire to combine the analytical depth of econometric models with the flexibility

of AI. While J. Zhou (2025) focused on markets with high data availability, the current work considered the issues of data scarcity and institutional instability, emphasising the limits of the application of such systems in countries with economies in transition.

And in the work of C. Gargalo *et al.* (2024) a universal methodology for building hybrid models was proposed – from technical systems to financial analytics. The authors developed modelling patterns that combined first-principles methods with machine learning algorithms, ensuring structural flexibility and reproducibility. In contrast to this generalised approach, in the current study, hybridisation had an applied dimension: it allowed to assess the real impact of LLM on forecasting in a specific economic environment. Thus, while C. Gargalo *et al.* (2024) presented the theoretical basis for building hybrid systems, the present study provided a practical illustration in the financial context of post-Soviet states. The comparative analysis demonstrated that hybrid financial models are gradually becoming a universal forecasting tool, capable of providing a balance between accuracy, flexibility and interpretability. Their effectiveness was determined not only by the technological component, but also by the quality of data, the institutional environment and the level of digital maturity of the market. In stable economies, hybrid architectures have proven their effectiveness at the technical level, while in countries with low transparency and limited data, they have gained analytical value as a tool for identifying structural imbalances.

Conclusions

The study showed that the implementation of LLM in financial analytics in Azerbaijan has a significant impact on increasing the efficiency, transparency and predictability of financial processes. The country's economic dynamics in 2020-2024 confirmed the close relationship between digitalisation, the development of artificial intelligence and the growth of macroeconomic indicators. During this period, Azerbaijan's GDP increased from AZN 72.4 billion to AZN 126.3 billion, and GDP per capita from USD 4,272 to USD 7,251, which indicates active economic growth and increased stability of the financial system. At the same time, the share of the financial sector in the GDP structure reached 21-25%, and the volume of loans to the population amounted to 21% of GDP, which demonstrates the expansion of access to financial services and the growth of trust in the banking system. The integration of digital technologies and LLM contributed to the growth of non-cash transactions to over 90% of all domestic transactions and the reduction of interbank settlement time to 5-20 seconds due to the Azerbaijan Interbank Payment System. This increased liquidity and reduced transaction costs, while ensuring a 24-hour financial cycle. The implementation of the international standard ISO 20022 (2022) strengthened the ability of banking systems to detect anomalies and improved interaction with international financial structures. Positive macroeconomic dynamics are confirmed by the decrease in inflation from a peak of 13.9% in 2022 to 2.2% in 2024, which

was the result of effective monetary policy and the use of analytical models capable of predicting risks in real time.

A strong digital infrastructure – with a 7% rise in the ICT index and internet coverage reaching 80-88% – created the basis for LLM implementation. Data openness improved, as shown by the Open Data Index growth from 56 to 61 points, while the Baku Stock Exchange's trading volumes doubled from AZN 37 to AZN 71 billion in 2024, reflecting the effect of automated analytics on liquidity and activity. However, the study revealed that LLM performance depended on data quality and completeness: only 26 listed companies, scarce historical data, and low transparency (22-23 CPI points) limited model accuracy. The key challenges remain improving reporting standards, data openness, and ethical regulation of AI use. A limitation of this study was that the analytical assessment of the

effectiveness of LLM was conducted on the basis of secondary statistical data, limited in time frame and the level of transparency of Azerbaijan's financial reporting. A prospect for future research is the development of empirical models using primary data from banking and investment institutions to more accurately assess the impact of LLM on the stability of financial markets in transition economies.

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Conflict of Interest

None.

References

- [1] Abayomi, A.A., Sharma, A., Adekunle, B.I., Ogeawuchi, J.C., & Onifade, O. (2023). Integrating machine learning algorithms in financial modeling: Evaluating accuracy and market impact. *International Journal of Management and Organizational Research*, 2(2), 117-123. doi: 10.54660/IJMOR.2023.2.2.183-189.
- [2] Abdul, N. (2025). *Baku stock exchange reports annual loss amid financial decline*. Retrieved from <https://surli.cc/ihhrap>.
- [3] Abdullayev, L., Ismailova, L., Rustamova, G., Boyukkishi, N., & Ahmadova, E. (2025). Innovative approaches to financial security in business management: Case study of Azerbaijan. *Intellectual Economics*, 19(1), 159-183. doi: 10.13165/IE-25-19-1-07.
- [4] Ahmadova, E. (2022). Modeling and analysis of the economic development of Azerbaijan based on the production function. *Proceedings of CBU in Economics and Business*, 3, 1-5. doi: 10.12955/peb.v3.283.
- [5] Avacharmal, R. (2023). [Hybrid AI/ML models that combine the strengths of different algorithms for improved performance and efficiency in financial risk management](#). *International Journal of Applied Engineering and Technology*, 5(2), 67-74.
- [6] Azerbaijan inflation. (n.d.) Retrieved from <https://www.focus-economics.com/country-indicator/azerbaijan/inflation/>.
- [7] Baku Stock Exchange. (n.d.). *Overview*. Retrieved from <https://surl.li/esfeqa>.
- [8] Bank ABB. (n.d.). *Investor relations*. Retrieved from <https://abb-bank.az/en/investorlarla-elaje>.
- [9] Beauty, A.M. (2025). Explainable AI in data-driven finance: Balancing algorithmic transparency with operational optimization demands. *International Journal of Research Publication and Reviews*, 2(6), 125-149. doi: 10.55248/gengpi.6.0625.2176.
- [10] CEIC. (2025). *Azerbaijan foreign direct investment*. Retrieved from <https://surl.li/yjsizn>.
- [11] Celik, B.A., & Celik, S. (2025). Hybrid forecasting of agricultural commodity prices: Integrating machine learning, time series, and stochastic simulation models. *Borsa Istanbul Review*, 25(6), 1440-1462. doi: 10.1016/j.bir.2025.10.004.
- [12] Elebe, O., Imediegwu, C.C., & Filani, O.M. (2022). Predictive financial modeling using hybrid deep learning architectures. *International Journal of Multidisciplinary Research and Growth Evaluation*, 3(2), 859-872. doi: 10.54660/IJMRGE.2022.3.2.859-872.
- [13] Gargalo, C.L., Malanca, A.A., Aouichaoui, A.R., Huusom, J.K., & Gernaey, K.V. (2024). Navigating Industry 4.0 and 5.0: The role of hybrid modelling in (bio)chemical engineering's digital transition. *Frontiers in Chemical Engineering*, 6, article number 1494244. doi: 10.3389/fceng.2024.1494244.
- [14] Ghosh, R.K., Gupta, B.K., Nayak, A.K., & Ghosh, S.K. (2025). Deep learning-based hybrid model with multi-head attention for multi-horizon stock price prediction. *Journal of Risk and Financial Management*, 18(10), article number 551. doi: 10.3390/jrfm18100551.
- [15] Guntupalli, R., Pradeepkumar, S.K.B., Duddeti, B.B., Ankireddy, N., Meena, V.P., & Jadoun, V.K. (2025). A hybrid ANN-AHP-GIS framework with dimensionality reduction and uncertainty quantification for solar site selection in Southern India. *Energy Conversion and Management: X*, 28, article number 101280. doi: 10.1016/j.ecmx.2025.101280.
- [16] Gür, Y.E., Toğaçar, M., & Solak, B. (2025). Integration of CNN models and machine learning methods in credit score classification: 2D image transformation and feature extraction. *Computational Economics*, 65, 2991-3035. doi: 10.1007/s10614-025-10893-5.

- [17] Han, B., Liu, A., Chen, J., & Knottenbelt, W. (2025). Can machine learning models better volatility forecasting? A combined method. *The European Journal of Finance*. doi: 10.1080/1351847X.2025.2553053.
- [18] Huseynov, A., Balsalobre-Lorente, D., Hamidova, L., & Samedova, E. (2025). Challenges and opportunities of digital economy development: Case of Azerbaijan. *Problems and Perspectives in Management*, 23(2), 265-276. doi: 10.21511/ppm.23(2).2025.18.
- [19] Information for media. (2024). Retrieved from <https://surl.li/sedmca>.
- [20] Ismailov, K. (2025). *Uzbekistan advances AI development with legal framework and pilot projects*. Retrieved from <https://www.trend.az/business/4106889.html>.
- [21] ISO 20022. (2022). *Financial services – universal financial industry message scheme*. Retrieved from <https://www.iso20022.org/>.
- [22] Javadov, S. (2025). *Azerbaijan launches open banking functionality*. Retrieved from <https://www.trend.az/business/4100139.html>.
- [23] Kapital Bank. (n.d.). *About bank*. Retrieved from <https://www.kapitalbank.az/en/reports>.
- [24] Kumar, S., Rao, A., & Dhochak, M. (2025). Hybrid ML models for volatility prediction in financial risk management. *International Review of Economics & Finance*, 98, article number 103915. doi: 10.1016/j.iref.2025.103915.
- [25] Lightspark Team. (2025). *Azerbaijan instant payments: Rails, fees, and the lightning network*. Retrieved from <https://surl.li/sjissy>.
- [26] Liu, Z., Zhang, Z., & Zhang, W. (2025). A hybrid framework integrating traditional models and deep learning for multi-scale time series forecasting. *Entropy*, 27(7), article number 695. doi: 10.3390/e27070695.
- [27] National Bank of Kazakhstan. (2024). *The report “Artificial Intelligence in the financial market of Kazakhstan” was published*. Retrieved from <https://nationalbank.kz/en/news/informacionnye-soobshcheniya/16693>.
- [28] Pires, O.M., Noobloth, M.Q., Silva, Y.A.C., da Silva, M.H., Galvão, L.Q., & Albino, A.S. (2024). Synthetic data generation with hybrid quantum-classical models for the financial sector. *European Physical Journal B*, 97, article number 178. doi: 10.1140/epjb/s10051-024-00786-1.
- [29] Rao, J., & Zhang, Q. (2025). Deep learning with LLM: A new paradigm for financial market prediction and analysis. *International Journal of Multidisciplinary Research and Growth Evaluation*, 6(2), 211-215. doi: 10.54660/IJMRGE.2025.6.2.211-215.
- [30] Rath, M., & Date, H. (2025). Quantum powered credit risk assessment: A novel approach using hybrid quantum-classical deep neural network for row-type dependent predictive analysis. *EPJ Quantum Technology*, 12, article number 75. doi: 10.1140/epjqt/s40507-025-00323-8.
- [31] Ravi, V., Srivastava, V.K., Singh, M.P., Chippagiri, S., Kassetty, N., Vardhineedi, P.N., Burila, R.K., & Prova, N.N.I. (2025). Large language models (LLMs) for financial sentiment analysis and market forecasting. In *Proceedings of the 2nd international conference on sustainable business practices and innovative models (ICSBPIM-2025)* (pp. 681-694). Dordrecht: Atlantis Press. doi: 10.2991/978-94-6463-872-1_43.
- [32] Rudolph, M., Kurz, S., & Rakitsch, B. (2024). Hybrid modeling design patterns. *Journal of Mathematics in Industry*, 14, article number 3. doi: 10.1186/s13362-024-00141-0.
- [33] Shafizada, E., & Aslanova, N. (2022). Innovative approaches to model and forecast of Azerbaijan’s economic growth. *Marketing and Management of Innovations*, 2, 198-208. doi: 10.21272/mmi.2022.2-18.
- [34] Frank, L., & Owen, J. (2024). *Hybrid models combining machine learning and econometric techniques*. Retrieved from https://www.researchgate.net/publication/383817571_Hybrid_Models_Combining_Machine_Learning_and_Econometric_Techniques.
- [35] Stempień, D., & Slepaczuk, R. (2025). Hybrid models for financial forecasting: Combining econometric, machine learning, and deep learning models. *ArXiv*. doi: 10.48550/arXiv.2505.19617.
- [36] The artificial intelligence strategy of the Republic of Azerbaijan for 2025-2028. (2025). Retrieved from <https://dig.watch/resource/the-artificial-intelligence-strategy-of-the-republic-of-azerbaijan-for-2025-2028>.
- [37] The economic opportunity of AI in Caucasus and Central Asia: Capturing the next wave of benefits from generative AI. (2025). Retrieved from <https://cms.implementconsultinggroup.com/media/uploads/articles/2025/The-economic-opportunity-of-ai-in-caucasus-and-central-asia/The-economic-opportunity-of-AI-in-Caucasus-and-Central-Asia.pdf>.
- [38] Trading Economics. (n.d.). *Azerbaijan GDP*. Retrieved from <https://tradingeconomics.com/azerbaijan/gdp>.
- [39] World Economic Forum. (2024). *IDEA: Investing in the Digital Economy of Azerbaijan*. Retrieved from https://www3.weforum.org/docs/WEF_IDEA_Investing_in_the_Digital_Economy_of_Azerbaijan_2024.pdf.
- [40] Xing, F., Du, K., Mengaldo, G., Cambria, E., & Welsch, R. (2025). AI reshaping financial modeling. *npj Artificial Intelligence*, 1, article number 29. doi: 10.1038/s44387-025-00030-w.
- [41] Zhou, J. (2025). Quantum finance: Exploring the implications of quantum computing on financial models. *Computational Economics*. doi: 10.1007/s10614-025-10894-4.

Гібридні підходи до фінансового моделювання: інтеграція класичних стохастичних моделей з машинним навчанням

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Анотація. Метою цього дослідження було оцінити потенціал великих мовних моделей у підвищенні точності фінансових прогнозів та стабільності ринку в країнах з перехідною економікою, зокрема в Азербайджані. Методологія визначила суть гібридних підходів до фінансового моделювання, які поєднують класичні економетричні інструменти, такі як авторегресійна інтегрована ковзна середня та векторна авторегресія, з алгоритмами глибокого навчання. В результаті було встановлено, що обсяг торгів на Бакинській фондовій біржі зріс з 37 до 71 млрд манатів у 2024 році, валовий внутрішній продукт зріс з 72,4 до 126,3 млрд манатів, а рівень інфляції знизився з 13,9 % у 2022 році до 2,2 % у 2024 році. Частка безготівкових операцій перевищила 90 %, а час міжбанківських розрахунків скоротився до 5-20 секунд завдяки впровадженню Азербайджанської міжбанківської платіжної системи. Індекс розвитку інформаційно-комунікаційних технологій зріс на 7 %, а індекс відкритих даних збільшився з 56 до 61 бала, створивши основу для ефективної цифрової аналітики. Дослідження показало, що ефективність великих мовних моделей була обмежена низькою прозорістю фінансової звітності, наявністю лише 26 компаній, зареєстрованих на фондовій біржі, та індексом сприйняття корупції на рівні 22-23. Практичне значення цього дослідження полягає в тому, що його результати можуть бути використані фінансовими аналітиками, урядовими органами та банківськими регуляторами в Азербайджані для розробки стратегій цифрової трансформації фінансового сектору та впровадження аналітичних систем на основі великих мовних моделей

Ключові слова: прогнозування; цифровізація; макроекономіка; штучний інтелект; ліквідність; інвестиції

Economic aspects of projects based on the Internet of Things

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Abstract. The aim of this study was to examine how the implementation of Internet of Things (IoT) technologies influences economic performance by evaluating their effects on efficiency, cost reduction, and the transformation of business processes. The methodology relied on theoretical analysis of scientific sources, content analysis of technical descriptions, comparative evaluation of corporate cases, and sector-specific analytical approaches. The results showed that the IoT provides a substantial and stable increase in efficiency across sectors. In industry, digitalisation reaches 57.5%, manual actions decrease by 40-60%, and labour costs fall by about 25%. Predictive maintenance lowers unplanned downtime by 25-35% and raises productivity by 20-30%. In logistics, intelligent routing reduces transportation costs by 10-25% and delivery time by 20-25%. In agriculture, drones and sensors cut agrochemical use by 30-45% and water consumption by up to 90%, with yields increasing by 15-30%. In the energy sector, smart meters reduce electricity consumption by 2.5-3.5% and Smart Grid systems reduce network losses by 15-25%. At the macro level, the digital economy in Organisation for Economic Cooperation and Development countries grew 2.5 times faster than gross domestic product, while a 10-percentage-point increase in IoT connectivity raised total factor productivity by 0.23 percentage points. The study also identified barriers to implementation, including limited interoperability, missing standards, security risks, a shortage of specialists, unstable regulation and high investment and operating costs with uncertain returns. Enterprises and public institutions to improve efficiency and optimise resource use can apply the results

Keywords: digital infrastructure; sensor networks; real-time data; operational efficiency; investment; cybersecurity

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Introduction

The expansion of connected devices and data-driven automation is transforming production systems, urban infrastructure, logistics, healthcare, and consumer services. As companies intensify the deployment of sensor networks, cloud platforms, and intelligent monitoring tools, the economic consequences of these transformations become increasingly significant. In the digital environment, a gap persists between the rapid diffusion of technologies and the readiness of economic and social systems to integrate them. K. Abdullayev *et al.* (2024) showed that, despite notable progress in Azerbaijan's digital infrastructure, challenges remain-uneven Internet access, limited digital literacy, cyber risks and the need for stronger regulatory mechanisms. The authors noted that infrastructure upgrades, expanded e-services, digital public administration and support for innovation can accelerate economic development and modernise business processes. T. Guluzade (2025) highlighted that technological renewal in Azerbaijan is uneven, with regional disparities, a shortage of specialists, and increased cybersecurity demands, yet state strategies, e-government, fintech growth, wider telecommunications networks and platforms such as Azerbaijan Service and Assessment Network and myGov have significantly improved transparency and reduced administrative burdens. T.T. Aslanova *et al.* (2024) emphasised that expanding digital platforms, innovative technologies and e-government tools enhances productivity, reduces shadow activity, strengthens business competitiveness, improves financial mechanisms and simplifies administrative procedures.

In economic systems, a gap persists between the rapid spread of Internet of Things (IoT) technologies and the capacity of institutions and businesses to integrate them into production and management. D. Singhal *et al.* (2024) showed that IoT reshapes economic processes by increasing the role of data, intelligent systems and automated monitoring, altering cost structures and enabling productivity gains in finance, transport, logistics, agriculture, energy and urban services. The authors demonstrated that IoT reduces downtime and operating costs, improves service quality and optimises resource use, with notable effects in predictive maintenance, secure transactions, smart city infrastructure, precision agriculture and automated energy management. C. Huang *et al.* (2024) highlighted that IoT transforms household and infrastructure systems by enhancing energy efficiency, lowering operational expenses and creating opportunities for new technology-driven employment. Despite technological progress, IoT adoption in construction remains slow due to fragmented management and weak standardisation. M. Massoud *et al.* (2025) showed that IoT integration in sustainable construction is constrained by technical incompatibility, security limitations, organisational unpreparedness and skill shortages; using Exploratory Factor Analysis, Structural Equation Modelling (SEM) and Artificial Neural Network (ANN), the authors identified five

barrier groups: connectivity difficulties, knowledge gaps, limited resources, organisational uncertainty and insufficient competencies.

In the context of digital transformation, there are significant challenges in ensuring consistency between the rapid development of technologies and the ability of organisations to integrate e-commerce tools, Radio Frequency Identification, automated systems, IoT and mobile platforms into daily operations. The study by K. Yogen Sevak & B. George (2024) demonstrated that the growing role of digital technologies is significantly changing the economic interaction between producers, consumers and logistics structures. The authors emphasise that IoT technologies, artificial intelligence (AI), big data and blockchain are shaping new models of value creation, increasing process efficiency and contributing to the emergence of innovative products and services.

In the field of IoT research, there is insufficient attention to how IoT technologies are changing circular economy models and affecting the environmental and economic performance of enterprises. X. Sun & X. Wang (2022), who showed that the integration of IoT technologies enhances operations related to life cycle design, green manufacturing, recycling, and remanufacturing, which in turn improves the environmental and economic performance of enterprises, has already addressed the impact of IoT on mechanisms for resource reuse, waste reduction, and business sustainability. The authors demonstrated that IoT contributes to more efficient management of resource flows, increases transparency, and supports the implementation of sustainable production systems. Further study is needed to quantify the economic efficiency of digital and IoT solutions, the long-term consequences of their implementation, the impact on structural changes and behaviour of market participants, issues of cybersecurity, standardisation, regulatory support, and factors that determine the readiness of organisations for digital transformation. The purpose of this study was to identify the key economic consequences of the implementation of IoT technologies and assess their impact on the efficiency, costs, and structure of modern business processes.

Materials and Methods

The study was theoretical in nature and was based on a targeted study of scientific literature, technical materials and analytical sources describing the architecture, economic characteristics and systemic effects of the implementation of the IoT in various sectors of the economy. To form the source sample, the criteria of relevance (2018-2025), scientific verifiability, availability of technical descriptions and economic parameters of IoT solutions were applied. The analysis included scientific articles, technical reports, corporate cases, and statistical reviews, and quantitative indicators were used as illustrative material for the analytical interpretation of the qualitative characteristics of technologies. The conceptual principles of the functioning of IoT

in the digital economy were determined through the analytical interpretation of the scientific works of D. Tsipianitis *et al.* (2025) and K. Do *et al.* (2025), which made it possible to reconstruct the logic of building sensor networks, digital platforms, data flows and algorithmic modules, as well as to clarify the role of IoT as a structural element of economic digitalisation. The classification of IoT solutions was examined using the materials of A1 Digital (2025) through a structural-systematisation method, which enabled the identification and grouping of key categories of industrial, transport, energy, agricultural and urban systems, as well as the determination of their functional and architectural characteristics relevant for production and economic environments.

The economic characteristics of IoT projects were examined using the source N. Abebe *et al.* (2025) to identify the underlying patterns of cost formation, reconstruct the structure of integration and capital expenditures, and assess the contribution of cybersecurity requirements to total project costs, which enabled the development of a generalised cost model for IoT solutions. The efficiency and scaling effects of IoT were examined using the structural-analytical method based on the conceptual framework of A. Jarašūnienė *et al.* (2023), which made it possible to generalise how IoT influences productivity, operational performance and cost dynamics as device networks and data volumes expand. The life cycle of IoT projects was processed according to S. Rathore (2025) by functional-structural analysis, which made it possible to track the sequence of phases of development, integration, operation and technical support, as well as to determine at which stages the greatest economic effects occurred.

The level of automation achieved through IoT implementation was evaluated using a quantitative content-analysis approach based on the data presented by R. Daws (2025), which made it possible to identify the extent to which manual operations decrease and digital process integration expands after adopting IoT solutions. The indicators of productivity change were identified using a quantitative descriptive method applied to the data provided in S. Zoting & A. Shivarkar (2025). Environmental benefits, including energy efficiency, emission reduction, resource optimisation and the formation of circular models, were analysed according to A. Addas *et al.* (2024) using a qualitative analytical method.

The industrial sector was examined using a sector-focused content-analysis method based on the publications of A. Ramanenkava (2025) and Y. Sapra (2025), which enabled the identification of IoT-driven mechanisms of process automation, predictive maintenance, production environment control and defect reduction by analysing quantitative indicators of automation levels, downtime reduction, labour cost savings and quality improvement presented in these sources. Case materials Siemens MindSphere (Holmes, 2018) and Bosch (Ten years of Industry 4.0, n.d.) were used to reconstruct real practices of industrial use of IoT. Transport applications were studied based

on a comparative analysis of corporate cases Unilever and DHL. This allowed to describe the principles of IoT routing, dynamic adjustment of logistics routes, monitoring of the technical condition of the fleet and monitoring driver behaviour using the examples of Walmart and Maersk (CodeXTeam, 2024). The use of materials Farnell (Amazon – a prime..., n.d.) made it possible to recreate the mechanisms of warehouse automation and digital inventory, while the sources Huawei (Tianjin port: Building..., n.d.) allowed to investigate the operation of sensor systems for monitoring port operations and managing cargo flows. These cases were selected because they represent well-documented and illustrative real-world implementations of IoT across different sectors, allowing for a comprehensive reconstruction of practical mechanisms of automation, monitoring and digitalised logistics. In the energy sector, a technical and organisational analysis was applied using the Department of Energy Security of the United Kingdom (2024) to describe the principles of operation of “smart meters” and algorithms for automated load management. The Siemens Energy case was analysed to examine how IoT-based remote monitoring and automated maintenance workflows are implemented in real industrial settings, enabling a deeper understanding of practical mechanisms of equipment diagnostics and operational optimisation (Siemens energy builds..., 2024). For the agricultural sector, an analytical-structural approach was used based on Indeema (How are drones..., 2025), which made it possible to describe sensor systems, IoT drones, precision farming algorithms and crop monitoring technologies. The analysis of urban infrastructure was carried out through a technical-functional method using materials of the AGC Lighting (2023), which provided a characterisation of adaptive light emitting diode algorithms and IoT integration with Heating, Ventilation, and Air Conditioning systems.

Macroeconomic analysis was carried out using the comparative analytical method based on O. Chang & J. Hsiao (2025), which made it possible to evaluate the contribution of digital technologies and IoT to GDP growth in Organisation for Economic Cooperation and Development (OECD) countries, the EU, the USA and China. These regions were selected because they represent the world's largest and most data-rich digital economies, allowing for reliable comparison of IoT-driven macroeconomic effects. Report of the OECD (2024) was used to analyse information and communication technologies (ICT) development dynamics through the ICT index, while report of the ITU (2025) served to assess how IoT penetration affects productivity indicators. Publications by H. Edquist *et al.* (2019) and H. Sloan (2024) were applied to reconstruct and quantify the macroeconomic mechanisms of IoT influence – specifically, to analyse how changes in productivity, cost structures, and resource efficiency translate into GDP and total factor productivity growth, based on empirical coefficients and macro-level estimations. The source by Yu. Shamrei (2024) was used to identify and compare the

economic sectors that generate the highest aggregate contribution to GDP, which provided the basis for selecting priority industries for deeper sectoral analysis.

The functioning of technical and organisational barriers to IoT scaling was analysed using a regulatory-analytical method involving international standards IEEE 2413-2019 (2020), IEEE 802.15.4-2011 (2011), ISO/IEC 27001:2022 (2022), and ISO/IEC 30141:2024 (2024). Additional aspects of cybersecurity and interoperability were assessed based on the ISA/IEC 62443 series of standards (n.d.) and ETSI EN 303 645 V3.1.3 (2024). The identification of IoT implementation barriers was carried out using a regulatory-analytical method, based on the interpretation of empirical evidence and conceptual classifications presented in A. Alenizi & K. Al-Karawi (2023) and S. Madanian *et al.* (2024). This approach made it possible to systematise constraints into five key groups-technical, cybersecurity, human-resource, regulatory, and economic barriers-which served as the basis for further analysis of risks and their influence on IoT scalability. The prospects for sustainable IoT development were determined using a conceptual and analytical method through the interpretation of the potential of circular models, energy optimisation, Smart Grid and AI integration.

Results

Theoretical and economic foundations of the functioning of IoT technologies

The IoT is one of the key technological platforms of the digital economy, which provides integration of physical objects with digital systems using sensors, communication modules and data processing algorithms. In the most general definition, IoT is a network of interconnected devices capable of collecting, transmitting and analysing information without direct human intervention. This is a transition from the traditional model, where data was collected periodically and manually, to an ecosystem of continuous monitoring and automated decision-making. IoT provides an environment in which real-world objects – from household appliances to industrial equipment – become active participants in digital processes and form new economic mechanisms of interaction (Tsipianitis *et al.*, 2025).

The functioning of IoT is based on several basic principles: automated data collection using sensors, information transmission via communication networks, data processing in cloud or peripheral computing systems, generation of control signals and integration with other digital platforms. At the technological level, this means a combination of hardware components (sensors, controllers, gateways), communication protocols (Wi-Fi, Bluetooth, low-power wide-area network, 5G), software (analytical platforms, forecasting systems, visualisation modules) and cyber protection mechanisms. Such an architecture make it possible to form complex multi-level systems in which data is transformed into a key economic resource that determines the efficiency of processes, productivity and speed of decision-making (Do *et al.*, 2025).

The classification of IoT covers several dimensions. By scope of application, industrial IoT, household (smart homes), transport (intelligent transport systems), medical, agricultural, energy (Smart Grid) and urban (Smart City) are distinguished. Each category has specific technical requirements and economic mechanisms, but they are united by the ability to create added value through increased accuracy of operations, automation, resource savings and integration with other digital tools. From the point of view of architecture, there are edge, cloud and hybrid IoT systems, which differ in the way data is processed and the level of autonomy. At the same time, in the digital economy it is important to consider the classification by business models: subscription-based service solutions, data-driven models, “product as a service” and ecosystem platforms that connect manufacturers, consumers and developers (AI Digital, 2025).

The economic characteristics of IoT projects are formed at the intersection of three key dimensions: cost structure, efficiency and scalability parameters, as well as the features of the solution life cycle. Unlike traditional IT projects, where the main emphasis is on software and licenses, in the case of IoT, a significant share of costs is made up of physical devices (sensors, controllers, and gateways), network components, integration with existing systems and cyber protection. Initial investments include the purchase of equipment, deployment of network infrastructure, configuration of a platform for data collection and analytics, integration with business processes, as well as personnel training costs. Subsequent operating costs include maintenance, firmware updates, security support, data storage and processing in cloud or hybrid environments. As a result, the cost structure of an IoT project combines a significant amount of capital expenditure at the start with a gradual increase in operating expenses during operation, which requires the use of valuation models based on total cost of ownership and taking into account the full life cycle of the solution (Abebe *et al.*, 2025).

The assessment of the effectiveness of IoT projects is based on a combination of financial and non-financial indicators. Key economic parameters include reduced operating costs, reduced equipment downtime, increased labour productivity, reduced resource losses, increased revenue from new services, and improved customer service. At the enterprise level, the effects of IoT implementation are manifested in more accurate planning, predictive maintenance, logistics automation, energy-efficient management, and reduced risk of accidents or shortages. For quantitative assessment, return on investment, net present value, internal rate of return, as well as specialised metrics related to productivity and resource savings are used. An important aspect is scalability: as the number of connected devices and the volume of data expand, the average cost per device and unit of data tends to decrease, while the overall economic effect increases due to scale and network effects. At the same time, scaling requires a reliable network infrastructure, the ability of platforms to process large amounts of data in real time, and the availability of

standards that ensure the interoperability of devices and systems (Jarašūnienė *et al.*, 2023). As shown in Figure 1, the structure of the economic characteristics of an IoT

project is formed on the basis of cost, efficiency, and life cycle parameters that determine the sustainability of the solution in the long term.



Figure 1. IoT project life cycle

Source: compiled by authors based on S. Rathore (2025)

The life cycle of IoT solutions has its own characteristics compared to classic IT projects. At the initiation stage, goals are formulated, economic expectations are determined, architectural approaches and deployment models (on premise, cloud, hybrid) are selected. This is followed by design and pilot implementation, where technical viability and basic economic effects are verified. At the large-scale deployment stage, the IoT system is integrated with enterprise resource planning, customer relationship management and other corporate platforms, a stable data flow is formed for analytics and decision-making. In the operation phase, update management, security, and maintenance of sensor and network performance become key; it is at this stage that the main part of the economic effect is gradually realised due to cumulative cost savings and increased productivity. The final stage includes modernisation or replacement of outdated devices, migration to new protocols and platforms, as well as disposal of equipment taking into account environmental requirements.

The economic characteristics of an IoT project are therefore determined not only by the initial costs, but also by how effectively the solution is integrated into the digital infrastructure of the enterprise, how quickly it scales and what long-term benefits it generates at all stages of the life cycle. That is why, in order to justify the feasibility of implementing IoT, it is necessary to combine cost analysis, efficiency assessment and life cycle modelling, taking into account both direct financial results and strategic effects related to innovation and competitiveness. After implementing IoT technologies, enterprises demonstrate an increase in the level of automation, as IoT eliminates a significant part of manual actions and allows them to be replaced by digital processes. On average, after IoT integration, about 57.5% of operational processes are automated, although in some companies this figure reaches 75% already during the first year of use (Daws, 2025). The reduction in manual operations is generally from 40% to 60%, which is due to the transition to remote monitoring, automatic control and predictive maintenance (Kurduban, 2024). The use of IoT in combination with AI algorithms further enhances these effects: for example, predictive maintenance has an implementation rate of 71%, IT automation – 53%, which allows enterprises to reduce the number of manual interventions and achieve an increase in overall efficiency by 20-30%. The real effect of automation is also manifested in cost savings, in particular in reducing labour costs by about 25%.

One of the key areas of productivity improvement is downtime reduction. Due to IoT-supported equipment condition monitoring, enterprises reduce unplanned downtime by an average of 25-35%. This is achieved by early detection of anomalies, automatic call of technical teams and optimisation of the maintenance schedule (Oxmaint, 2025). Predictive maintenance makes it possible to reduce the response time to malfunctions by 70%, reduce repair costs by 50% and extend the service life of equipment by approximately 20%. As a result, industrial enterprises record up to 40% reduction in downtime and 20-30% increase in productivity due to stable equipment operation and more accurate planning of production processes (Zoting & Shivarkar, 2025).

IoT is also a central element in the development of analytics, since the amount of data generated by devices ranges from tens of terabytes to several petabytes per year within one enterprise. The use of real-time analytics provides an average increase in productivity by 10-30%, a reduction in scrap rates by 18%, an increase in production output by 10-15%, and optimisation of logistics and warehouse operations (ARO, 2023). Due to this, IoT creates conditions for the formation of data-driven decision-making models that increase the adaptability of enterprises and accelerate innovation processes (Tely AI Team, 2025).

The spread of IoT is changing the logic of business functioning and stimulating the development of new business models. In the EU and the United States, from 20% to 30% of companies use subscription models (subscription IoT), and the global service market is estimated at USD 293.4 billion in 2025 with a forecast growth to USD 1.86 trillion by 2035. The development of models such as “product-as-a-service” enhances the economic flexibility of enterprises and ensures long-term revenue growth, in particular due to the high profitability of data-driven services (Future Market Insights, 2025a).

In the context of global trends of sustainable development, IoT provides tangible environmental benefits. Optimisation of transport routes based on IoT reduces CO₂ emissions by 10-20%, while the use of optimisation algorithms, including Hybrid Genetic Algorithms, allows for a reduction of up to 23% (Bar, 2025). Smart energy technologies reduce energy consumption of enterprises, reduce losses and increase the efficiency of resource use. One of the most dynamic areas is smart waste management: the global market for such solutions is estimated at USD 3.17 billion

in 2025 with a forecast of growth to USD 14 billion by 2035 (Future Market Insights, 2025b). The use of bin fullness sensors and automated sorting can reduce waste volumes by 20-45%, improve collection logistics efficiency by 32%, and increase waste recycling rates by 25-45% (Addas *et al.*, 2024). These results confirm that IoT is becoming not only a tool for economic transformation, but also a key technology for shaping energy-efficient, low-carbon, and circular development models.

In summary, the economic properties of IoT implementation form a complex multiplier effect, which is manifested simultaneously at the level of costs, productivity, management decisions and environmental performance. The combination of automation, predictive analytics and scalable digital infrastructure creates a new model of enterprise functioning, in which data becomes the basic resource for creating value. Reducing manual operations, reducing downtime, increasing the accuracy of processes and flexibility of business models provide enterprises with both short-term savings and long-term strategic advantages, in particular, resistance to market fluctuations, faster adaptation to technological changes and the formation of new sources of income. Thus, IoT is transformed from a separate technological tool into a system-forming platform for economic development, which changes the logic of production, management and competition in the digital economy.

Economic impact of implementing IoT projects at the micro and macro levels

The IoT is demonstrating significantly different but systematically positive economic returns in key sectors – industry, logistics, energy, agro-industrial complex, urban infrastructure and healthcare. The impact of IoT is manifested through process automation, predictive maintenance, resource optimisation, defect reduction, cost reduction, improved asset management, reduced transaction time and increased decision-making accuracy. At the same time, specific economic effects are observed in each sector, determined by the nature of operations, level of digital maturity, scale of equipment and density of data flows. In industry, IoT is one of the main catalysts for the transition to “smart factories”. One of the key effects is automation: enterprises that have implemented IoT automate an average of 57.5% of operational processes, and some – up to 75% within the first year, which leads to a reduction in labour costs by 25% and an increase in productivity by 20-30% (Ramanenkova, 2025). The reduction in manual operations reaches 40-60%, and unplanned downtime is reduced by 25-50% due to predictive maintenance, which is also rarely possible without IoT-based equipment monitoring. Companies that have integrated IoT into quality and control of production environments record a reduction in product defects by 25-50%, and in some cases up to 70%, while the use of robotics connected to IoT sensors provides flexible reconfiguration of production scenarios, increases accuracy and reduces losses (Sapra, 2025).

Examples of corporate cases confirm the scale of the effects. Siemens MindSphere provides an improvement in overall equipment effectiveness from a baseline of 40-50% to 60-85%, an increase in production up to 25%, and a reduction in defects due to the closure of the quality management loop (Holmes, 2018). Bosch demonstrates an increase in production efficiency by 25-30%, an increase in equipment productivity by 15-20%. (Ten years of Industry 4.0, n.d.). Thus, for the industrial sector, IoT is a mechanism for generating economies of scale, which manifests itself simultaneously at the capital expenditure and operating expenses levels.

In transport and logistics, IoT also has a significant economic impact associated with cost reduction, route optimisation, and increased delivery speed. IoT routing reduces transportation costs by an average of 10-25%, while dynamic traffic optimisation reduces fuel consumption by 10-15% and reduces repair costs caused by accidents and wear and tear by monitoring driver behaviour and fleet condition. Unilever demonstrates a 25% reduction in delivery times through the use of IoT and AI route optimisers, DHL – 20% reduction in delays, while Walmart and Maersk – from 10% to 25%, depending on transportation models (CodeXTeam, 2024). Amazon Web Services IoT provides full automation of order processing, inventory management, and delivery monitoring: order reprocessing is reduced, picking is accelerated, and inventory accuracy is significantly improved by integrating sensors into warehouse operations (Amazon – a prime..., n.d.). Huawei's IoT connectivity enables real-time equipment and cargo monitoring, rapid fault detection, and automatic adjustment of port operations, reducing ship downtime by 7% and shortening operation planning time from 24 hours to 10 minutes (Tianjin port: Building..., n.d.).

In the energy sector, IoT provides a significant reduction in energy consumption and increases the efficiency of network management. The use of “smart meters” allows households to reduce electricity consumption by 2.5-3.5%, and in some cases up to 3.4% in the first year, with the trend continuing in subsequent years. Automated Smart Grid management reduces losses in networks by 15-25%, reduces peak loads by 10-25%, improves reliability and reduces the duration of emergency shutdowns (Department of Energy Security of the United Kingdom, 2024). Siemens Energy demonstrates a reduction in manual data collection time by 50%, maintenance costs by 25%, and equipment availability increases by up to 15% (Siemens energy builds..., 2024).

The agro-industrial complex receives significant economic benefits through the use of IoT drones, sensor systems and analytics. Targeted application of agrochemicals using IoT drones reduces pesticide and fertiliser use by 30-45%, while crop yields increase by 15-30% through point-to-point monitoring of crop conditions. Water consumption is reduced by up to 90% in precision irrigation systems, and crop forecast accuracy increases to 85-90%, providing better stability of the production cycle and minimising financial risks (How are drones..., 2025)

Urban infrastructure benefits from IoT through energy optimisation, reduced data processing time, and improved quality of municipal services. IoT lighting reduces electricity consumption by 30-75%, depending on the level of light emitting diode integration and adaptation algorithms, while integration with Heating, Ventilation, and Air Conditioning provides additional 20-40% savings (AGC Lighting, 2023). Edge data processing speeds up city services by 70-71%, optimising response to critical events. In waste management, IoT provides fuel savings of 25-40%, reduces the number of routes by 25-30%, reduces waste going to landfills by 10-30%, and increases the accuracy of sensor monitoring to 95% (Pioli *et al.*, 2024). In healthcare, IoT is helping to radically improve diagnostic accuracy, reduce costs, and improve the quality of care for chronic patients. The interaction of wearable medical devices with hospital systems provides monitoring accuracy of 87-95%, and the sensitivity of condition detection algorithms is up to 94-95%. Implementation of Remote Patient Monitoring reduces readmissions by up to 38%, saving about USD 6,500 per patient per year.

As a result, IoT creates a comprehensive economic effect in every sector of the economy, forming a synergy of technological automation, resource optimisation and intelligent management. Industry receives the greatest aggregate economic growth through automation and reduced downtime; logistics – due to a significant reduction in costs and accelerated deliveries; energy – through network optimisation and reduction of peak loads; the agricultural sector – through the accuracy of forecasts and resource savings; cities – through reduced energy consumption and improved operational efficiency; healthcare – through increased monitoring accuracy, early diagnosis and reduced hospitalisations. Thus, IoT is not only a tool for technological modernisation, but also one of the key drivers of increased productivity, innovative dynamics and economic sustainability at the national and global levels.

Digital technologies and IoT significantly contribute to GDP growth across countries and regions such as OECD members, the EU, the USA, and China, although the extent and nature of this impact vary. In OECD countries, the ICT sector has grown approximately three times faster than the overall economy between 2013 and 2023. During this period, the ICT sector demonstrated an average annual growth rate of 6.3%, which further increased to 7.6% in 2023. This sector remains a key driver of global economic expansion; however, the adoption of advanced technologies such as AI and IoT in non-ICT industries is still limited. This indicates significant untapped potential for accelerating economic performance through broader technological diffusion. At the same time, investments in AI continue to rise, strengthening the economic relevance of digital technologies in OECD (2024) economies. In the United States, GDP growth in early 2025 was strongly driven by investments in AI data centres and IT infrastructure, confirming the central role of digital technologies in maintaining economic momentum. The North American

IoT market accounts for a substantial share of global spending on IoT devices and solutions, underscoring its contribution to productivity increases and sector-specific efficiencies (Chang & Hsiao, 2025).

Globally, IoT applications are estimated to generate trillions of dollars in annual economic value, with projections reaching up to USD 11 trillion by 2030. Industrial IoT alone could add approximately USD 14.2 trillion by 2030, particularly benefiting manufacturing and healthcare by boosting operational efficiency and introducing new value-creation mechanisms. Although the provided sources contain limited specific data for China, the country's well-documented large-scale investments in IoT, AI, and digital infrastructure indicate that these technologies substantially support national GDP growth by enhancing industrial productivity, advancing smart city programmes, and expanding the digital economy in line with global trends (Shamrei, 2024). Overall, digital technologies and IoT contribute significantly to GDP dynamics by accelerating ICT sector development, enabling AI-supported efficiency improvements, and transforming industries through connected systems. OECD countries and the USA benefit from both direct ICT sector expansion and the broader potential associated with increased technology diffusion, while the global economy is positioned to experience continued growth as IoT transforms production and service ecosystems. Connectivity, as a foundational component of IoT, demonstrates a measurable macroeconomic effect. A 10% increase in fixed or mobile broadband penetration is associated with about a 1.5-1.6% rise in GDP per capita. This effect tends to be stronger in advanced economies due to larger digitalisation scale effects. In the United States, the digital economy represents roughly 18% of GDP as of 2024, contributing to rapid job creation, innovation, and productivity growth. Overall, the global digital economy is growing approximately 2.5 times faster than global GDP, with IoT functioning as a central mechanism for transitioning toward more connected and data-driven economic models (ITU, 2025).

Changes in productivity, efficiency, and cost structures resulting from IoT implementation are reflected in macroeconomic indicators such as GDP growth and total factor productivity. A 10-percentage-point increase in IoT connections per capita correlates with approximately a 0.23-percentage-point increase in total factor productivity growth, which directly raises economic output. Recent assessments estimate that IoT contributes about USD 849 billion annually to global GDP through productivity gains (Edquist *et al.*, 2019). IoT improves productivity by optimising resources, enabling predictive maintenance, streamlining workflows, and reducing energy consumption—particularly in manufacturing, healthcare, and urban infrastructure. These efficiency gains lower operating costs, reduce capital intensity, and encourage innovation, collectively increasing GDP and strengthening economic competitiveness. A 10% rise in machine-to-machine interactions (an indicator of IoT growth) could increase US GDP by USD 2.3 trillion over the next 30 years. Notably, IoT's

indirect impacts – productivity spillovers and cross-sector complementarities – further amplify these macroeconomic benefits (Sloan, 2024).

Sectors generating the largest contributions to GDP through IoT include manufacturing, transport, healthcare, energy, and services. Manufacturing remains the leading contributor, with industrial IoT offering economic potential of USD 1.2-3.7 trillion by 2025 through improved monitoring, predictive maintenance, and supply chain optimisation. The transport and automotive sectors also gain substantially due to IoT-enabled fleet management and connected vehicle technologies, with the automotive IoT market expected to exceed USD 500 billion by 2025. Healthcare represents another major contributor, with the IoT healthcare market projected to reach USD 534 billion by 2025 as connected devices improve diagnostics and reduce costs. In the energy sector, smart grids and IoT-based monitoring significantly enhance energy efficiency and resource management, generating considerable economic value, including estimated electricity savings of 1.8 petawatt-hour in the US by 2030. Service industries, including retail and smart cities, also experience substantial benefits from IoT applications that streamline operations and improve infrastructure management (Shamrei, 2024). In summary, the largest GDP contributions from IoT come from manufacturing and transport, followed by healthcare and energy, while service sectors add value through innovation and infrastructure improvements. IoT acts as a powerful driver of productivity, investment, and efficiency gains across economies, strongly influencing GDP and national competitiveness at the macroeconomic level.

Barriers, risks and prospects for scaling IoT in economic systems

The implementation of IoT systems is becoming crucial for the transformation of enterprises and sectors of the economy, but the scaling of such solutions is accompanied by a number of technical, organisational, institutional and economic barriers. In practice, IoT projects are complicated by the lack of common standards, low compatibility of equipment, high requirements for cyber security, a shortage of qualified specialists and the need to adapt internal business processes. At the same time, state regulation and international standards form the framework conditions for the functioning of IoT, and the economic risks of integration stimulate the development of models for minimising uncertainty. In the medium and long-term development horizon, IoT becomes a key basis for circularity, energy optimisation and strategic growth of the economy.

Technical and organisational barriers are the most difficult, as they are manifested directly in operational activities. One of the central challenges is interoperability: sensor and platform manufacturers often use different communication protocols, which complicates system integration, creates data duplication and requires additional adapters or gateways. The low level of standardisation slows down the scaling of solutions and increases the dependence of

businesses on individual vendors. In parallel, the importance of cybersecurity is growing: the increase in the number of connected devices opens up a wider “attack field”, and therefore requires advanced methods of encryption, authentication and network segmentation. Many companies also face staffing constraints, as IoT integration requires specialists in related competencies – network engineering, cyber security, big data analytics, development and operations. In addition, organisational barriers are manifested in the need to reorient internal processes, rebuild asset management systems and train personnel, which increases the time and financial cost of the transition to IoT. Integration of IoT into business processes is always accompanied by economic risks. Investment risks are formed due to the high cost of equipment, the need to modernise network infrastructure, costs for cyber security and operational updates. Additionally, there are security risks associated with possible cyberattacks, interference with production equipment or unauthorised access to critical data. The risk of not achieving economic effect is due to the fact that the effectiveness of IoT depends on the quality of sensors, algorithms, integration with enterprise resource planning and customer relationship management systems, staff readiness and digital culture of the enterprise. In practice, various models of risk minimisation are used in implementation: phased scaling of minimum viable product (solutions, testing on local sites, cloud models for reducing capital costs, cybersecurity frameworks and hybrid architecture with the distribution of critical functions between edge and cloud (Gerodimos *et al.*, 2023).

The technical barriers to IoT implementation are largely determined by the lack of interoperability and the lack of a unified technical framework, which makes it difficult to scale systems at the enterprise and industry level. International standards play a key role in overcoming these limitations. In particular, ISO/IEC 30141:2024 (2024), developed by ISO and the IEC, forms a universal reference architecture for IoT, which defines the levels of device interaction, data exchange requirements and logic of functional modules. Its compliance ensures the coordinated creation of IoT platforms and interoperability between manufacturers. An important component of technical interoperability are wireless communication standards, in particular the IEEE 802.15.4-2011 (2011), developed by IEEE. It defines the basic parameters of data transmission in low-power networks, on which Zigbee, Thread and P6 over Low power Wireless Personal Area Networks (6LoWPAN) technologies are based, which form the basis for sensor networks of smart homes, meters and industrial sensors. For broader system coordination, IEEE 2413-2019 (2019) is also used, which describes a conceptual model of interaction between various IoT solutions and platforms, ensuring interoperability and data consistency.

The problem of security standardisation should be noted separately, since most IoT projects operate in conditions of large-scale data processing, constant network connectivity and high vulnerability to cyberattacks. The key

standard in this direction is ISO/IEC 27001:2022 (2022), which defines requirements for information security management systems, including risk assessment, encryption, access control and verification of environmental reliability. In the industrial sector, the basis of cyber security is formed by ISA/IEC 62443 series of standards (n.d.) (Industrial Communication Networks – IT Security for Industrial Automation Systems), which sets requirements for network segmentation, protection of controllers, Supervisory Control and Data Acquisition (SCADA) and other automation systems.

In the consumer sector, the basic standard is the ETSI EN 303 645 V3.1.3 (2024), which prohibits the use of standard passwords, regulates firmware updates, encryption and protection of personal data. Institutional barriers are also associated with the lack of harmonised regulatory regimes. International standards provide the basis, but the

implementation of IoT requires state coordination mechanisms, adaptation of regulatory frameworks and establishment of requirements for security and interoperability. National regulatory frameworks should be based on international standards to ensure the rapid implementation of innovations, and include institutional incentives for infrastructure modernisation. In this regard, the technical, organisational and regulatory aspects of IoT implementation are interconnected. International standards – ISO/IEC 30141, ISO/IEC 27001, IEC 62443, IEEE 802.15.4, IEEE P2413 and ETSI EN 303 645 V3.1.3 (2024) – form the basic framework for interoperability, security, architectural consistency and compliance of technological systems, ensuring the scalability of IoT at the level of industry, energy, agriculture and urban infrastructure. The main barriers and risks are highlighted in Table 1.

Table 1. Key barriers and risks of IoT system implementation

Barrier group	Nature of the barrier	Impact on implementation	Typical consequences
Technical	Low interoperability, lack of standards	Complicated integration	Data duplication, increased project costs
Cybersecurity	Attack risks, weak network segmentation	High protection requirements	Process shutdowns, data leaks
Human resources	Shortage of IoT/ development and operations/security specialists	Slower scaling	Rising project costs
Regulatory	Instability of requirements, bureaucracy	Slower implementation	Certification delays
Economic	High capital expenditure/operating expenses, uncertain return on investment	Low profitability at early stages	Risk of not achieving the expected effect

Source: compiled by authors based on A. Alenizi & K. Al-Karawi (2023), S. Madanian *et al.* (2024)

The prospects for sustainable development of IoT are determined by the fact that this technology becomes the core of the circular economy, energy optimisation and low-carbon transformation. The circular economy involves closed material cycles, resource reuse, waste reduction and increased logistics efficiency. IoT provides detailed monitoring of the life cycle of products, control of storage conditions, traceability and sensor-based control of equipment wear, which reduces the resource intensity of production. In the energy sector, IoT provides the ability to integrate distributed generation, optimise loads, flexible network management and transition to intelligent Smart Grids. Emissions monitoring systems, energy consumption analysis and microgeneration plant management contribute to the low-carbon transition and environmental sustainability. At the micro level, key strategic trajectories are increasing the operational efficiency of enterprises, automation of logistics, optimisation of production processes, real-time asset management and implementation of predictive maintenance models. Enterprises are moving to digital twins, robotic processes, and data flow analytics, and comprehensive automation, which can reduce costs, improve product quality, and reduce waste. In urban infrastructure, IoT opens up prospects for intelligent mobility, energy-efficient construction, automated traffic management, pollution reduction, and utility optimisation (Rejeb *et al.*, 2022).

At the macro level, IoT is becoming one of the key drivers of national competitiveness. Countries with a high rate of digitalisation, in particular China, European Union countries, Japan, the Republic of Korea, Taiwan, China, and the United Kingdom, demonstrate accelerated GDP growth, active development of high-tech exports, and increased investment in digital infrastructure. IoT scaling contributes to productivity growth, increases the efficiency of economic sectors, enhances innovation capabilities, and creates conditions for the expansion of digital markets. The combination of institutional support, unified standards, and strategic investments in digital ecosystems provides countries with the ability to make technological breakthroughs and strengthen economic resilience (World Bank Group, 2024).

As a result, the barriers to IoT implementation are multidimensional and cover technical, organisational, institutional, and economic dimensions. However, a systematic approach to overcoming them, combining standards, cyber security, institutional incentives, and strategic planning, provides the opportunity for large-scale integration of IoT into all levels of the economy. Sustainable development, digital transformation, and energy optimisation are shaping new conditions in which IoT is not just a technology, but also a fundamental infrastructure for economic and social progress.

Discussion

The rapid spread of digital solutions has gradually changed economic dynamics, affecting both the structure of production and resource management mechanisms. Various scientific approaches to digitalisation shared a common theme: digital technologies have become the foundation of economic modernisation. This was clearly evident in the results of this study and in the conclusions of R. Li & J. Zheng (2025), where the digital economy was assessed as a factor in increasing productivity and transitioning to higher quality production. In both works, digital solutions enhanced innovation and rationalised the use of resources, although the emphasis differed. R. Li & J. Zheng (2025) focused on the manufacturing sector and identified the role of digital literacy and manufacturing agglomeration as factors that modified the strength of the effect, while in this study, the effectiveness of IoT was traced in an inter-sectoral context without modelling such moderators.

The differences became more pronounced when compared to the study by K. Bai *et al.* (2024). In K. Bai *et al.* (2024) the digital economy emerged as a tool not only for modernisation, but also for increasing inclusiveness and equalising socio-economic opportunities, while in this study, the sectoral and applied dimensions dominated – analysis of automation, reduction of downtime, resource savings, and productivity gains. K. Bai *et al.* focused on institutional barriers and digital inequality, while here the main constraints were technical and organisational factors of IoT integration. Despite this, both studies demonstrated that digital solutions shaped a renewed model of economic efficiency. The contrast was even more pronounced when compared to Y. Liu *et al.* (2024). Y. Liu *et al.* viewed digitalisation through the prism of socioeconomic equality-income growth, reduced inequality, and expanded opportunities for rural areas. In this study, digitalisation had a different research perspective: IoT was evaluated in terms of its impact on productivity, cost dynamics, and the overall efficiency of economic processes, without analysing socio-distributional outcomes. Despite this, both studies confirmed that digital technologies triggered mechanisms of structural change.

A similar correlation was observed in comparison with J. Ding (2024). J. Ding analysed the digital economy in interaction with new infrastructure – 5G, AI, transport and energy networks –, which created a large-scale economic multiplier effect. This study focused on sectoral IoT mechanisms, which allowed for a detailed analysis of specific technical and economic benefits, but did not cover the infrastructural and social dimensions characteristic of J. Ding's approach. Despite different horizons of analysis, both works saw digitalisation as the basis for productivity and innovation. A comparison with X. Wang *et al.* (2024) showed that digital technologies in all the studies analysed formed the basis for economic renewal, but X. Wang *et al.* emphasised socio-economic transformations – changes in employment, the role of human capital, and institutional prerequisites for development. Here, the analysis was based

on an assessment of sectoral technical results, which distinguished the study in terms of its analytical horizon, but not in terms of the overall logic of its conclusions.

A comparison of this study with the results of X. Wang *et al.* (2024) showed that, regardless of the scale of the analysis, digital technologies consistently demonstrated the ability to enhance productivity and reduce transaction and operating costs. However, further consideration revealed significant differences in the interpretation of these processes. In X. Wang *et al.* (2024) digitalisation was part of a broader socio-economic transformation that included changes in the labour market, human capital development, and institutional prerequisites for structural reforms. Here, digital solutions were evaluated in more applied context-through real changes in operational processes, automation, reduced downtime, and total factor productivity growth in specific sectors. The focus on social effects, characteristic of X. Wang *et al.* (2024) was not central to this study. This division between the macro and applied levels was also clearly evident in comparison with A.F. Kineber (2024). In A.F. Kineber, the digital economy was viewed primarily as a strategic resource for national development, influencing investment flows, market structure, and the transformation of business models. In contrast, in this study, digitalisation emerged through the direct technical and economic effects of IoT, which manifested themselves in cost reduction, resource optimisation, acceleration of production cycles, and stable productivity growth at the enterprise and sector levels. Both approaches emphasised the modernisation potential of digital technologies, but differed in the scope of their analytical perspective.

The contrast in research perspectives became even more noticeable when compared with C. Zhang *et al.* (2024). C. Zhang *et al.* analysed digitalisation as a factor in regional equalisation, sustainable development, and environmental efficiency. The researchers integrated the digital economy into the broader context of spatial disparities and institutional differences, emphasising the ability of digital technologies to reduce inequality and stimulate innovative activity in cities. In the same study, digital infrastructure manifested itself through other mechanisms – by increasing the accuracy of management decisions, optimising resource flows, and reducing production losses in sectoral systems. The environmental and regional impacts of digitalisation were not included in the analysis. The generalisation of the comparative results showed that digital technologies in all considered approaches formed the basis of economic renewal, although the interpretation of this process differed depending on the research optics. In some works, digitalisation appeared as an element of large-scale socio-economic transformations, while in this study, applied analysis of sectoral effects of IoT – automation, cost optimisation and productivity growth – dominated. Despite differences in focus, all comparisons confirmed that digital infrastructure remained a key factor in long-term growth, innovation and sustainability of economic systems.

Conclusions

The research systematised the key theoretical and economic principles of the IoT as a foundational technology of the digital economy. Analysis of scientific sources showed that IoT creates a new architecture of economic processes by integrating sensor networks, real-time algorithms, communication platforms and analytical modules into a unified digital environment. The classification of IoT solutions demonstrated their wide applicability, while the evaluation of economic characteristics revealed that the cost structure is shaped mainly by capital investments, integration and cybersecurity. The analysis of the IoT life cycle confirmed that the strongest economic effects emerge during the operational stage due to resource savings, predictive maintenance and automated management.

The sectoral analysis showed that IoT has a multidimensional impact on economic efficiency. In industry, automation after IoT implementation ensures about 57.5% digitalisation of operations, reduces manual actions by 40-60% and lowers labour costs by nearly 25%. Predictive maintenance decreases unplanned downtime by 25-35%, and sometimes up to 40%, increasing productivity by 20-30%. In logistics, IoT-based routing reduces transportation costs by 10-25% and fuel consumption by 10-15%. In the energy sector, smart meters reduce consumption by 2.5-3.5%, while Smart Grid decreases network losses by 15-25%. In agriculture, IoT drones lower agrochemical use by 30-45%, cut water consumption by up to 90% and increase yields by 15-30%. In urban infrastructure, IoT lighting reduces energy consumption by 30-75%, and heating, ventilation, and air conditioning integration adds

20-40% savings, confirming the decisive role of IoT in transforming operational models.

At the macroeconomic level, the study found that the digital economy in OECD countries grew 2.5 times faster than GDP, while a 10-pp increase in IoT connections raises total factor productivity by 0.23 p.p. and generates a global effect of about USD 849 billion annually. The largest macroeconomic contribution comes from industry, transport, healthcare and energy, while services also benefit from automation and new digital models.

The study additionally showed that IoT scaling is limited by interoperability issues, insufficient standardisation, cybersecurity risks and shortages of qualified personnel. Nevertheless, long-term prospects are linked to circular economy models, energy system optimisation, Smart Grid expansion, digital platforms and deeper integration of AI. A limitation of the study is that it relied on available aggregated statistical data and secondary sources, which limited the depth of comparative analysis between individual industries and countries. Further research could be aimed at developing industry-specific models for assessing the effectiveness of IoT and deepening the analysis of long-term economic effects across countries.

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Conflict of Interest

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References

- [1] AI Digital. (2025). *11 IoT examples across different industries*. Retrieved from <https://www.ai.digital/knowledge-hub/11-iot-examples-across-different-industries/>.
- [2] Abdullayev, K., Abdullayev, R., Yusifov, E., Babazade, I., & Fataliyeva, G. (2024). Main areas of development of the digital economy in the Republic of Azerbaijan. *Economics of Development*, 23(1), 78-88. doi: 10.57111/econ/1.2024.78.
- [3] Abebe, N., Perera, A., Novak, T., & Adebayo, Y. (2025). *Total cost of ownership (TCO) optimization in IoT ecosystems using AI-driven predictive models*. Retrieved from https://www.researchgate.net/publication/395713030_Total_Cost_of_Ownership_TCO_Optimization_in_IoT_Ecosystems_Using_AI-Driven_Predictive_Models.
- [4] Addas, A., Khan, M.N., & Naseer, F. (2024). Waste management 2.0: Leveraging Internet of Things for an efficient and eco-friendly smart city solution. *PLoS One*, 19(7), article number e0307608. doi: 10.1371/journal.pone.0307608.
- [5] AGC Lighting. (2023). *Smart IoT lighting and sustainability*. Retrieved from <https://www.agcled.com/blog/smart-iot-lighting-sustainability.html>.
- [6] Alenizi, A.S., & Al-Karawi, K.A. (2023). Internet of Things (IoT) adoption: Challenges and barriers. In X.-S. Yang, S. Sherratt, N. Dey, & A. Joshi (Eds.), *Proceedings of the seventh international congress on information and communication technology* (pp. 217-229). Singapore: Springer. doi: 10.1007/978-981-19-2394-4_20.
- [7] Amazon – a prime example of an IoT implementation. (n.d.). Retrieved from <https://fr.farnell.com/amazon-a-prime-example-of-an-iot-implementation>.
- [8] ARO. (2023). *IoT devices “to generate nearly 80 zettabytes of data” by 2025*. Retrieved from <https://aro.tech/insights/blog/iot-devices-to-generate-nearly-80-zettabytes-of-data-by-2025/>.
- [9] Aslanova, T.T., Fatahova, N.R., & Fatahov, I. (2024). *Digitalization perspectives of the Azerbaijan economy*. *Journal of Propulsion Technology*, 45(1), 342-350.
- [10] Bai, K., Shen, Z., Zhou, S., Su, Z., Yang, R., & Song, M. (2024). How does digitalization promote productivity growth in China? *Journal of Innovation & Knowledge*, 9(4), article number 100586. doi: 10.1016/j.jik.2024.100586.
- [11] Bar, M. (2025). *How route optimisation reduces carbon emissions*. Retrieved from <https://surl.lt/asaidsz>.

- [12] Chang, O., & Hsiao, J. (2025). *US economic growth in early 2025 driven largely by AI data centers and IT investments*. Retrieved from <https://www.digitimes.com/news/a20251014PD201/2025-data-economy-expansion-gdp.html>.
- [13] CodeXTeam. (2024). *AI and supply chain optimization leading to a 25% reduction in delivery times*. Retrieved from <https://www.codex.team/blog/ai-and-supply-chain-optimization-leading-to-a-25-reduction-in-delivery-times>.
- [14] Daws, R. (2025). *Industrial AIoT adoption drives operational efficiency*. Retrieved from <https://iottechnews.com/news/industrial-aiot-adoption-drives-operational-efficiency/>.
- [15] Department of Energy Security of the United Kingdom. (2024). *Monitoring smart meter energy savings using the National Energy Efficiency Data-Framework*. Retrieved from <https://assets.publishing.service.gov.uk/media/672df39f5437e298ae64ce94/monitoring-smart-meter-energy-savings-using-NEED.pdf>.
- [16] Ding, J. (2024). The impact of the digital economy and new infrastructure on China's economic development. *Highlights in Business Economics and Management*, 24, 832-838. doi: 10.54097/5xmbq40.
- [17] Do, K., Klymova, I., Naumova, E., Herevych, M., & Yankovskyi, O. (2025). Data processing and analysis methods in IoT using machine learning. *Navigation and Communication Control Systems*, 2(80), 119-124. doi: 10.26906/SUNZ.2025.2.119.
- [18] Edquist, H., Goodridge, P., & Haskel, J. (2019). The Internet of Things and economic growth in a panel of countries. *Economics of Innovation and New Technology*, 30(3), 262-283. doi: 10.1080/10438599.2019.1695941.
- [19] ETSI EN 303 645 V3.1.3. (2024). *Cyber security for consumer Internet of Things: Baseline requirements*. Retrieved from https://www.etsi.org/deliver/etsi_en/303600_303699/303645/03.01.03_60/en_303645v030103p.pdf.
- [20] Future Market Insights. (2025a). *Business as a service market size and share forecast outlook 2025 to 2035*. Retrieved from <https://www.futuremarketinsights.com/reports/business-as-a-service-market>.
- [21] Future Market Insights. (2025b). *Smart waste management market growth – trends & forecast 2025 to 2035*. Retrieved from <https://www.futuremarketinsights.com/reports/smart-waste-management-market>.
- [22] Gerodimos, A., Maglaras, L., Ferrag, M.A., Ayres, N., & Kantzavelou, I. (2023). IoT: Communication protocols and security threats. *Internet of Things and Cyber-Physical Systems*, 3, 1-13. doi: 10.1016/j.iotcps.2022.12.003.
- [23] Guluzade, T. (2025). Development prospects of the digital economy in Azerbaijan. *Porta Universorum*, 1(7), 51-59. doi: 10.69760/portuni.0107006.
- [24] Holmes, K. (2018). *Siemens factory in Mexico rolls out MindSphere on AWS IoT project in less than 8 weeks*. Retrieved from <https://aws.amazon.com/ru/blogs/apn/case-study-siemens-factory-rolls-out-aws-iot-project-in-less-than-8-weeks/>.
- [25] How are drones used in agriculture for higher yields and lower costs. (2025). Retrieved from <https://indeema.com/blog/how-are-drones-used-in-agriculture-for-higher-yields-and-lower-costs--indeema-software>.
- [26] Huang, C., Chen, Q., Lin, Z., Su, W., Zhang, Z., & Liu, S. (2024). The economic impact and application challenges of IoT technology in smart home and infrastructure. *Journal of Innovation and Development*, 6(1), 35-39. doi: 10.54097/y54jkb60.
- [27] IEEE 2413-2019. (2020). *IEEE Standard for an architectural framework for the Internet of Things*. (2019). Retrieved from <https://standards.ieee.org/ieee/2413/6226/>.
- [28] IEEE 802.15.4-2011. (2011). *IEEE standard for local and metropolitan area networks – part 15.4: Low-rate wireless personal area networks (LR-WPANs)*. Retrieved from <https://standards.ieee.org/ieee/802.15.4/5050/>.
- [29] ISA/IEC 62443 series of standards. (n.d.). Retrieved from <https://www.isa.org/standards-and-publications/isa-standards/isa-iec-62443-series-of-standards>.
- [30] ISO/IEC 27001:2022. (2022). *Information security, cybersecurity and privacy protection – information security management systems – requirements*. Retrieved from <https://www.iso.org/standard/27001>.
- [31] ISO/IEC 30141:2024. (2024). *Internet of Things (IoT) – reference architecture*. Retrieved from <https://www.iso.org/standard/88800.html>.
- [32] ITU. (2025). *The impact of digital transformation on the economy*. Retrieved from https://www.itu.int/dms_pub/itu-d/opb/pref/D-PREF-ECON.MOD-2025-PDF-E.pdf.
- [33] Jarašūnienė, A., Čižiūnienė, K., & Čereška, A. (2023). Research on impact of IoT on warehouse management. *Sensors*, 23(4), article number 2213. doi: 10.3390/s23042213.
- [34] Kineber, A.F. (2024). Identifying the Internet of Things (IoT) implementation benefits for sustainable construction projects. *HBRC Journal*, 20(1), 700-766. doi: 10.1080/16874048.2024.2369462.
- [35] Kurduban, V. (2024). *IoT in manufacturing: Applications and benefits of smart factories*. Retrieved from <https://www.digi.com/blog/post/iot-in-manufacturing>.
- [36] Li, R., & Zheng, J. (2025). Digital economy and sustainable development in China: From the perspective of high-quality development of manufacturing. *Sustainability*, 17(14), article number 6438. doi: 10.3390/su17146438.
- [37] Liu, Y., Tian, G., & Zhang, X. (2024). Digital economy and China's path to common prosperity. *Digital Economy and Sustainable Development*, 2, article number 8. doi: 10.1007/s44265-024-00031-8.

- [38] Madanian, S., Chinbat, T., Subasinghage, M., Airehrour, D., Hassandoust, F., & Yongchareon, S. (2024). Health IoT threats: Survey of risks and vulnerabilities. *Future Internet*, 16(11), article number 389. doi: [10.3390/fi16110389](https://doi.org/10.3390/fi16110389).
- [39] Massoud, M., Kineber, A., Elshaboury, N., Abunada, Z., Arashpour, M., Alatroush, M., Mostafa, S., & Alhusban, M. (2025). Identifying and assessing the Internet of Things implementation barriers for sustainable building projects: SEM-ANN approach. *KSCE Journal of Civil Engineering*, 30(1), article number 100310. doi: [10.1016/j.kscej.2025.100310](https://doi.org/10.1016/j.kscej.2025.100310).
- [40] OECD. (2024). *Growth of the digital economy outperforms overall growth across the OECD*. Retrieved from <https://www.oecd.org/en/about/news/press-releases/2024/05/growth-of-digital-economy-outperforms-overall-growth-across-oecd.html>.
- [41] Oxmaint. (2025). *Predictive maintenance with IoT and AI: Reduce downtime & save costs*. Retrieved from <https://oxmaint.com/blog/post/predictive-maintenance-iot-ai>.
- [42] Pioli, L., de Macedo, D.D.J., Costa, D.G., & Dantas, M.A.R. (2024). Towards an AI-driven data reduction framework for smart city applications. *Sensors*, 24(2), article number 358. doi: [10.3390/s24020358](https://doi.org/10.3390/s24020358).
- [43] Ramanenkava, A. (2025). *How predictive maintenance in IIoT reduces downtime: Real-world impact*. Retrieved from <https://timspark.com/blog/predictive-maintenance-iiot-reduces-downtime/>.
- [44] Rathore, S. (2025). *IoT application development lifecycle: From idea to deployment*. Retrieved from <https://www.hashstudioz.com/blog/iot-application-development-lifecycle-from-idea-to-deployment/>.
- [45] Rejeb, A., Suhaiza, Z., Rejeb, K., Seuring, S., & Treiblmaier, H. (2022). The Internet of Things and the circular economy: A systematic literature review and research agenda. *Journal of Cleaner Production*, 350, article number 131439. doi: [10.1016/j.jclepro.2022.131439](https://doi.org/10.1016/j.jclepro.2022.131439).
- [46] Sapra, Y. (2025). *Zero-defect manufacturing: The role of big data in achieving 100% quality control*. Retrieved from <https://www.hashstudioz.com/blog/zero-defect-manufacturing-the-role-of-big-data-in-achieving-100-quality-control/>.
- [47] Shamrei, Yu. (2024). *2025 trends: Impact of Internet of Things (IoT) on the business & economy*. Retrieved from <https://sumatosoft.com/blog/impact-of-internet-of-things-iot-on-the-business-economy-trends>.
- [48] Siemens energy builds industrial IoT platform and drives smart manufacturing using AWS IoT. (2024). Retrieved from <https://aws.amazon.com/ru/solutions/case-studies/siemens-energy-video-case-study/>.
- [49] Singhal, D., Garg, I., Vani, V., & Pundeer, K. (2024). The economic impact of Internet of Things. *Futuristic Trends in IOT*, 3, 196-206. doi: [10.58532/V3BDIO3P2CH5](https://doi.org/10.58532/V3BDIO3P2CH5).
- [50] Sloan, H. (2024). *How IoT impacts the economy*. Retrieved from <https://www.ietfforall.com/how-iot-impacts-economy>.
- [51] Sun, X., & Wang, X. (2022). Modeling and analyzing the impact of the Internet of Things-based Industry 4.0 on circular economy practices for sustainable development: Evidence from the food processing industry of China. *Frontiers in Psychology*, 13, article number 866361. doi: [10.3389/fpsyg.2022.866361](https://doi.org/10.3389/fpsyg.2022.866361).
- [52] Tely AI Team. (2025). *10 ways real-time data analytics boost manufacturing operations*. Retrieved from <https://examples.tely.ai/10-ways-real-time-data-analytics-boost-manufacturing-operations/>.
- [53] Ten years of Industry 4.0. (n.d.). Retrieved from <https://www.bosch.com/stories/10-years-industry-4-0-at-bosch/>.
- [54] Tianjin port: Building a world-class smart port. (n.d.). Retrieved from <https://www.huaweicloud.com/intl/en-us/about/takeacloudleap2024/tianjin-port.html>.
- [55] Tsiplanitis, D., Misirli, A., Lavidas, K., & Komis, V. (2025). IoT devices and their impact on learning: A systematic review of technological and educational affordances. *IoT*, 6(3), article number 45. doi: [10.3390/iot6030045](https://doi.org/10.3390/iot6030045).
- [56] Wang, X., Dong, F., Liu, Y., & Li, Y. (2024). How does the internet affect regional sustainable development? Fresh evidence from China. *Humanities and Social Sciences Communications*, 11, article number 1591. doi: [10.1057/s41599-024-04111-0](https://doi.org/10.1057/s41599-024-04111-0).
- [57] World Bank Group. (2024). *Digital progress and trends report 2023*. Washington: World Bank. doi: [10.1596/978-1-4648-2049-6](https://doi.org/10.1596/978-1-4648-2049-6).
- [58] Yogen Sevak, K., & George, B. (2024). The evolution of Internet of Things (IoT) research in business management: A systematic review of the literature. *Journal of Internet and Digital Economics*, 4(3), 242-265. doi: [10.1108/JIDE-12-2023-0026](https://doi.org/10.1108/JIDE-12-2023-0026).
- [59] Zhang, C., Liu, B., & Yang, Y. (2024). Digital economy and urban innovation level: A quasi-natural experiment from the strategy of "Digital China". *Humanities and Social Sciences Communications*, 11, article number 574. doi: [10.1057/s41599-024-03122-1](https://doi.org/10.1057/s41599-024-03122-1).
- [60] Zoting, S., & Shivarkar, A. (2025). *Industrial IoT market size, share, and trends 2025 to 2034*. Retrieved from <https://www.precedenceresearch.com/industrial-iot-market>.

Економічні аспекти проектів на основі Інтернету речей

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Анотація. Метою цього дослідження було вивчити, як впровадження технологій Інтернету речей (IoT) впливає на економічні показники, оцінивши їхній вплив на ефективність, зниження витрат та трансформацію бізнес-процесів. Методологія базувалася на теоретичному аналізі наукових джерел, контент-аналізі технічних описів, порівняльній оцінці корпоративних кейсів та галузевих аналітичних підходах. Результати показали, що IoT забезпечує істотне та стабільне підвищення ефективності в усіх секторах. У промисловості цифровізація досягає 57,5 %, ручні дії зменшуються на 40-60 %, а витрати на робочу силу знижуються приблизно на 25 %. Прогнозне технічне обслуговування знижує незаплановані простої на 25-35 % і підвищує продуктивність на 20-30 %. У логістиці інтелектуальне маршрутизування зменшує транспортні витрати на 10-25% і час доставки на 20-25 %. У сільському господарстві дрони та датчики скорочують використання агрохімікатів на 30-45 % і споживання води до 90 %, а врожайність збільшується на 15-30 %. В енергетичному секторі інтелектуальні лічильники зменшують споживання електроенергії на 2,5-3,5 %, а системи Smart Grid зменшують втрати в мережі на 15-25 %. На макrorівні цифрова економіка в країнах Організації економічного співробітництва та розвитку зростала в 2,5 рази швидше, ніж валовий внутрішній продукт, а 10-відсоткове збільшення підключень до Інтернету речей підвищило загальну продуктивність факторів виробництва на 0,23 відсоткових пункти. Дослідження також виявило перешкоди для впровадження, зокрема обмежену сумісність, відсутність стандартів, ризики безпеки, нестачу фахівців, нестабільне регулювання та високі інвестиційні й операційні витрати з невизначеною віддачою. Результати можуть бути застосовані підприємствами та державними установами для підвищення ефективності та оптимізації використання ресурсів

Ключові слова: цифрова інфраструктура; сенсорні мережі; дані в режимі реального часу; операційна ефективність; інвестиції; кібербезпека

Methodology for implementing digital financial controlling tools in companies in Kyrgyzstan

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Abstract. This study aimed to analyse approaches to the effective use of digital technologies to improve the performance of the financial controlling system in companies in Kyrgyzstan. The methodological basis of the research was a systemic approach, including the analysis of corporate reporting, a comparative analysis of digitalisation practices and an assessment of the functional components of financial controlling. Within the framework of the study, a comprehensive analysis was carried out of three open joint-stock companies – OJSC Eldik Bank, OJSC “Electric Power Stations” and “Kumtor Gold Company”, which made it possible to identify differences in the levels of digital maturity of financial management in the banking, energy and industrial sectors. The analysis showed that in the financial sector integrated information systems are most actively implemented; these ensure the automation of management accounting, centralised access to financial data and the development of analytical tools to support managerial decision-making. In the industrial sector, digitalisation has covered the automation of production and financial accounting, as well as the introduction of Business Intelligence platforms for data analysis and the conduct of electronic tenders. This contributed to improving the accuracy of cost-forecasting, reducing the time needed for budgeting and ensuring the output of 13.567 kg of gold with tax payments that exceeded KGS 17.2 billion in 2023. In conclusion, practical recommendations are presented for Kyrgyz companies, including a comprehensive diagnosis of accounting systems, the development of a digital transformation roadmap, the introduction of enterprise resource planning platforms with integrated management accounting modules, and the development of staff competences in analytics and financial forecasting. The practical value of the study lies in the proposal of specific recommendations for Kyrgyz enterprises and financial managers on the implementation of digital controlling tools

Keywords: forecasting; strategic planning; analytics; management decisions; budgeting

Introduction

In the context of accelerated digital transformation, expressed in the introduction of cloud technologies, automated accounting systems and the transition to electronic document management, one of the priority tasks of companies in Kyrgyzstan is to improve the efficiency of financial flow management and control over the use of resources. Trends associated with the widespread automation of business processes, the growth in data volumes, the strengthening role of analytics and the need for rapid responses to market changes require a transition from traditional methods of financial controlling to innovative digital tools that ensure prompt access to data, automation of analysis and

improved accuracy of managerial decisions. Despite the growing interest in digital technologies, the process of the introduction into the financial controlling system of Kyrgyz enterprises faces a number of problems. The main ones include an insufficient level of digital maturity of organisations, limited qualified personnel in the field of financial technologies, as well as the absence of unified methodological approaches to the integration of digital tools into the controlling system. On this basis, the relevance of the study is determined by the need to develop scientifically grounded recommendations and methods aimed at improving the effectiveness of financial controlling through digitalisation.

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Issues of digitalisation of financial controlling have become the subject of scientific research, which indicates a growing interest in the problem of increasing the transparency and efficiency of financial management in the digital economy. M.T. Kologonov (2024) examined the influence of cloud technologies on the system of management accounting and financial analysis. The author proved that the transition to cloud solutions allows companies to increase the speed of processing financial information, reduce infrastructure costs and ensure data availability for all management levels. P. Hofmann *et al.* (2020) focused on the transparency and reliability of financial data. The study showed that the introduction of electronic document management systems and automated reporting forms helps to reduce the number of errors and eliminate the duplication of information.

The development of the theme was traced in the study by N. Temirov *et al.* (2023), who examined the possibilities of integrating digital tools into planning and budgeting processes. According to the study, the use of automated controlling systems makes it possible not only to reduce the time needed to generate planned indicators, but also to ensure flexibility of adjustments when market conditions change. J.B. Awotunde *et al.* (2021) supplemented this point of view by examining the potential of Big Data technologies in the system of financial analysis. The authors found that the use of analytical platforms with elements of machine learning helps to identify hidden patterns in financial flows and to predict possible risks.

In turn, S. Yuldoshboy *et al.* (2025) focused on the managerial risks of digitalising controlling. The researchers emphasised that the introduction of technologies without a preliminary audit of existing information systems may lead to inefficiency and duplication of functions. The role of the human factor in the digital transformation of financial controlling was examined by M. Buenestado-Fernández *et al.* (2023). The authors proved that the level of digital competence of financial specialists is a key success factor in the implementation of new technologies. Without systematic staff training, even modern digital solutions do not provide the desired effect, which is relevant for developing economies.

The practical significance of the digitalisation of controlling was demonstrated by G. Dzieża & M. Sikora (2022), who studied the introduction of monitoring dashboards at industrial enterprises. The scholars found that such tools increase the transparency of financial processes, accelerate communication between divisions and help to reduce the time needed to prepare management reports. Similar conclusions were drawn by A. Kadyraliev *et al.* (2024), who noted that the automation of controlling processes makes it possible to significantly reduce the costs of internal audit and to minimise the risk of subjective errors. The authors emphasised that digital tools provide a transition from reactive to proactive management, in which the company is able to anticipate deviations and prevent financial risks at early stages.

In the work by V. Corvello *et al.* (2023), the influence of digital controlling on the resilience of enterprises in crisis conditions was considered. The authors concluded

that companies that had implemented digital solutions for financial analysis and monitoring demonstrate more stable results even when market activity declines. E. Llazo *et al.* (2024) proposed a systemic approach to the digitalisation of controlling, considering it as an element of a unified corporate information environment. The researchers proved that the integration of digital tools with accounting, planning, and analysis systems makes it possible to create a continuous management circuit in which data become the basis of strategic decisions.

The analysis of the above-mentioned studies showed that digital technologies increase the effectiveness of financial controlling. Despite the progress in studying the influence of digital technologies on the system of financial controlling, there remain a number of aspects that require further scientific reflection. Firstly, methodological approaches to the comprehensive introduction of digital tools into controlling practice, taking into account the peculiarities of the organisational structure and digital maturity of enterprises in Kyrgyzstan, have not been sufficiently studied. In addition, scientific sources do not sufficiently present practical algorithms for integrating digital platforms that ensure end-to-end control of financial flows – from planning to the analysis of results.

The aim of the study was to analyse ways of integrating digital technologies into the management control system of companies in Kyrgyzstan in order to increase its efficiency and adaptability to economic conditions. Within the framework of the study, tasks were set to examine current trends and conceptual approaches to the digital transformation of financial controlling, to diagnose the level of digital maturity of companies in Kyrgyzstan and the readiness to implement the relevant tools, and to develop methodological recommendations for adapting and integrating digital technologies into the controlling system, taking into account national and organisational characteristics.

Materials and Methods

The study was based on the integrated use of systemic, comparative and analytical approaches, which made it possible to consider financial controlling as an integrated part of corporate governance under conditions of digital transformation. The methodological basis included the analysis of the theoretical provisions of modern controlling and the study of digital tools for planning, analysis and accounting using the example of enterprises in Kyrgyzstan, Germany, the United States (US), Eastern (Poland and the Czech Republic) and Northern Europe (Finland). These regions were selected due to differences in models of controlling digitalisation: from highly mature integrated systems to adaptive solutions forming under conditions of structural changes in the economy.

The object of the study was Enterprise Resource Planning (ERP) and Business Intelligence (BI) platforms used in financial controlling. The systems Standard Assessment Procedure (SAP, n.d.), Oracle (n.d.), Microsoft Dynamics 365, as well as BI tools Power BI, Tableau and QlikView were considered. For each platform, the degree of integra-

tion with management accounting, the availability of budgeting tools, the level of reporting automation, the coverage of business processes, support for predictive analytics and artificial intelligence (AI), scalability and data visualisation capabilities were analysed. These criteria made it possible to compare the functional potential of the systems and to determine the applicability for forming a digital controlling circuit at enterprises in Kyrgyzstan.

Within the framework of the comparative analysis, enterprises demonstrating different models of controlling automation were examined. In Germany, the analysis included the use of SAP S/4HANA and Qlik Sense using the example of Siemens AG, where controlling is organised on the basis of integrated information solutions; for the study of the structure and tools of corporate controlling, the “Annual Report for fiscal 2022” of Siemens AG (2022) was analysed. In the US, the corporations General Electric Company (n.d.) and IBM (n.d.) were examined, applying the platforms Predix and IBM Planning Analytics, oriented towards working with large data sets and analytical models. In Eastern Europe, attention was paid to Żywiec Group (n.d.) (Poland) and Group CEZ (n.d.) (the Czech Republic), which use Oracle NetSuite and Microsoft Dynamics 365 as tools for standardising planning and management accounting processes. In Finland, the analysis covered the integration of environmental, social, governance (ESG) indicators into controlling systems, which reflects the expansion of the functional purpose of digital platforms. The comparison carried out was aimed at identifying elements of international experience that are potentially adaptable to the conditions of Kyrgyz companies.

The analysis included enterprises with available financial reporting and data on digital transformation: Eldik Bank (2023), Consolidated financial statements... (2024) and Kumtor Gold Company (n.d.). The selection was due to sectoral specificity and differences in the degree of digital maturity, which made it possible to trace the features of controlling development in the banking, energy and industrial-mining sectors in Kyrgyzstan. The analysis included the study of the platforms used, the integration of automated accounting systems and the mechanisms for using analytical tools in managerial processes. Materials were examined for the period 2021-2024, since it was during this time that the active introduction of integrated digital systems took place and the role of financial analytics in ensuring the managerial sustainability of enterprises strengthened. Thus, the materials and methods applied ensured a comprehensive study of the digital transformation of financial controlling in the Kyrgyz Republic and made it possible to link theoretical concepts with practical results reflecting the real impact of ERP and BI technologies on the effectiveness of corporate governance.

Results

Financial controlling is a mandatory element of the modern enterprise management system and represents an integrated mechanism that combines the functions of planning,

analysis, accounting, and control. Its essence lies not merely in observing financial results, but in managing these results through a system of information, forecasting and regulation. Controlling provides managers with reliable and timely data necessary for making well-founded managerial decisions (Li *et al.*, 2020). Unlike classical control, which focuses on identifying errors post factum, controlling is aimed at preventing deviations, forming development scenarios and achieving the strategic goals of the enterprise. Thus, it performs the role of a navigational tool that helps the organisation maintain financial stability under conditions of a changing external environment.

The essence of controlling is manifested in its systemic nature. It covers the entire managerial cycle – from strategic planning to the analysis of budget execution and the adjustment of managerial decisions. Controlling is not limited to individual functions of accounting or audit, but integrates these functions into a unified analytical system. Its main purpose is the coordination of planning and control processes in such a way that the enterprise can not only achieve its set goals, but also adapt to changing market conditions (Alawaqleh, 2021). In this context, controlling becomes the foundation of business, linking the strategic and operational levels of management. It creates the information basis on which the whole system of managerial decisions is built.

Functionally, financial controlling performs several key tasks without which effective management of an organisation is impossible. First and foremost, this is the planning and analytical function, which includes the formation of budgets and financial plans, forecasting income and expenditure, as well as the analysis of the implementation (Fuentes *et al.*, 2020). On its basis, management gains the opportunity to assess the correspondence of actual results to planned goals and to adjust strategy in a timely manner. The second function is coordination. Controlling ensures the alignment of interests between divisions, helps to eliminate the duplication of functions and to optimise the use of resources (Basiru *et al.*, 2023). This is important for large enterprises where financial, production and marketing departments operate in a fragmented way.

The control function of controlling is expressed not only in checking the correctness of accounting, but also in assessing the efficiency of economic activity. It makes it possible to identify inefficient processes, excessive costs and internal risks in a timely manner. However, unlike classical control, controlling is not limited to recording errors – it offers mechanisms for the prevention and elimination (Tamulevičienė & Androniceanu, 2020). Another important function is information support, which consists in the collection, processing, and interpretation of data for managerial needs. Modern enterprises work with a huge volume of information, and it is precisely controlling that ensures its structuring, reliability and analytical value (Dědečková, 2020). Owing to this, managers are able to make decisions based on objective indicators rather than on intuition.

The role of financial controlling in the enterprise management system goes beyond financial analysis or budget

planning. In modern conditions, it performs a strategic function, contributing to the formation of the company's long-term sustainability. Controlling ensures a balance between profitability, liquidity and risks, helps to optimise the capital structure and to allocate resources rationally. It transforms financial information into a management tool oriented towards achieving specific economic results. Under conditions of high market volatility, controlling becomes a key instrument of crisis management, enabling rapid responses to changes and preventing threats to financial stability.

The role of financial controlling has been significantly strengthened by the development of digital technologies. Modern digital solutions, including business analytics (BI) systems, artificial intelligence and machine learning, make it possible to analyse huge data sets with high speed and accuracy (Paramesha *et al.*, 2024). As a result, financial controlling acquires a proactive character: managerial decisions are formed on the basis of not only historical but also forecast indicators. This approach significantly increases the adaptability of the enterprise, shortens planning cycles and improves the quality of strategic decisions.

ERP systems acquire particular importance in the pro-

cess of digital transformation of controlling, as these systems ensure the comprehensive integration of financial, production, HR and logistics data, forming a single information space of the enterprise. The use of such platforms as SAP (n.d.), Oracle (n.d.) ERP Cloud and Microsoft Dynamics 365 makes it possible to combine fragmented data flows into a single management accounting system, which contributes to the formation of end-to-end financial analytics – from operational indicators to strategic metrics. These systems differ in the level of integration with budgeting processes, the depth of reporting automation, scalability, and the application of artificial intelligence for predictive analytics. BI platforms such as Power BI, Tableau and QlikView play an equally important role in the controlling system, providing tools for data visualisation, analysis and forecasting. These solutions differ in the level of integration with ERP systems, the depth of analytics, user interface and the capabilities for implementing predictive models. For a systematic comparison of the capabilities of ERP and BI platforms, Table 1 is presented, reflecting the key criteria for assessing the effectiveness in the context of financial controlling.

A comparative analysis showed that ERP and BI platforms possess different functional advantages and optimal

Table 1. Comparative characteristics of ERP and BI platforms according to digital controlling criteria

Evaluation criterion	SAP	Oracle ERP Cloud	Microsoft Dynamics 365	Power BI	Tableau	QlikView
Integration with management accounting	High, support for comprehensive management analysis	Medium, can be customised for the sector	Medium, with limitations in the basic version	High with Microsoft Dynamics	Medium with Oracle ERP	High with SAP
Budgeting tools	Full cycle of planning and forecasting	Flexible configuration of budget scenarios	Basic functions, integration via Power Apps	Configuration of budget dashboards	Support for reporting	Analytics of budget indicators
Reporting automation	Full, with support for IFRS and local standards	Automated, with the possibility of user templates	Partial, requires further development	Automatic data updates	Interactive reports	Visual analytics
Coverage of business processes	Production, logistics, finance, HR, procurement	Finance, procurement, CRM, HR	Finance, sales, service	Analytics across all ERP modules	Financial and operational analytics	Comprehensive KPI analysis
Support for AI and predictive analytics	Built-in SAP Analytics Cloud modules	Uses Oracle Artificial Intelligence (AI) and ML Services	Support via Azure AI	Forecasting based on ML	Advanced analytics via Einstein Discovery	Forecasting based on SAP data
Scalability and adaptability	High, corporate level	High, cloud architecture	Medium, suitable for SMEs	High, depends on ERP integration	Medium	High
Level of data visualisation	High via SAP Analytics Cloud	Medium, reports in Oracle Analytics	Medium, Power BI dashboards	Maximum	Maximum	High

Note: CRM – Customer Relationship Management, HR – Human Resources, KPI – Key Performance Indicators, IFRS – International Financial Reporting Standards, ML – Machine Learning

Source: compiled by the author based on SAP (n.d.), Oracle (n.d.)

areas of application: SAP provides the highest level of integration with management accounting and advanced tools for scenario modelling; Oracle ERP Cloud is distinguished by flexible configuration of budgeting processes and reporting automation; Microsoft Dynamics 365 is characterised

by an accessible architecture for small and medium-sized businesses and combines management accounting with the capabilities of analytics and machine learning. Among BI tools, Power BI demonstrates high compatibility with Microsoft Dynamics 365, Tableau with Oracle ERP, and

QlikView with SAP, which makes it possible to form comprehensive systems for real-time data analysis. Overall, the combination of SAP and QlikView represents the most comprehensive option for deep integration of accounting and visualisation, whereas the bundle of Microsoft Dynamics 365 and Power BI is the most rational for medium-sized enterprises in Kyrgyzstan in terms of cost, functional sufficiency and ease of implementation.

A significant contribution to the development of digital controlling is made by the use of cloud technologies. The transition to cloud solutions provides companies with access to financial data regardless of location and allows optimising IT infrastructure costs (Nutralapati, 2024). For companies in Kyrgyzstan, where resources are often limited, cloud platforms have become a real alternative to expensive corporate systems. Such platforms offer the opportunity to automate the main processes of financial accounting, and when integrated with BI tools, to obtain full-scale analytics and forecasting (Narayan, 2022). Thus, digital transformation makes financial controlling accessible not only to large corporations, but also to small and medium-sized businesses, forming the basis for more rational and transparent management.

Digitalisation also changes the role of the financial controller. The controller becomes a digital strategist capable of managing data and creating analytical models for forecasting future scenarios. The controller of a new generation combines financial, technological and managerial competences, which requires a revision of approaches to the training of specialists. In this context, the development of a financial analytical culture – the ability to use data not only for reporting but also for developing decisions aimed at creating added value – becomes particularly relevant.

Financial controlling in companies in Kyrgyzstan is at a formative stage and has not yet become a full-fledged element of the management system. Enterprises are limited to accounting and tax accounting, while the functions of planning, analysis and forecasting are poorly developed. This is explained by the historical orientation of business towards short-term goals – ensuring liquidity, minimising costs and fulfilling tax obligations – rather than towards long-term strategic development. One of the main problems is the absence of specialised controlling units. At enterprises, the functions of analysis and control are distributed between the accounting and finance departments, which leads to fragmented information and reduced effectiveness of managerial decisions. Controlling is perceived not as a tool of strategic management, but as a technical part of reporting (Ashymova, 2020).

The second significant factor is the low level of digital maturity of business. The most widespread solutions – 1C:Enterprise and local cloud platforms – are used predominantly for accounting. The capabilities of these systems for management analysis, budgeting and BI monitoring remain unrealised. The main reason is the lack of specialists capable of working with analytical tools and interpreting financial data in a managerial context. Staff

shortages are one of the key problems. In universities in Kyrgyzstan, controlling is studied superficially, without an emphasis on digital technologies and integrated management systems. Therefore, even financial specialists often do not master modern tools of analysis and forecasting (Dzhumagulov & Mistriukova, 2025).

Nevertheless, trading and manufacturing companies in Bishkek and Osh have begun to introduce elements of management accounting and BI dashboards for the analysis of sales and costs (World Bank Group, 2025). This makes it possible to accelerate the preparation of reports and increase the transparency of financial flows. The main barriers to the development of controlling are a fragmented digital infrastructure, data fragmentation and the high dependence of business on external factors (exchange rates, tax instability, import dependence). However, the growing interest in analytics and participation in national digitalisation programmes create preconditions for the formation of modern digital controlling.

In countries with developed economies, the digitalisation of financial controlling has become an important direction for improving management efficiency and the transparency of business processes. For example, in Germany, where controlling has formed as an independent management concept, leading companies actively use SAP S/4HANA ERP systems and Qlik Sense BI platforms to integrate data from various divisions. For instance, the Siemens AG group (2022) implemented a centralised system of digital controlling that makes it possible to monitor cost indicators in real time, forecast cash flows and analyse the efficiency of investment projects. This made it possible to accelerate the preparation of management reporting by more than 40% and to reduce the number of manual operations. German experience demonstrates that digital controlling is not limited to automation; it becomes a tool for strategic analysis and support for decisions at the level of corporate governance.

In the United States, financial controlling is developing in close connection with artificial intelligence technologies and big data analytics. Large corporations such as General Electric Company (n.d.) and IBM (n.d.) have integrated machine-learning tools into the controlling system, which forecast financial results and identify anomalies in data flows. For example, at General Electric Company, the digital platform Predix is used to build financial models reflecting the influence of production and market factors on profitability. Due to this, controllers can quickly identify inefficient areas and reallocate resources. Similar systems make it possible to move from retrospective analysis to predictive management, when decisions are made on the basis of scenario forecasting rather than post factum reports. IBM has implemented a similar approach by introducing the intelligent IBM Planning Analytics platform, built on TM1 technology and integrated with Watson artificial intelligence tools. This system ensures automated budget formation, scenario analysis and cash flow forecasting with consideration of market factors.

In Eastern European countries, the digital transformation of controlling has become relevant in the context of integration into the European economic system. For example, in Poland and the Czech Republic, cloud ERP solutions such as Oracle NetSuite and Microsoft Dynamics 365 are being actively implemented, allowing small and medium-sized enterprises to build transparent management processes at moderate costs. The Polish company Żywiec Group (n.d.) (a subsidiary of Heineken) has implemented a comprehensive controlling system that combines planning, budgeting and analysis functions in a single digital space. This made it possible to increase the accuracy of financial forecasts by 25% and to accelerate the process of report consolidation within the international group. A similar approach was implemented by the Czech energy company Group CEZ (n.d.), one of the largest in Central Europe. As part of digital transformation, the Microsoft Dynamics 365 system was integrated with the BI tools Power BI and Qlik Sense, which ensured the automation of financial flow monitoring, management of investment programmes and cost forecasting for power plant modernisation projects.

The Scandinavian experience is noteworthy, where controlling is closely linked to the concept of sustainable development (ESG). Finnish companies integrate digital controlling dashboards not only for the analysis of financial indicators, but also for monitoring environmental and social indicators. Nokia (n.d.) uses Tableau and Power BI tools to combine financial and non-financial data, which makes it possible to monitor not only profitability but also energy efficiency, CO₂ emissions and social metrics. This approach reflects a modern trend: controlling becomes a tool of comprehensive corporate governance, where digitalisation strengthens not only the economic but also the social responsibility of business.

In Kyrgyzstan, the digitalisation of financial controlling is developing unevenly; however, a number of companies already demonstrate successful examples of the implementation of modern tools. With properly organised processes, even under conditions of limited resources, it is possible to create effective systems of management analytics and control. The financial sector of Kyrgyzstan demonstrates the most advanced level of digital controlling. Eldik Bank (n.d.) is one of the most illustrative examples of digital transformation in the financial sector of Kyrgyzstan. The bank has implemented a digitalisation strategy aimed

at improving the efficiency of internal processes, expanding client services and strengthening its market position. One area of development has been the creation of the mobile application “Eldik”, which has become the central element of the bank’s digital ecosystem. To support technological initiatives, in 2024, Eldik Bank established the subsidiary company ElTech, responsible for the development and implementation of digital products (Akhmatova, 2024). The creation of this structure made it possible to optimise the bank’s internal processes related to financial accounting, analytics and the integration of management data. In the same year, in cooperation with the mobile operator MEGA, the Ishker24 platform was launched (version 1.0 – July 2024), aimed at supporting entrepreneurs (RSK Bank & MEGA..., 2024). The service provides functionality for online payments, accounting of financial operations and interaction with state digital services. The implementation of these initiatives became an important step towards the digitalisation of financial controlling, ensuring increased transparency, greater data-processing speed and the automation of management reporting.

Moreover, Eldik Bank (2023) implements programmes in the field of sustainable finance and digital financial inclusion, which is reflected in its strategic documents and sustainability reports. In particular, the bank participates in state projects to support entrepreneurship and to expand access to financial services in the regions. The publication of the “Sustainability report 2023” according to GRI and IFRS standards testifies to the introduction of a systematic approach to data collection, analysis and presentation, which is directly related to the principles of financial controlling. The bank also became the first in Central Asia to connect to the Chinese Cross-border Interbank Payment System (CIPS), providing cross-border settlements in yuan (The CIPS system..., 2025). This strengthened the bank’s digital infrastructure and made it possible to integrate international financial flows into a single management system. The acquisition of the telecommunications operator Beeline Kyrgyzstan (Sky Mobile) also demonstrates the striving to create a comprehensive digital ecosystem that combines finance, communications, and analytics (Eldik Bank acquired..., 2025). Table 2 presents the elements of the company’s digital controlling tools.

Eldik Bank can be considered one of the leading examples of digitalisation of the financial sector of Kyrgyzstan,

Table 2. Elements of financial controlling of Eldik Bank

Controlling component/digital tool	What has already been implemented at Eldik Bank	Shortcomings / areas for development
ERP/management accounting	No indirect data were found on an ERP system with full management accounting modules. The main digital products are the mobile application, digital platforms and GovFintech services	Integration of management accounting, budgeting and cost analysis modules is required
BI/real-time analytics	Through the mobile application and the Ishker24 platform, digital services and analytics of client operations are provided. Subscription to ESG metrics and the sustainability report form part of external analytics	Lack of data on BI dashboards for internal controlling
Infrastructure and digital ecosystem	The creation of ElTech, the acquisition of Beeline and connection to CIPS all indicate the creation of a digital ecosystem and the expansion of payment channels and cross-border operations	Deeper integration between banking and telecom data is required

Continued Table 2

Controlling component/digital tool	What has already been implemented at Eldik Bank	Shortcomings / areas for development
Performance evaluation, metrics	Historical profit, growth in capitalisation, positions in rankings, fulfilment of sustainable development, and external reporting are available.	There are no open data on the impact of digital tools on the effectiveness indicators of management control.

Source: compiled by the author based on Eldik Bank (n.d., 2023), I. Akhmatova (2024), RSK Bank & MEGA launched version 1.0 of the Ishker24 microfinance system to transition to the new tax regime (2024), The CIPS system has been launched: Eldik Bank has opened direct payments in yuan for businesses in Kyrgyzstan (2025), Eldik Bank acquired the operator Beeline Kyrgyzstan (2025)

where elements of digital controlling are beginning to be formed within the framework of a broader digital development strategy. Despite significant progress in automation, analytics and service integration, the bank's system still lacks a transparent methodology of internal financial controlling at the level of management accounting and forecasting. The further development of these areas will allow Eldik Bank to move from the digitalisation of services to a full-fledged system of digital controlling, providing strategic management based on data.

OJSC Electric Power Plants (n.d.) is an electricity producer in Kyrgyzstan, managing hydroelectric and thermal power plants throughout the country. The company is actively working on the modernisation of its infrastructure and the introduction of digital technologies to improve management efficiency. As part of the development of the financial controlling system, digital tools were introduced to integrate accounting and management accounting, which made it possible to reduce the time needed to prepare management reporting from 10-12 to 3-5 working days, and the discrepancies between planned and actual indicators on average from 8-10% to 2-3%. The introduction

of digital cost-control modules ensured regular monitoring of budget execution by centres of financial responsibility, as a result of which the proportion of uncontrolled overspending decreased by approximately 15-20%, and the accuracy of planning operating expenses increased by 10-12% (Consolidated financial statements..., 2024). Owing to this, the enterprise achieved more rational allocation of resources, reduced equipment downtime and increased the overall efficiency of production processes.

Regular publication of annual reports on the company's official website makes it possible to track financial results, the implementation of digital solutions and the impact on business processes. Despite significant progress, the company faces the need to integrate the Automated Electricity Metering System (AEMS) with other accounting and management systems, to develop analytical tools for the real-time analysis of financial data and to create a unified digital ecosystem that combines all aspects of activity. Table 3 presents the elements of the company's digital controlling tools.

Thus, OJSC "Electric Power Stations" demonstrates active work on the introduction of digital tools in the field of

Table 3. Elements of financial controlling of the Open Joint-Stock Company (OJSC) "Electric Power Stations"

Controlling component/digital tool	What has already been implemented at OJSC "Electric Power Stations"	Shortcomings/areas for development
ERP/management accounting	The processes of accounting and management accounting have been partially automated; digital data processing is used for costs, revenue, and responsibility centres.	There is no unified ERP platform, and integration of fragmented accounting systems into a single financial controlling framework is required.
BI/real-time analytics	Digital monitoring of key financial and production indicators is carried out, and internal analytical reports are generated in electronic form.	Full-function BI dashboards for online KPI analysis and financial forecasting have not been implemented.
Infrastructure and digital ecosystem	Corporate information systems and internal digital platforms are used for the exchange of financial and production data.	Insufficient integration of IT systems between divisions, and the absence of a unified digital architecture for financial management.
Performance evaluation, metrics	Annual financial results are published and a basic analysis of budget execution is carried out.	No internal KPI system of digital controlling has been formed, and regular evaluation of the economic effect of digitalisation is not applied.

Source: compiled by the author based on OJSC Electric Power Plants (n.d.), Consolidated financial statements... (2024)

financial controlling. The implementation of the Automated System of Electricity Metering, the development of digital channels of interaction with customers and the publication of financial information indicate the company's striving to increase the efficiency and transparency of its financial processes. However, for the full-scale digitalisation of financial controlling, further development of analytical tools,

integration of data from various sources and staff training for the effective use of new technologies are required.

Kumtor Gold Company (n.d.) is a large mining enterprise in Kyrgyzstan and one of the most transparent in terms of publishing financial and operational information. The company introduces digital technologies with the aim of improving management efficiency, optimising costs and

strengthening financial controlling. One of the key areas of digital transformation within the enterprise has been the implementation of automated systems of production and financial accounting, which integrate data on extraction, ore processing, fuel costs, equipment depreciation and wages. The company, with revenue of more than USD 989 million and a staff of about 3,436 employees, has managed to significantly improve the accuracy of calculating production cost and ensure more reliable financial reporting (Kumtor Gold Company, 2024). The use of integrated monitoring and analytical systems facilitated control over budget execution and cash flow forecasting, which became an important element of the transition to managerial controlling.

In 2023, Kumtor Gold Company (n.d.) announced the launch of projects on the digitalisation of document

management, the introduction of BI platforms for the analysis of production and financial data, and the automation of procurement. This made it possible for the management to monitor key performance indicators in real time, control the implementation of plans and make more well-grounded decisions. In addition, due to the introduction of remote equipment monitoring systems and automatic data collection from production sites, the company gained the opportunity to integrate these data with financial statements, which strengthened managerial controlling through the comparison of operational and financial metrics. Table 4 presents the elements of the company's digital controlling tools.

Thus, Kumtor Gold Company demonstrates one of the most advanced examples of the implementation of digital

Table 4. Elements of financial controlling of OJSC “Kumtor Gold Company”

Controlling component/ digital tool	What has already been implemented at OJSC “Kumtor Gold Company”	Shortcomings / areas for development
ERP/management accounting	A system of cost accounting and production indicators has been implemented, integrated with accounting and tax reporting; regular publication of audited financial statements is carried out.	Full integration of ERP with extraction and supply systems is required for end-to-end analysis of all stages of the production cycle.
BI/analytics and forecasting	BI platforms are used for the analysis of production and financial indicators; data are aggregated for KPI monitoring and report preparation for management.	Predictive analytics needs to be introduced for forecasting gold prices, planning extraction and financial scenarios.
Automation of document management and procurement	Electronic tenders, digital signatures and internal electronic document flow have been introduced, which accelerated the approval of expenditure and increased the transparency of financial processes.	The system should be expanded to all subsidiary units and include real-time monitoring of contract execution.
Infrastructure and data collection	Systems of remote equipment monitoring and production data collection have been introduced, integrated with financial statements.	Centralisation of data in a single cloud storage and the integration with the BI system for automatic analytics are required.
Performance evaluation, metrics	Data on extraction (13.567 kg of gold in 2023), tax payments (KGS 17.2 billion) and staff numbers (about 3,000 employees) are published.	Expansion of the KPI system is required, including indicators of reporting speed, forecast accuracy and cost savings after digitalisation.

Source: compiled by the author based on Kumtor Gold Company (n.d.; 2024)

tools of financial controlling in Kyrgyzstan. The company is consistently integrating automation into accounting, analysis and planning processes, ensuring a high level of transparency and efficiency. Further development of digital solutions should be aimed at deepening analytics, unifying data from different divisions and introducing intelligent forecasting tools to improve business manageability.

The analysis of three companies showed that the introduction of digital tools of financial controlling in Kyrgyzstan is developing unevenly, but demonstrates a stable positive dynamic. The financial sector (using the example of Eldik Bank) is already using digital technologies: BI systems, online platforms, automation of internal control and analytics. This made it possible to increase the transparency of operations, improve risk management and accelerate the preparation of reports. In the energy sector (using the example of Electric Power Stations), digitalisation has a more infrastructural nature – the main attention is paid to the automation of accounting, monitoring of technical processes and increasing data accuracy, which creates the basis for the implementation of full-scale controlling based on ERP

solutions. In the industrial sector, represented by Kumtor Gold Company, digital technologies are already integrated into production and financial processes: cost accounting is automated, monitoring systems, electronic document management and BI analytics have been introduced, which ensures a high level of manageability and transparency.

Based on the analysis of digital tools of financial controlling, as well as the study of the experience of countries – including examples of system implementation in Germany, the US, Poland, the Czech Republic, Finland, and Kyrgyz companies – practical recommendations were formulated for Kyrgyz enterprises striving to implement digital financial controlling and increase management efficiency through the integration of analytical and managerial technologies. Firstly, enterprises are recommended to carry out a comprehensive diagnosis of the existing system of financial and managerial accounting in order to identify inefficient links – duplication of operations, low speed of report preparation, dependence on manual data entry, and lack of integration between divisions. Based on the results of the analysis, it is advisable to develop a digital transformation

roadmap providing for the transition from fragmented software solutions to a unified ERP platform that ensures the consolidation of data on procurement, production, sales and financial flows. Such integration makes it possible to increase the accuracy of reporting, reduce operating costs and ensure the completeness of managerial information.

The next stage of development is the introduction of BI tools designed for the visualisation of key indicators and real-time analytics. BI technologies make it possible to automate the processes of cost analysis, evaluation of cost efficiency, revenue forecasting and modelling of financial development scenarios. For enterprises operating under conditions of high market volatility, this tool becomes an integral element of modern controlling, ensuring increased adaptability and accuracy of managerial decisions.

Digitalisation of document management and the transition to electronic forms of approval and authorisation of financial operations are also of importance. The use of electronic signatures and automated document management systems contributes to the reduction of administrative costs, increased transparency and a reduction in the time required for financial data processing. At the same time, the introduction of cloud technologies ensures flexibility and scalability of infrastructure, as well as access to data in real time, which is relevant for companies with a geographically distributed structure.

In the context of the integration of operational and financial information, it is advisable to introduce systems for monitoring production indicators linked with financial analysis tools. Such systems, implemented, for example, at Kumtor Gold Company, make it possible to form end-to-end analytics by comparing the dynamics of production processes with financial results, which increases the accuracy of assessing resource-use efficiency and allows timely adjustment of cost-management strategies. An integral element of modern controlling is the development of a system of key performance indicators integrated into digital control panels. Such a system ensures continuous monitoring of financial, production and organisational metrics, creating conditions for increasing transparency and forming an objective system of staff motivation.

An important direction of development is the improvement of staff qualifications involved in financial analysis and managerial accounting processes. Effective use of digital tools requires not only technical skills, but also analytical thinking, the ability to interpret data and apply these data in decision-making processes. In this regard, it is advisable to introduce corporate training programmes and the formation of digital competences at all levels of management. Ensuring information security and data protection is also necessary, since the growth of digital information volumes increases the risks of unauthorised access and leakage of confidential data. Companies must establish internal regulations on data management, introduce backup systems and control access to information.

Thus, the development of digital financial controlling in Kyrgyz enterprises should be carried out gradually and

systematically, covering technological, organisational and personnel aspects. Comprehensive digitalisation of financial processes will enable companies to increase the transparency of managerial decisions, reduce costs, improve forecasting and ensure sustainability in the conditions of the digital transformation of the economy.

Discussion

Financial controlling plays a key role in the management of a modern enterprise, acting as a tool for integrating planning, analysis and control. Its distinctive feature lies not only in recording deviations, but also in its ability to prevent risks, model development scenarios and support strategic decision-making. Companies that perceive controlling as a tool for navigation and resource management are able to respond more flexibly to the dynamics of the external environment, ensuring the stability and integrity of financial processes. This underlines the importance of controlling not only as a means of reporting, but also as a managerial mechanism linking strategic and operational levels. C. Bagwe (2024), in the research, considered controlling as a tool for identifying errors and inaccuracies in financial reporting. Such an approach emphasised the retrospective function of control, limiting its role to corrective action after problems arise. In the conducted research, financial controlling was considered more broadly: it performs the function of a navigational tool that makes it possible to forecast the development of processes and manage resources, and not only correct mistakes. The common feature is the recognition of the importance of controlling in working with financial flows, while the difference lies in the orientation – from reactive control to strategic management.

Functionally, controlling integrates planning, coordination, control, and information support. In organisations where a comprehensive controlling system has been implemented, it ensures synchronisation of the work of divisions, optimisation of resource use and the creation of a transparent management system. An important aspect is the integration of financial information with production and operational flows, which allows managers to see the full picture of the company's activities and make decisions based on objective data. In the study by C. Kuntadi & L. Puspasari (2023), it was established that the use of digital tools in the processes of budget planning and cost management contributes to increasing the transparency of financial flows and accelerating decision-making, however the author limited himself to examining exclusively financial functions, without addressing the aspect of integration with managerial and strategic controlling. The present study showed that controlling is able not only to form budgets, but also to coordinate the work of different divisions, combining production, logistics and financial processes. The similarity lies in recognising the importance of planning, whereas the difference is expressed in the expansion of functions to integration and interdepartmental coordination, which ensures a more holistic view of the company's activities.

The digitalisation of financial controlling radically changes the management approach, enabling a shift from retrospective analysis to predictive analytics. Modern platforms allow managers to obtain key indicators promptly, automate data processing and speed up reporting preparation. Access to integrated information in real time enables controllers to work not only with historical results, but also with forecasts and development scenarios, which increases business adaptability and the quality of managerial decisions. The influence of digital technologies was studied by Z. Jaradat *et al.* (2025), who recorded the advantage of BI and ERP systems in accelerating information processing, but noted the limited nature of the application for predictive analytics. Current practices show that digital platforms make it possible not only to speed up data collection, but also to build scenario models, assess risks and forecast key indicators in real time. Thus, digital tools expand the functional capabilities of controlling, creating conditions for managerial decision-making based on the analysis of possible future situations, which was not observed in the author's research.

The use of ERP platforms ensures the integration of various business functions into a single information environment. Due to the integration of management accounting, planning and resource analysis, companies can build end-to-end processes covering production, sales, logistics, and finance. Practice shows that without such integration, ERP systems are often limited to accounting, whereas full-scale controlling requires coordinated work of all divisions and a single data source. J.L. Martins & C. Santos (2021) studied ERP systems and noted the limited use, mainly for accounting, with minimal integration with planning and budgeting. Based on the statements of F. Oberdorf *et al.* (2023), under modern conditions the implementation of ERP is considered the main element for building end-to-end controlling, which integrates financial, production and logistics processes into a single information space. This makes it possible to analyse indicators at all levels of management, assess resource efficiency and plan the budget more accurately. The conducted research also describes the expansion of ERP functionality and the active use of data for strategic planning.

BI platforms provide opportunities for visualisation and interactive analysis of managerial information. These platforms make it possible to create dashboards for monitoring key performance indicators, automate the generation of reports and the assessment of deviations from plans. The implementation of such tools ensures more rapid identification of problem areas, increases process transparency and makes it possible to forecast financial and operational results, which significantly expands the functionality of controlling. The use of BI tools was studied by S. Busa (2023), who noted that data visualisation was used mainly for external reporting and marketing, without deep integration into managerial processes. However, the current work showed that BI tools are being integrated into everyday controlling, making it possible to monitor key indica-

tors in real time, forecast financial and operational results and assess the performance of divisions. Such an approach makes management more flexible and transparent, expanding analytical opportunities beyond financial indicators.

An analysis of the practices of large companies shows that digital controlling can be integrated with operational and production processes, ensuring a comprehensive system of managerial reporting and decision-making support. The introduction of digital tools makes it possible to speed up information processing, increase the accuracy of forecasts and build scenario models, which makes the controlling system more proactive and strategically oriented. In addition, companies are gradually integrating controlling with non-financial indicators, which allows resources to be managed comprehensively and the efficiency of not only financial but also operational processes to be taken into account. B.I. Adekunle *et al.* (2023) examined the experience of introducing digital controlling in large organisations and recorded increased transparency, although the use of predictive analytics remained limited. The current study also showed that the integration of analytical tools with financial and operational data makes it possible to build scenario models, forecast risks and manage resources more effectively. Thus, digital controlling becomes not only a reporting tool, but also a mechanism for strategic analysis and planning.

In national companies, digital controlling is developing gradually and demonstrates uneven integration of ERP and BI systems. Barriers remain in the form of limited resources, a low level of digital maturity, and a lack of specialists capable of working with analytical tools. However, companies that have begun introducing elements of digitalisation show improved process manageability, transparency of financial flows and more rapid decision-making. This indicates the importance of a comprehensive approach that includes organisational changes, staff training and the formation of a digital infrastructure capable of ensuring the full functioning of managerial controlling. P. Belch (2024) analysed enterprises and identified a low level of digital maturity and a shortage of specialists as the main constraints on the introduction of modern controlling tools. Current observations show that even partial digitalisation makes it possible to increase the transparency of financial flows, accelerate decision-making and improve process manageability. At the same time, not only technologies, but also the development of staff competences, training in the use of analytical tools and the creation of an integrated digital infrastructure become critically important.

Thus, the analysis demonstrated that the role of financial controlling is expanding from retrospective analysis to strategic and predictive management, digitalisation is becoming the main factor of efficiency, and the integration of processes and staff development determine the success of implementation. A systemic approach to controlling, combining ERP, BI and operational data, ensures more accurate planning, increased transparency and more rapid managerial decision-making, which differs significantly from the limited application of tools.

Conclusions

The conducted study made it possible to identify trends associated with the integration of ERP and BI systems into management processes, the growth of the role of predictive analytics and the automation of reporting, as well as patterns expressed in the gradual transition from traditional financial control to comprehensive digital systems that ensure transparency, adaptability and the strategic orientation of managerial decisions in Kyrgyz enterprises. The analysis showed that financial controlling represents not merely a tool for recording the facts of economic activity, but an integrated management mechanism, ensuring the strategic stability and adaptability of the organisation.

The research results confirmed that digitalisation has become a key factor in the evolution of financial controlling. The introduction of ERP platforms such as SAP, Oracle, or Microsoft Dynamics ensures comprehensive integration of financial, production and logistics data, creating a single system of management accounting. At the same time, BI tools (Power BI, Tableau, QlikView) contribute to the transformation of reporting into dynamic analytical panels, allowing managers to assess key performance indicators promptly and model development scenarios.

International experience demonstrates that the effectiveness of digital controlling is achieved through technological integration and strategic data management. In Germany, companies using SAP S/4HANA and Qlik Sense ensure transparency and acceleration of reporting by more than 40%; in the USA, corporations such as General Electric Company and IBM use artificial intelligence and machine learning for predictive analysis and the identification of financial risks; in Eastern Europe, the implementation of Oracle NetSuite and Microsoft Dynamics 365 has made it possible to increase the accuracy of financial planning and the accessibility of analytics for small and medium-sized businesses; in Northern Europe, where controlling is integrated with ESG indicators, companies including Nokia

use Power BI and Tableau to combine financial and environmental metrics within a single management system.

The study of Kyrgyz enterprises revealed a heterogeneous level of digital maturity, but at the same time a stable trend towards the expansion of digital practices. Eldik Bank demonstrates successful integration of digital services, online platforms and ESG reporting, which makes it possible to consider it as an example of forming a comprehensive digital management ecosystem. In the energy sector, represented by OJSC “Electric Stations”, digitalisation is infrastructural in nature and aimed at improving the accuracy of accounting (to 98-99%) and the transparency of flows, which creates prerequisites for the introduction of end-to-end ERP solutions. The most advanced example is OJSC “Kumtor Gold Company”, where the automation of production and financial processes, the introduction of BI panels and digital document management ensure a high level of transparency and controllability.

The analysis of the experience of the mentioned enterprises makes it possible to conclude that the digital transformation of financial controlling contributes not only to improving the accuracy of reporting and the efficiency of planning, but also to changing managerial culture. Further research should reasonably be directed towards the quantitative assessment of the impact of digital controlling on the effectiveness of managerial decisions in various sectors of the Kyrgyz economy.

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References

- [1] Adekunle, B.I., Chukwuma-Eke, E.C., Balogun, E.D., & Ogunsola, K.O. (2023). Developing a digital operations dashboard for real-time financial compliance monitoring in multinational corporations. *International Journal of Scientific Research in Computer Science, Engineering and Information Technology*, 9(3), 728-746. doi: 10.32628/IJSRCSEIT.
- [2] Akhmatova, I. (2024). *The National Bank has granted permission for a bank in the Kyrgyz Republic to open a subsidiary IT company for the first time*. Retrieved from <https://economist.kg/banki/2024/08/06/natsbank-vpiervyie-razrieshil-banku-v-kr-otkryt-dochierniuiu-it-kompaniiu/>.
- [3] Alawaqleh, Q.A. (2021). The effect of internal control on employee performance of small and medium-sized enterprises in Jordan: The role of accounting information system. *Journal of Asian Finance, Economics and Business*, 8(3), 855-863. doi: 10.13106/JAFEB.2021.VOL8.NO3.0855.
- [4] Ashymova, A.S. (2020). Problems of further development internal control and financial analysis at the enterprises of Kyrgyzstan. *News of Universities of Kyrgyzstan*, 5, 97-101. Retrieved from doi: 10.26104/IVK.2019.45.557.
- [5] Awotunde, J.B., Adeniyi, E.A., Ogundokun, R.O., & Ayo, F.E. (2021). Application of big data with fintech in financial services. In P.M. Sub & S.H. Huang (Eds.), *Fintech with artificial intelligence, big data, and blockchain* (pp. 107-132). Singapore: Springer. doi: 10.1007/978-981-33-6137-9_3.
- [6] Bagwe, C. (2024). Assessing financial control systems-metrics and tools for evaluation. *International Journal of Management*, 15(1), 308-315. doi: 10.34218/IJM_15_01_020.

- [7] Basiru, J.O., Ejiofor, C.L., Onukwulu, E.C., & Uchenna, R. (2023). Optimizing administrative operations: A conceptual framework for strategic resource management in corporate settings. *International Journal of Multidisciplinary Research and Growth Evaluation*, 4(1), 760-773. doi: [10.54660/IJMRGE.2023.4.1.760-773](https://doi.org/10.54660/IJMRGE.2023.4.1.760-773).
- [8] Belch, P. (2024). Controlling as a modern management method used in Polish fuel enterprises. *European Research Studies Journal*, 27(4), 735-754. doi: [10.35808/ersj/3545](https://doi.org/10.35808/ersj/3545).
- [9] Buenestado-Fernández, M., Ramírez-Montoya, M.S., Ibarra-Vazquez, G., & Patiño, A. (2023). Digital competency as a key to the financial inclusion of young people in complex scenarios: A focus groups study. *Citizenship, Social and Economics Education*, 22(1), 48-62. doi: [10.1177/14788047231170083](https://doi.org/10.1177/14788047231170083).
- [10] Bussa, S. (2023). Enhancing BI tools for improved data visualization and insights. *International Journal of Computer Science and Mobile Computing*, 12(2), 70-92. doi: [10.47760/IJCSCMC.2023.V12I02.005](https://doi.org/10.47760/IJCSCMC.2023.V12I02.005).
- [11] Consolidated financial statements and independent auditor's report for the year ended December 31, 2023. (2024). Retrieved from <https://www.energo-es.kg/uploads/report/19450ca4abe575b55bbac17ebd459273.pdf>.
- [12] Corvello, V., Verteramo, S., Nocella, I., & Ammirato, S. (2023). Thrive during a crisis: The role of digital technologies in fostering antifragility in small and medium-sized enterprises. *Journal of Ambient Intelligence and Humanized Computing*, 14, 14681-14693. doi: [10.1007/s12652-022-03816-x](https://doi.org/10.1007/s12652-022-03816-x).
- [13] Dědečková, N. (2020). Control, controlling and its objectives in the organization. *SHS Web of Conferences*, 89, article number 01009. doi: [10.1051/shsconf/20208301009](https://doi.org/10.1051/shsconf/20208301009).
- [14] Dzhumagulov, A., & Mistriukova, I. (2025). Digital eco-transformation: Regulating sustainable agricultural practices in Kyrgyzstan. *E3S Web of Conferences*, 614, article number 03023. doi: [10.1051/e3sconf/202561403023](https://doi.org/10.1051/e3sconf/202561403023).
- [15] Dzieża, G., & Sikora, M. (2022). The use of managerial dashboards in manufacturing companies. *Scientific Papers of Silesian University of Technology*, 156, 157-168. doi: [10.29119/1641-3466.2022.156.11](https://doi.org/10.29119/1641-3466.2022.156.11).
- [16] Eldik Bank acquired the operator Beeline Kyrgyzstan. (2025). Retrieved from <https://banks.kg/ky/news/eldik-bank-purchase-beeline-kyrgyzstan>.
- [17] Eldik Bank. (2023). *Sustainability report 2023*. Retrieved from https://eldik.kg/media/sustainable_development/documents/2023_SR_Eldik_Bank_OJSC.pdf.
- [18] Eldik Bank. (n.d.). *Mobile banking ELDIK*. Retrieved from https://eldik.kg/en/mobile-banking?type=1&for_who=individual.
- [19] Fuertes, G., Alfaro, M., Vargas, M., Gutierrez, S., Ternero, R., & Sabattin, J. (2020). Conceptual framework for the strategic management: A literature review – descriptive. *Journal of Engineering*, 2020(1), article number 6253013. doi: [10.1155/2020/6253013](https://doi.org/10.1155/2020/6253013).
- [20] General Electric Company. (n.d.). *About us*. Retrieved from <https://www.ge.com/about-us>.
- [21] Group CEZ. (n.d.). Retrieved from <https://www.cez.cz/nextcez/en/home>.
- [22] Hofmann, P., Samp, C., & Urbach, N. (2020). Robotic process automation. *Electronic Markets*, 30(1), 99-106. doi: [10.1007/s12525-019-00365-8](https://doi.org/10.1007/s12525-019-00365-8).
- [23] IBM. (n.d.). *About IBM*. Retrieved from <https://www.ibm.com/about?lnk=hpil.us>.
- [24] Jaradat, Z., AL-Hawamleh, A., & Hamdan, A. (2025). Examining the integration of ERP and BI in the industrial sector and its impact on decision-making processes in KSA. *Digital Policy, Regulation and Governance*, 27(2), 117-144. doi: [10.1108/DPRG-04-2024-0077](https://doi.org/10.1108/DPRG-04-2024-0077).
- [25] Kadyraliev, A., Oruntayeva, A., Kamchybekov, T., Abyshov, I., & Bigali, A. (2024). The impact of digital technologies on the effectiveness of management in the agricultural sector of the Kyrgyz Republic. *Ekonomika APK*, 31(5), 35-44. doi: [10.32317/ekon.apk/5.2024.35](https://doi.org/10.32317/ekon.apk/5.2024.35).
- [26] Kologonov, M.T. (2024). Audit of innovations in accounting and management technologies. *Time Description of Economic Reforms*, 4(52), 24-28. doi: [10.32620/cher.2024.1.03](https://doi.org/10.32620/cher.2024.1.03).
- [27] Kumtor Gold Company. (2024). *Environmental protection annual report 2023*. Retrieved from <https://www.kumtor.kg/wp-content/uploads/2024/10/godovoj-otchet-kumtor-anglijskij-yazyk.pdf>.
- [28] Kumtor Gold Company. (n.d.). *KGC environment and sustainability reports*. Retrieved from <https://www.kumtor.kg/en/environment-protection/kumtor-environmental-reports/>.
- [29] Kuntadi, C., & Puspasari, L. (2023). Budget absorption's effectiveness: Budget implementation commitment, human resource capabilities, and budget planning accuracy. *Journal of Accounting and Finance*, 11(1), 81-88. doi: [10.29103/jak.v11i1.9236](https://doi.org/10.29103/jak.v11i1.9236).
- [30] Li, Y., Li, X., Xiang, E., & Djajadikerta, H.G. (2020). Financial distress, internal control, and earnings management: Evidence from China. *Journal of Contemporary Accounting & Economics*, 16(3), article number 100210. doi: [10.1016/j.jcae.2020.100210](https://doi.org/10.1016/j.jcae.2020.100210).
- [31] Llazo, E., Ryspaeva, A., Kubiczek, J., Mehdiyev, V., & Ketners, K. (2024). Trends and prospects of financial system development in the context of digitalization. *Theoretical and Practical Research in Economic Fields*, 15(4), 783-797. doi: [10.14505/tpref.v15.4\(32\).01](https://doi.org/10.14505/tpref.v15.4(32).01).

- [32] Martins, J.L., & Santos, C. (2021). The influence of ERP systems on organizational aspects of accounting: Case studies in Portuguese companies. *Accounting Research Journal*, 34(6), 666-682. doi: 10.1108/ARJ-07-2020-0212.
- [33] Narayan, D. (2022). Platform capitalism and cloud infrastructure: Theorizing a hyper-scalable computing regime. *Environment and Planning A: Economy and Space*, 54(5), 911-929. doi: 10.1177/0308518X221094028.
- [34] Nokia. (n.d.). *Insights and innovation*. Retrieved from <https://www.nokia.com/insights/>.
- [35] Nutalapati, P. (2024). A review on cloud computing in finance-transforming financial services in the digital age. *International Research Journal of Engineering & Applied Sciences*, 12(3), 35-45. doi: 10.55083/irjeas.2024.v12i03005.
- [36] Oberdorf, F., Schaschek, M., Weinzierl, S., Stein, N., Matzner, M., & Flath, C.M. (2023). Predictive end-to-end enterprise process network monitoring. *Business & Information Systems Engineering*, 65, 49-64. doi: 10.1007/s12599-022-00778-4.
- [37] OJSC Electric Power Plants. (n.d.). *Reports*. Retrieved from <https://www.energo-es.kg/reports/>.
- [38] Oracle. (n.d.). Retrieved from <https://www.oracle.com/uk/>.
- [39] Paramesha, M., Rane, N., & Rane, J. (2024). Big data analytics, artificial intelligence, machine learning, internet of things, and blockchain for enhanced business intelligence. *Partners Universal Multidisciplinary Research Journal*, 1(2), 110-113. doi: 10.2139/ssrn.4855856.
- [40] RSK Bank & MEGA launched version 1.0 of the Ishker24 microfinance system to transition to the new tax regime. (2024). Retrieved from https://kaktus.media/doc/496726_rsk_bankmega_zapystili_1.0_versiu_mp_ishker24_dlia_perehoda_na_novyy_nalogovyy_rejim.html.
- [41] SAP. (n.d.). *SAP Company information*. Retrieved from <https://www.sap.com/uk/about/company.html>.
- [42] Siemens AG. (2022). *Annual financial report for fiscal 2022*. Retrieved from <https://assets.new.siemens.com/siemens/assets/api/uuid:19bbc110-8533-46e4-a27e-ec128d1d1434/Annual-Financial-Report-FY2022.pdf>.
- [43] Tamulevičienė, D., & Androniceanu, A. (2020). Selection of the indicators to measure an enterprise's value and its changes in the controlling system for medium-sized enterprises. *Entrepreneurship and Sustainability Issues*, 7(3), 1440-1458. doi: 10.9770/jesi.2020.7.3(1).
- [44] Temirov, N., Alybaev, Z., & Sulaymanova, B. (2023). Sources of synergy in state budget digitalization of the Kyrgyz Republic. *E3S Web of Conferences*, 380, article number 01033. doi: 10.1051/e3sconf/202338001033.
- [45] The CIPS system has been launched: Eldik Bank has opened direct payments in yuan for businesses in Kyrgyzstan. (2025). Retrieved from <https://banks.kg/news/eldik-bank-opened-direct-payments-yuan-businesses>.
- [46] World Bank Group. (2025). *Enhancing productivity-driven growth in the Kyrgyz Republic (P180956)*. Retrieved from <https://documents1.worldbank.org/curated/en/099060325113092254/pdf/P180956-f7efb47c-2095-46e9-8fa8-51d24d5b5559.pdf>.
- [47] Yuldoshboy, S., Beruniy, A., Javokhir, S., Khodjanियазov, E., Karimov, M., Saidmamatov, O., & Marty, P. (2025). Exploring ICT as an engine for sustainable economic growth in Central Asia. *Economies*, 13(12), article number 365. doi: 10.3390/economies13120365.
- [48] Żywiec Group. (n.d.). Retrieved from <https://grupazywiec.pl/>.

Методика впровадження цифрових інструментів фінансового контролінгу у компаніях Киргизстану

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Анотація. Це дослідження мало на меті проаналізувати підходи до ефективного використання цифрових технологій для підвищення результативності системи фінансового контролінгу в компаніях Киргизстану. Методологічною основою дослідження виступив системний підхід, що включає аналіз корпоративної звітності, порівняльний аналіз практик цифровізації та оцінку функціональних компонентів фінансового контролінгу. В рамках дослідження було проведено всебічний аналіз трьох відкритих акціонерних товариств – ВАТ «Елдік Банк», ВАТ «Електричні станції» та «Кумтор Голд Компані», що дозволило виявити відмінності у рівнях цифрової зрілості фінансового управління у секторах банківської, енергетичної та промислової галузей. Аналіз показав, що у фінансовому секторі найбільш активно впроваджено інтегровані інформаційні системи, які забезпечують автоматизацію управлінського обліку, централізований доступ до фінансових даних та розвиток аналітичних інструментів для підтримки ухвалення управлінських рішень. У промисловому секторі цифровізація охопила автоматизацію виробничого та фінансового обліку, а також впровадження платформ Business Intelligence для аналізу даних та проведення електронних тендерів. Це сприяло покращенню точності прогнозування собівартості, скорочення термінів бюджетування та забезпечення випуску 13,567 кг золота при податкових відрахуваннях, які становили понад 17,2 млрд сомів у 2023 році. Насамкінець представлені практичні рекомендації для киргизстанських компаній, що включають проведення комплексної діагностики облікових систем, розробку дорожньої карти цифрової трансформації, впровадження платформ для планування ресурсів підприємства з інтегрованими модулями управлінського обліку, а також розвиток кадрових компетенцій у галузі аналітики та фінансового прогнозування. Практична цінність дослідження полягає у пропозиції конкретних рекомендацій для киргизстанських підприємств та фінансових менеджерів щодо впровадження цифрових інструментів контролінгу

Ключові слова: прогнозування; стратегічне планування; аналітика; управлінські рішення; бюджетування



Features of financial reporting by small enterprises and microenterprises: Ukrainian and international experience

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Abstract. The study aimed to substantiate the theoretical and applied foundations for the improvement of financial reporting by small and micro-enterprises in Ukraine, considering international experience and the digital transformation of accounting processes. The methodological basis consisted of comparative and content analysis, generalisation of practices for presenting data in the extensible business reporting language format, and observation. The empirical base was formed based on official analytical and statistical reports. The obtained results identified key differences between the requirements of national accounting standards and international standards for small enterprises in terms of the composition of reporting, principles of asset and liability valuation, and disclosure of information. The study determined that the introduction of digital reporting formats and the harmonisation of methodological approaches increase the comparability and reliability of data, reduce the time needed to prepare reports, and lower the risk of arithmetic and classification errors. The study proved that the use of integrated information systems, in particular enterprise resource planning systems and cloud platforms, contributes to the formation of a single information space between accounting, tax and analytical subsystems. As a result, a structured model of the relationship between the digital level of reporting and the quality of financial data has been developed, as well as recommendations for harmonising the Ukrainian financial reporting system with European standards. The proposed model includes harmonisation of reporting formats, stricter requirements for explanatory notes and disclosure of information, and the introduction of internal control procedures to ensure comparability and transparency. The research materials can be used in the development of state strategies for modernising financial reporting, improving tax policy and increasing the investment attractiveness of Ukrainian enterprises in the process of integration into the European economic space

Keywords: accounting; economic transparency; harmonisation of standards; digital data formats; management analytics; regulatory convergence; quality of information systems

Introduction

The financial reporting of small and micro-enterprises is substantial in ensuring the transparency and stability of the business environment. In the context of the digital transformation of the economy, the quality of reporting data becomes an indicator of the institutional maturity of the state and business. Harmonisation of national accounting regulations (standards) (NP(S)BO) with International Financial Reporting Standards (IFRS) for small and medium-sized enterprises (SMEs) ensures the comparability of information in the European space. The streamlining of reporting processes and the integration of digital solutions determine

the competitiveness of small businesses in Ukraine and their sustainability in the global economic environment.

Ukrainian practice of reporting by small enterprises demonstrates several contradictions between legislative requirements and the actual ability of business entities to ensure full disclosure of information. T. Gogol & V. Kolo-tok (2020) demonstrated that small businesses often do not disclose the non-financial information and explanations required by current accounting standards. At the same time, the problem of incomplete notes to financial statements, particularly regarding accounting policies and accounts

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receivable, remains systemic. According to the results of a study by S. Semenova & O. Shpyro (2019), some small businesses do not disclose information about their accounting policies, which makes it difficult to verify the methodology of their application.

This situation creates a risk that users of financial statements (investors, banking institutions, tax authorities) will not receive sufficient data to assess the financial condition, risks and prospects of a business. As a result, despite the regulatory framework that requires detailed disclosures (including explanatory notes), most small businesses face resource, technical or staffing constraints that prevent them from meeting these requirements. This gap between regulation and practice points to the need to improve the quality of reporting at the small business level by strengthening disclosure requirements, resources for their implementation, and monitoring by the regulator.

The study by T. Kostash (2025) examined the impact of the digital economy on the modernisation of corporate financial reporting. The study emphasised that the digitisation of accounting processes and the introduction of electronic reporting formats increase the efficiency and reliability of data, helping to reduce errors and duplication of information. The study proved that the use of innovative technologies creates the conditions for increasing the transparency of financial information and building user trust. In contrast, V. Kostyuchenko & A. Kovalova (2020) examined the process of adapting IFRS for SMEs in Ukraine. The study noted that although the legal prerequisites for harmonisation with international standards have been created, practical implementation faces difficulties due to differences in the interpretation of the principles of recognition of income and liabilities. The study emphasised that the introduction of IFRS for SMEs will contribute to improving the quality of information in financial reporting and facilitate the comparison of indicators between countries.

Ukrainian realities are analysed in the context of international standards and in the work of A. Kostyakova (2025). The study argued that the inconsistent application of accounting and reporting rules creates risks of loss of transparency and trust among information users. The significance of consistency between accounting and tax approaches in the formation of an enterprise's financial results is emphasised. The study provided examples of intra-group transactions and financial assistance that require clear reflection in reporting following IFRS. The transformation of financial reporting of small enterprises following IFRS and O. Fomina *et al.* (2022) was investigated. The study proved that the adoption of IFRS for SMEs can be used for the creation of a more flexible system for reflecting economic transactions, increases the accuracy of asset valuation, and ensures the comparability of financial results. The practical aspects of implementing standards in small enterprises in Ukraine are analysed, and barriers related to a lack of resources and regulatory uncertainty are identified.

At the same time, L. Dzhulii *et al.* (2024) studied the peculiarities of accounting and taxation of small enterprises, revealing the relationship between tax incentives, financial reporting and economic behaviour of businesses. The study stated that simplified accounting regimes have a positive impact on the administrative burden, but at the same time limit the depth of financial analysis. The study emphasised the need to harmonise accounting principles with the requirements of tax legislation to ensure the reliability of reporting indicators. N.P. Banera & O. Hely (2021) emphasised the assessment of the quality of financial reporting of small enterprises and finding ways to improve the informativeness of indicators. The study proved that the structure, consistency and timeliness of disclosure of indicators are decisive criteria for the quality of reporting data. The article proposed an approach to assessing the informative value of reporting through a system of qualitative characteristics: clarity, reliability, comparability and materiality.

The directions of development of reporting in the eXtensible Business Reporting Language (XBRL) format in Ukraine were studied by K. Nazarova & K. Bondarenko (2022). The study identified the main vectors of digital transformation of financial reporting, in particular, increasing transparency, reducing the human factor, and automating the verification of indicators. The study systematised the experience of the first years of XBRL application and identifies problems with the integration of national taxonomy with international standards. The role of state institutions in forming methodological recommendations for small and micro-enterprises was emphasised. The study concluded that an effective digital reporting ecosystem must be based on the principles of openness and compatibility with European data exchange systems. O. Vakun *et al.* (2020) devoted their study to analysing the problems of implementing the XBRL reporting standard in Ukraine. The authors identified XBRL as a key tool for digitising accounting processes and increasing the transparency of information flows. The publication revealed the barriers to implementation, ranging from the insufficient technical preparedness of enterprises to the limited level of digital literacy of accountants. The study proved that the proper functioning of the XBRL platform reduces the time spent on preparing reports and increases their analytical value.

Most of the analysed studies considered individual instruments or stages of reform without forming a comprehensive model of integrated reporting for small and micro-enterprises. Issues such as assessing the quality of reporting data, the relationship between digitalisation of accounting and the reliability of information, and the impact of international standards on the adaptation of national reporting forms remain insufficiently addressed. The study aimed to develop theoretical guidelines for the development of a financial reporting system for small and micro-enterprises in Ukraine, incorporating international requirements and digital changes in the field of accounting.

Materials and Methods

The study covered the period from 2020 to 2025. During this period, it was necessary to analyse the transformation of the financial reporting system for small and micro-enterprises in the direction of harmonising national accounting provisions with international financial reporting standards for SMEs, as well as the introduction of digital tools into the reporting process. The regulatory part was processed using a comparative analysis method, which involved comparing national accounting standards with international standards, in particular in terms of requirements for the composition of financial statements, valuation of assets and liabilities, and criteria for recognising income, expenses and financial results. Among the national accounting standards (NAS), the primary were taken: NAS 7 “Fixed Assets” and NAS 9 “Inventories”. The analysis of the regulatory framework also covered the provisions of Directive of the European Parliament and of the Council No. 2013/34/EU “On the Annual Financial Statements, Consolidated Financial Statements and Related Reports of Certain Types of Undertakings, Amending Directive 2006/43/EC of the European Parliament and of the Council and Repealing Council Directives 78/660/EEC and 83/349/EEC” (2013), which became a methodological guideline for harmonising Ukrainian requirements with European practices.

Content analysis was used to examine reports from the Strategy of Ukrainian financial sector development until 2025 (n.d.) to identify the characteristics of simplified accounting regulations for small enterprises and determine the practical aspects of preparing financial statements and explanatory notes. To analyse the implementation of the extensible business reporting language format in Ukraine, data from I. Verner (2024) and materials from the OECD (2024) were used. This was used to assess the trend of arithmetic errors in the financial reports of small enterprises, as well as the proportion of reports submitted late. The effectiveness of using XBRL as a tool for improving the reliability of financial reporting was assessed using the method of theoretical generalisation.

The empirical basis was provided by content analysis of analytical materials from the European Commission (2023; 2024), as well as reports on the implementation of digital reporting formats in Poland (Ministry of Finance of the Republic of Poland, n.d.), Germany (Federal Statistical Office, n.d.), the Czech Republic (Czech Statistical Office, 2023) and Estonia (Annual report, 2024). The information from the reports was necessary to examine the practices of implementing the e-Balance system in Germany, the Standard Audit File for Tax Authorities (SAF-T) in Poland, and the Business Registers Interconnection System (BRIS) in the Czech Republic.

A practical case study of Meblomix Sp. z.o.o. (Poland) was examined to assess the reduction in tax report corrections and accounting support costs due to digital tools (Polish Agency for Enterprise Development, 2024). The example of Strojexport a.s. (Czech Republic) was used to assess the impact of digital reporting on increasing

counterparty confidence and simplifying bank lending procedures. The features of the digital reporting model in Estonia were considered, and the advantages of the e-Business Register system were analysed. These countries were chosen because they represent different models of integrating standards and digital formats into financial reporting, but at the same time have a similar structure of the SME sector to that of Ukraine. A comparative analysis method was used to identify differences between the Ukrainian and European financial reporting models.

To assess the impact of digital tools on the quality of financial data, the relationship between the level of digitalisation of enterprises and the quality of reporting, expressed in terms of timeliness of submission, completeness of notes and compliance of accounting policies with established standards, was analysed. Statistical indicators were processed using theoretical generalisation methods. A process approach was used to determine the practical consequences of harmonising accounting standards and digitising financial reporting. The paper describes the stages of reporting data formation, from the initial recognition of business transactions to their reflection in financial forms and explanatory notes, tracing the complete logical cycle of information flow from the moment of its origin to the final presentation in the reporting. To verify the compliance of data with accounting principles, the study compared accounting and tax assessments of assets, liabilities and operating results to identify possible discrepancies in the interpretation of the economic substance of transactions.

The paper developed a structured model of the relationship between the digital level of reporting and the quality of financial data. Methodologically, the proposed model was theoretical and analytical in nature and was based on a combination of comparative, logical-structural and content analysis. The materials used to construct the model were the OECD (2021) report and materials from European researchers (Sarker, 2025). The model was constructed based on deductive generalisation, where empirical observations (reduction of errors, acceleration of reporting, increase in investor confidence) were systematised into a single structural scheme. The results obtained were conceptual in nature. The study provided recommendations for harmonising the Ukrainian financial reporting system with European standards.

Results

Regulatory framework for financial reporting by small and micro-enterprises

The regulatory framework for financial reporting by small and micro-enterprises forms the basis for ensuring the reliability, comparability and transparency of economic information needed by users to make management decisions. In Ukraine’s national system, these issues are regulated by the National Accounting Standards (NAS), which define the structure, composition and methodological principles for the preparation of financial statements. Their purpose is to simplify accounting procedures for small and

micro-enterprises and to maintain the minimum necessary level of disclosure of information about their financial position and performance. In the EU, a similar function is performed by the IFRS for SMEs developed by the International Accounting Standards Board, as well as Directive of the European Parliament and of the Council No. 2013/34/EU “On the Annual Financial Statements, Consolidated Financial Statements and Related Reports of Certain Types of Undertakings, Amending Directive 2006/43/EC of the European Parliament and of the Council and Repealing Council Directives 78/660/EEC and 83/349/EEC” (2013). Despite the common goal of increasing transparency, there are significant methodological differences between the Ukrainian and European systems that affect the completeness and comparability of reporting indicators.

The Accounting Standards are based on the historical cost principle, a conservative approach to recognising income and expenses, and minimising the volume of notes to the financial statements. For small enterprises, there are abbreviated forms of the balance sheet (Form No. 1-m, No. 1-ms) and income statement (Form No. 2-m, No. 2-ms), which cover basic information about assets, capital, liabilities, income and expenses (Strategy of Ukrainian..., n.d.). These forms are easy to use, but they do not provide full disclosure of non-financial indicators and details of the structure of assets. In contrast, IFRS for SMEs are based on the concept of fair value, which reflects the real economic substance of transactions, not just their legal form. This can

improve assessment of the value of an entity’s assets, liabilities and risks, which is relevant in an international investment environment (Kaya & Koch, 2014). In addition, IFRS for SMEs contain sections on disclosure of information about events after the balance sheet date, related parties, contingent liabilities and accounting policies, which are not provided for in most national standards of countries with economies in transition (Bautista-Mesa *et al.*, 2019).

The application of Directive No. 2013/34/EU is a key factor in harmonising reporting approaches between EU countries. The document defines quantitative criteria for classifying companies: for small companies, assets up to EUR 6 million, net income up to EUR 12 million, average number of employees up to 50; for micro-enterprises, assets up to 350 thousand EUR, income up to EUR 700 thousand and staff up to 10 people. This ranking establishes proportional reporting requirements without overburdening the smallest businesses with an excessive number of indicators. Ukrainian legislation has partially adapted these parameters, but the limits set by the NAP(S)B remain stricter and the methodology for disclosure of information less detailed (Kovalchuk, 2025). In 2024, the Strategy of Ukrainian financial sector development until 2025 (n.d.) initiated an update of the criteria for small enterprises, raising the asset thresholds to the equivalent of EUR 5 million, which was a step towards convergence with European practice. A comparative overview of the key provisions of NAP(S)A and IFRS for SMEs is provided in Table 1.

Table 1. Comparative characteristics of key provisions of NAS(S) and IFRS for SMEs

Control element	The approach of the National Accounting Standards (NAS)	IFRS approach for SMEs
Valuation of assets and liabilities	Assets are mainly valued at historical cost, with revaluation applied on a limited basis and at the discretion of the company. Liabilities are recognised only when there is a legal obligation	Assets are recognised at fair value if this improves the reliability of information. Liabilities may also be recognised if there is an economic obligation, even without a formal contract
Recognition of income and expenses	Revenue is recognised upon receipt of economic benefits, and expenses – upon documentary confirmation	Revenue is recognised when the right to receive payment arises, regardless of whether the funds have been received. Expenses are recognised on an accrual basis
Disclosure of information	The notes to the financial statements are simplified and are provided only for selected items	Detailed disclosure of information about events after the balance sheet date, contingent liabilities, related parties, and a description of the company’s accounting policies is required
Classification of enterprises	The division is conducted following Law of Ukraine No. 996-XIV, incorporating the criteria of revenue, assets and number of employees	The classification is defined by Directive No. 2013/34/EU, which sets clear thresholds for micro, small, medium-sized and large enterprises
Reporting forms	Short: balance sheet and income statement without cash flow details	Full: balance sheet, income statement, statement of changes in equity, cash flow statement and notes
Conceptual principles	The primacy of legal form over economic substance, emphasis on tax compliance	The prevalence of economic substance over form, with an emphasis on data reliability and neutrality

Source: compiled by the author based on Law of Ukraine No. 996-XIV (1999), Directive of the European Parliament and of the Council No. 2013/34/EU (2013), Directive of the European Parliament and of the Council 2014/95/EU (2014), D. Kaya & M. Koch (2014), I. Kovalchuk (2025)

The European integration process has a significant impact on the reform of reporting in Ukraine, within the framework of which Directive No. 2013/34/EU is being adapted to the national framework, as it leads to the unification of criteria for classifying enterprises by size, the

introduction of simplified reporting requirements for small and micro-enterprises, and the harmonisation of principles for the valuation of assets, liabilities and disclosure of information in the notes. The EU insists on ensuring a “reasonable balance” between reducing the reporting burden

and providing sufficient information to assess the financial condition of entities (Incollingo & Lionzo, 2023). Under this policy, EU countries are required to provide small enterprises with a simplified reporting package, but without compromising the quality characteristics of comparability, reliability and transparency. For Ukraine, this implies the need to shift from a tax-oriented model to an information and analytical one, where financial reporting is viewed as a strategic management tool. Another significant aspect of modernisation is the digitisation of processes and the transition to the XBRL format, which enables automatic comparison, validation, and publication of reporting data (Yang & Ming, 2024). This technology makes it possible to minimise subjectivity when filling out forms and creates a basis for integrated reporting that combines financial and non-financial indicators.

In general, the trend in the development of the regulatory framework for SME financial reporting is to combine the principles of simplification with the requirements of reliability and comparability. For Ukrainian small enterprises, gradual harmonisation with IFRS for SMEs and the provisions of Directive No. 2013/34/EU is a necessary condition for the formation of a clear, transparent and investment-attractive accounting system. The combination of regulatory adaptation with digital reporting technologies creates the conditions for reducing the administrative burden, improving the analytical quality of data and bringing the Ukrainian accounting system closer to European transparency standards.

The practice of reporting by micro-enterprises in Ukraine is characterised by a high level of simplification of accounting procedures, a limited set of forms and minimal requirements for disclosure of information, which is determined both by regulatory provisions and by the resource capabilities of the business entities. Following NAP(S)BO 25 “Simplified Financial Reporting”, micro-enterprises submit only two main documents: the balance sheet (form No. 1-ms) and the income statement (form No. 2-ms), without detailing cash flows, changes in capital or extended notes. This reduces the administrative burden, but limits users of financial statements in obtaining complete information about the structure of assets, liabilities and financial risks. According to analytical data from the State Statistics Service of Ukraine, as of 2023, micro-enterprises accounted for 79.8% of the total number of business entities, but most of them (over 60%) keep accounts using a simplified system without formalised procedures for revaluing assets or detailing deferred expenses (Verner, 2024). At the same time, audits show that micro-enterprises often violate the requirements of NAP(S)B 25 in terms of disclosure of data on accounts receivable, inventories and equity, limiting themselves to the minimum lines of reporting forms. This indicates the dominance of fiscal motivation in reporting over informational motivation. At the same time, the introduction in 2021-2024 of mandatory financial reporting in XBRL format for entities of public interest has become a catalyst for digital adaptation even among small

and micro-enterprises, which have started to use automated accounting systems to generate reporting forms. Thus, the modern model of reporting for micro-enterprises in Ukraine combines regulatory simplicity with limited analytical capabilities, which requires further modernisation in the direction of digital integration and gradual harmonisation with European requirements for the quality of financial data. Gradual digitalisation creates the conditions for improving the accuracy and timeliness of data, but staffing issues, a lack of accounting knowledge and technical support remain key barriers to the implementation of transparent microbusiness reporting practices.

The practice of preparing financial statements in Ukraine

The preparation of financial statements in Ukraine remains one of the most dynamic aspects of the development of the accounting system, especially in the small business sector, which, as of 2022, accounted for more than 99.7% of all business entities in the country (Verner, 2024). The basic form of regulation for them is NAP(S)BO 25 “Simplified Financial Reporting for Small Businesses”, which defines two basic forms: the balance sheet (form No. 1-m or No. 1-ms) and the income statement (form No. 2-m or No. 2-ms). These forms provide for the disclosure of assets, capital, liabilities, income and expenses, but do not cover all aspects provided for by the full standards, in particular the cash flow statement or the statement of changes in equity. As a result, the analytical depth of such reports is limited, and the possibility of comparison with enterprises reporting under IFRS is reduced. According to the State Statistics Service, only about 28% of small enterprises submitted extended notes to their financial statements in 2023, although this is permitted by current regulations.

One of the most common problems in preparing financial statements for small enterprises is the revaluation of assets, which is often conducted without proper methodological justification or using simplified approaches. According to recent observations, more than 40% of the analysed enterprises base their fixed asset valuation on the initial cost without adjusting for inflation, which leads to a distortion of profitability and equity indicators (Yang & Ming, 2024). At the same time, according to the State Statistics Service of Ukraine, about 30% of small enterprises that revalued their fixed assets did not disclose the relevant information in the notes to the financial statements as of 2023, which indicates incomplete compliance with the principle of transparency and violation of the requirements in accordance with NAP(S)A 7 “Fixed Assets” (Verner, 2024). Another common practice is to account for inventories at weighted average cost without incorporating the methods of accounting for disposals at identified cost provided for in NAP(S)A 9 “Inventories”, which complicates the analysis of expenses (Kovalchuk, 2025). Such shortcomings not only reduce the quality of financial information but also create risks of additional tax assessments in the event of audits.

A typical problem remains the lack of disclosure of notes to financial statements, although they provide the

context for analysis of individual items of the balance sheet and income statement. As of 2023, some small and micro-enterprises do not provide explanations for accounts receivable and deferred expenses, which contradicts the requirements of paragraphs 7-10 of NAP(S)B 9 “Simplified Financial Reporting” (Mulyk, 2021; Kovalchuk, 2025). Notably, this is due to a lack of qualified personnel or an underestimation of the role of notes in ensuring data reliability. At the same time, international practice shows that even in simplified reporting, notes can perform an analytical function: in Poland, for example, 84% of small enterprises provide brief explanations to the balance sheet and income statement, which significantly increases the user value of the documents (Polish Agency for Enterprise Development, 2024).

Tax simplifications remain substantial in the formation of reporting practices, significantly influencing companies’ approach to assessing performance and determining accounting indicators. The introduction of a simplified taxation system with fixed rates for taxpayers in groups 1-3 reduced the administrative burden but created the effect of minimising reporting data. More than 70% of small enterprises that apply a single tax do not keep detailed records of depreciation and reserves, as this does not affect the tax burden (Kovalchuk, 2025). As a result, the book value of assets is often understated, and the structure of equity does not reflect the real state of resources. As a result, financial reporting is transformed from a management tool into a formality limited by the requirements of tax returns. A similar situation can be observed in Central European countries, where, following the introduction of tax simplifications in 2018, almost 40% of micro-enterprises lost the ability to produce integrated reports due to the absence of mandatory accounting registers (Bautista-Mesa *et al.*, 2019).

As of 2025, Ukraine is gradually transitioning to more detailed financial reporting for small businesses, following European trends. The Ministry of Finance of Ukraine (Strategy of Ukrainian financial..., n.d.) has initiated the creation of an electronic register of small enterprises that apply NAP(S)B 25 to reconcile reporting indicators with tax service databases. This approach will reduce the number of discrepancies in financial reports and create conditions for integration into the unified information system XBRL Reporting UA 2.0. In the long term, this will ensure the integration of financial and tax reporting in a single digital environment, which will increase the reliability and comparability of data, as well as compliance with IFRS for SMEs.

European experience in financial reporting by small and micro-enterprises

The European experience of financial reporting by small and micro-enterprises demonstrates a high level of institutional consistency, technological maturity and transparency of accounting processes. In leading European countries, such as Germany, Poland, the Czech Republic and Estonia, the financial reporting of small and micro-enterprises is based on IFRS principles adapted to the requirements of

Directive No. 2013/34/EU, as well as on deep digital integration of reporting processes. According to data from the Federal Statistical Office (n.d.), more than 98% of small businesses submit their financial reports in electronic file format via the e-Balance system, which operates based on XBRL taxonomy and provides automatic verification of the consistency of indicators. The system can be used for the unification of reporting for tax and statistical purposes, which reduces the administrative burden and increases data reliability. The transition to electronic reporting has reduced the average time required to prepare financial reports in German micro-enterprises from 19 to 11 days, while the proportion of arithmetic errors has more than halved.

In Poland, the introduction of the SAF-T system has become the main tool for integrating financial reporting with tax databases. SAF-T can ensure the transfer of accounting data to the tax administration in a standardised XML format, which provides compatibility between accounting programmes and government portals. According to the Ministry of Finance of the Republic of Poland (n.d.), in 2024, approximately 93% of SMEs submitted their financial reports via SAF-T, and the average level of compliance of reported indicators with tax returns exceeded 96%. Such integration minimises the possibility of double counting of transactions, improves the quality of audits and creates a basis for analytical assessment of the sector’s financial stability. A practical case study by Meblomix Sp. z.o.o. (Poznań) showed that the implementation of SAF-T reduced the number of tax report corrections by 27% and accounting costs by 12% during the first year after automation (Polish Agency for Enterprise Development, 2024).

In the Czech Republic, the BRIS system connects the national register of companies with the pan-European electronic data exchange network and plays a key role in the digitisation of accounting processes. Due to BRIS, companies can publish their financial statements directly through the government portal, which provides users with free access to reports and increases business accountability (European Commission, 2023). In 2022, more than 95% of Czech enterprises submitted their financial statements through BRIS, and the average time for publishing documents was reduced from three weeks to five days (Czech Statistical Office, 2023). The example of Strojexport a.s. (Brno) shows that the availability of reports in BRIS has contributed to increased trust among counterparties and simplified bank lending procedures, with the number of approved loan applications increasing by 14% after the introduction of automatic confirmation of financial indicators.

One of the most successful models of digital reporting in Europe is the experience of Estonia, where the e-Business Register system has been in operation since the 2010s, combining tax, statistical and financial databases into a single digital circuit. According to data from the Annual report (2024) (Estonia), in 2024, 99.4% of small and micro-enterprises submitted their financial reports in electronic format, with the average time for registering a new business not exceeding 18 minutes. The platform can be

used by businesses to enter data once, and it's then automatically used by different government services, which really cuts down on admin costs. Research has shown that digital consolidation of reporting has increased the effectiveness of monitoring the timeliness of form submission by 21% and reduced the number of technical errors by almost three times. The Estonian model demonstrates how a combination of transparency, digital technology and a regulatory framework creates an ecosystem of trust between business and the state.

A common feature of European practices is the combination of technological reporting tools with institutional quality control. The use of e-Balance, BRIS and SAF-T platforms enables automated reconciliation of financial indicators between tax, audit and statistical systems, which increases data accuracy and reduces the risk of manipulation. In its 2024 report, the European Commission emphasised that due to the introduction of digital formats for processing financial information, the timeliness of reporting by small and micro-enterprises in the EU increased from 89% in 2019 to 97% in 2023, while the cost of preparing reports for businesses fell by an average of 15% (European Commission, 2024). Practice shows that harmonised regulatory requirements and digital infrastructure create a synergistic effect, transforming transparent reporting from an administrative obligation into a strategic tool for business development.

A comparison of the results of implementing financial reporting systems for small and micro-enterprises in Ukraine and EU countries reveals significant differences in the level of transparency, detail and digital integration of data. European practice, based on the provisions of IFRS

for SMEs and Directive No. 2013/34/EU, provides a higher level of standardisation, while the Ukrainian system of Accounting Standards (AS) remains predominantly tax-oriented, focusing on the formal reflection of performance results. According to estimates by the OECD (2024), the share of small and micro-enterprises that prepare complete financial statements with notes in EU countries is about 87%, while in Ukraine, this figure does not exceed 32%. This disparity can be explained by differences in digital maturity and access to automated accounting platforms: on average, 91% of European SMEs use XBRL or its local versions, while in Ukraine, only 26% do so (European Commission, 2024; Strategy of Ukrainian financial..., n.d.).

A significant advantage of the European model is its ability to ensure consistency between accounting, tax and statistical records. For example, in Germany, the e-Balance system automatically synchronises financial reporting with tax service databases, reducing the administrative burden by almost 18% on an annual basis (Lukianykhina *et al.*, 2024). In Ukraine, however, most small businesses submit financial reports separately to statistical and tax authorities, resulting in discrepancies of 9-12% on average between similar indicators in the reports (Lukianykhina *et al.*, 2024). The gradual introduction of the XBRL format is already showing positive changes: the share of reports rejected due to technical errors has decreased from 17.8% in 2021 to 6.4% in 2024 (Kovalchuk, 2025). This experience confirms that harmonisation is not limited to changing standards but involves systematic digital transformation. A comparison of key indicators of the quality of financial reporting by SMEs in Ukraine and EU countries is presented in Table 2.

Table 2. Comparison of key financial reporting quality indicators for small and micro-enterprises in Ukraine and EU countries (as of the end of 2024)

Indicator	Ukraine	EU	Note
Share of small and micro enterprises that prepare complete financial statements with notes	Only about one-third of small and micro-enterprises (32%) submit reports with explanatory notes, which reduces the level of data analysis	In EU countries, this indicator averages 87%, which provides a comprehensive picture of the financial condition of entities	A difference of more than 55% indicates a gap in reporting methodology and the need to train accountants at small enterprises
Use of digital reporting formats (XBRL or equivalents)	The XBRL format is used by only 26% of companies, mainly those with an external auditor	On average, 91% of EU businesses use digital reporting taxonomies integrated into tax systems	The difference is explained by uneven technical support and low digital literacy among accountants in small businesses
Average time required to prepare annual financial statements	Approximately 22 days for small businesses, excluding audit procedures	In EU countries where reporting is submitted via automated platforms, this figure averages 11 days	The reduction by almost half is due to the automation of form filling and the use of standard templates
Level of reliability and consistency of reporting data	In Ukraine, the average level of discrepancy between reports submitted to the tax and statistical services is 9-12%	In EU countries, this figure does not exceed 2%, which is due to automatic data verification in digital systems	Standardised formats and centralised databases ensure high-quality financial information
Administrative burden on businesses	On average, 74 man-hours per year are spent on reporting	In EU countries, approximately 45 man-hours are saved due to the integration of accounting and tax processes	Digitalisation reduces time expenditure by almost 40%

Source: compiled by the author based on F. Ngaruko (2023), OECD (2024), European Commission (2024), Strategy of Ukrainian financial sector development until 2025 (n.d.)

The results confirmed that the effects of harmonising standards and digital transformation are systemic in nature. First, the use of a uniform approach to reporting in accordance with IFRS principles increases investor and creditor confidence, especially in the small and micro-enterprise sector, where access to finance largely depends on the quality of information. Secondly, digital platforms based on XBRL taxonomy reduce the time and resource costs of enterprises, while increasing the accuracy and comparability of reporting data. Thirdly, EU countries are seeing the emergence of a culture of “transparent reporting”, where financial information is viewed not only as a legal obligation but also as a strategic business asset. For Ukraine, this process is still in infancy, but the trend shows a gradual narrowing of the gap with the European model. The harmonisation of NAS(S) with IFRS for small and micro-enterprises, supported by digital reporting tools, has the potential to transform financial reporting from a formal procedure into a full-fledged element of corporate governance and economic policy.

Digitalisation of reporting: Impact on data quality and transparency

The digitisation of financial reporting has become one of the key factors in improving its reliability, timeliness and comparability, especially in the small business sector. Ukraine began implementing the XBRL system in 2020, when the National Securities and Stock Market Commission introduced a unified taxonomy for business reporting. Initially, only about 5% of enterprises submitted digital reports, mostly medium-sized companies with experience in IFRS auditing (Lukianykhina *et al.*, 2024). By 2024, this figure increased to 28% and, according to the Ministry of Finance's forecasts, the share of electronic reporting will reach 45% in 2026 (Strategy of Ukrainian financial..., n.d.). The changes are explained by the integration of new electronic data submission platforms and the improvement of the XBRL taxonomy SME Reporting UA 2.0, which ensures better compatibility between accounting systems.

The use of XBRL has a direct impact on the quality of financial data. After switching to electronic format, the number of arithmetic errors in the financial reports of small enterprises decreased from 16.2% in 2021 to 6.4% in 2024, and the share of late reports decreased from 12.5% to 4.1% (Verner, 2024). Studies show that automatic verification of XBRL documents can be used to detect more than 80% of errors related to discrepancies between assets and liabilities. This helps to increase confidence in financial information among investors and government regulators. As a result, the digital transformation of the accounting process reduces the amount of manual work and creates the conditions for a transition from “post-factum” reporting to “real-time” reporting.

The integration of digital financial accounting platforms is actively underway through Enterprise Resource Planning (ERP) systems and cloud solutions. According to estimates, more than 39% of Ukrainian small businesses

use cloud accounting services for automatic reporting, compared to only 14% in 2020. The most popular solutions are BAS ERP, Finmap, and local services such as “My Accounting” and “SME Office”, which can be used to generate balance sheets and financial statements following NAP(S) B 25. In practice, the implementation of ERP systems reduces the time required to prepare reports by 35-40% and reduces the number of discrepancies between accounting and tax data (Knuth *et al.*, 2021). For example, in 2023, due to the integration of BAS ERP with the XBRL module, Ekopak LLC reduced the time spent on preparing its annual report from 20 to 11 days and increased data accuracy by 23% (Lukianykhina *et al.*, 2024). Thus, the digitalisation of financial reporting in Ukraine is gradually moving from the experimental implementation stage to systematic development. The combination of XBRL taxonomy, ERP platforms, and cloud services creates conditions for transparent, automated, and reproducible financial accounting. At the same time, the key task remains to improve the digital competence of accountants, which will ensure the full integration of the national reporting system into the European financial information space.

Innovative technologies in accounting are substantial in increasing the productivity of enterprises, their investment attractiveness and competitiveness in the market. Digitalisation enables businesses to reduce the cost of routine accounting operations, respond more quickly to changes in the external environment, and provide users of financial statements with more reliable, timely, and structured information. For example, the use of data analytics and digital platforms in SMEs creates conditions for faster decision-making, diversification of business models and entry into new markets (OECD, 2021). Thus, the introduction of reporting technologies as a means of management communication directly strengthens the strategic position of the company, rather than merely fulfilling a regulatory reporting function.

Automated ERP systems significantly reduce human error and increase reporting accuracy. ERP system users report improved productivity, reduced reporting time, and increased integration between financial, operational, and management data. An analysis of the relationship between ERP and business results has found a positive effect on labour productivity when ERP is used in conjunction with supply chain management systems and CRM solutions (Latif *et al.*, 2025). In addition, the implementation of ERP in manufacturing SMEs contributes to the strengthening of management accounting and control. As a result, automation through ERP systems in the accounting process reduces manual corrections, improves the consistency of accounting and tax data, and reduces the risk of human error, which directly corresponds to the previously described reduction in arithmetic errors and improvement in the accuracy of Ukrainian reporting.

Regarding cloud platforms, blockchain and artificial intelligence, it is worth noting that their use in reporting creates new horizons for accounting transformation. It is

worth noting that cloud accounting systems help reduce the amount of manual work, improve access to data in real time, and facilitate collaboration between remote users and audit or tax authorities (Sarker, 2025). In turn, blockchain technology is gaining recognition as a means of increasing the reliability and transparency of accounting records due to the impossibility of changing data from previous periods, the creation of an audit trail, and the reduction of fraud risk (Akter *et al.*, 2024). The integration of artificial intelligence into accounting systems can automatically detect anomalies in reporting data, predict risks, and optimise verification procedures, creating a competitive advantage for companies that actively use such technologies. The implementation of these latest solutions as a whole transforms accounting from an “annual submission” to a continuous flow of information, which increases attractiveness for investors and strengthens the company’s competitiveness. Innovative technologies make it possible for small businesses in Ukraine not only to comply with regulatory requirements but also to create added value through operational management, transparent communication with

investors and government agencies, and the use of data as a tool for strategic development.

As a result, it is possible to form a structured model of the relationship between the level of digitalisation of reporting and the quality of financial data, which reflects how the depth of automation, integration of ERP systems, use of cloud solutions and implementation of the XBRL format directly affect the reliability, timeliness and comparability of information. The model is based on the assumption that each level of digital maturity of an enterprise, from basic automation of accounting operations to analytical data management, creates an additional effect of transparency that can be measured through the qualitative characteristics of reporting. For example, enterprises that use integrated real-time reporting platforms demonstrate consistently lower rates of errors and late submissions while increasing the level of data compliance with audit requirements. Thus, the digital level of reporting is not only a technological indicator but also an analytical criterion for assessing the quality of financial information within the national accounting system. The model is schematically presented in Figure 1.

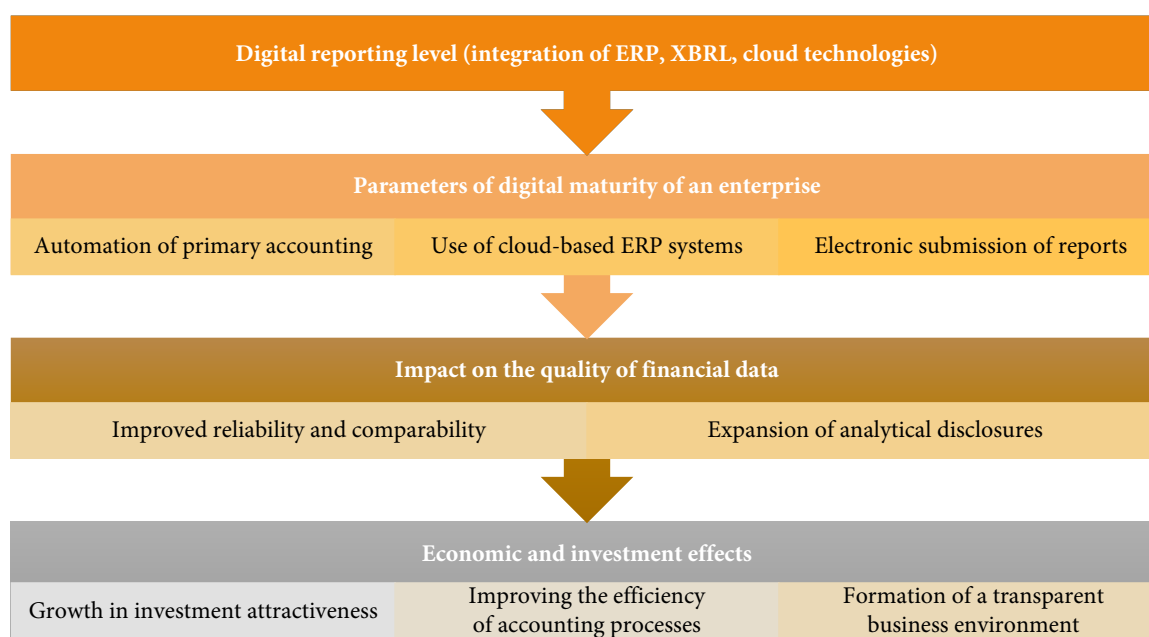


Figure 1. Model of the relationship between the digital level of reporting and the quality of financial data

Source: compiled by the author based on OECD (2021), J. Sarker (2025)

Based on the presented model, recommendations can also be formulated for harmonising the Ukrainian financial reporting system with European standards, which envisage three key areas. The first is the unification of reporting formats: a gradual transition to universal XBRL-type electronic taxonomies compatible with the European BRIS and e-Balance systems, which will ensure technical comparability of data. Second, strengthening requirements for explanatory notes and disclosure of information, especially regarding accounts receivable, liabilities, state aid and related party transactions; this approach will increase the

confidence of investors and analysts in the financial results of micro and small enterprises. Third, the introduction of internal control procedures in the digital environment, including automated data verification modules, audit logs and artificial intelligence-based error detection algorithms.

The implementation of these steps will create a unified, integrated financial reporting infrastructure that complies with the principles of transparency, neutrality and comparability defined in international standards. For Ukraine, this means not only technical modernisation, but also strategic strengthening of confidence in accounting

information, creating the conditions for attracting investment and ensuring the sustainable development of the national business sector in the European economic space.

Discussion

The topic of harmonising accounting standards, digitising reporting processes and the impact of these transformations on the quality of financial data in the SME sector remains central to many researchers. European practices showed that the introduction of International Financial Reporting Standards for SMEs and digital tools such as XBRL creates a new level of transparency, comparability and analyticality of financial data. The results of the study are fully consistent with this trend, demonstrating that it is digital integration and standardisation of reporting forms that increase the reliability of indicators and promote transparent financial management. This can be used to view financial reporting not only as an accounting requirement, but also as a strategic tool for sustainable business development. G. Bucior & E. Jaworska (2023) examined the experience of Polish micro-enterprises in the process of abandoning paper-based financial reporting. The study determined that the main challenge for enterprises was not so much technological adaptation as a change in organisational culture and managerial thinking. They proved that the success of the transition to electronic reporting depends on the willingness of management to delegate authority and trust automated systems. The study also noted that the transition to digital formats is accompanied by increased discipline in accounting processes and accuracy of reporting indicators. Present study demonstrated similar patterns: the study determined that the introduction of electronic reporting can reduce the number of arithmetic errors and increase the reliability of data, which indicates the universal nature of the challenges of digital transformation for microbusinesses.

M. Al-Okaily *et al.* (2024) examined how the introduction of the extensible business reporting language format affects the transparency of financial information in the digital environment. The study demonstrated that automated data verification in XBRL systems reduces information asymmetry between companies and users of financial statements. M. Al-Okaily *et al.* (2024) noted that this effect is even more pronounced in countries with transitional economies, as trust in electronic data increases in an environment of limited audit oversight. The study confirmed these findings, as the introduction of XBRL in Ukraine led to an improvement in the quality of audit procedures, a reduction in the number of non-systemic errors, and improved comparability of financial indicators between companies in different industries. Thus, digital reporting is not just a technological innovation, but a mechanism for increasing trust and accountability in business.

Instead, J.A. Smith *et al.* (2022) emphasised the need to redefine the role of accounting in small businesses as an element of public accountability. The study highlighted that SMEs tend to perceive accounting as a compulsory administrative procedure, whereas in European practice it

increasingly serves as a means of communication between business, government and society. The authors emphasised that digital forms of reporting expand opportunities for analysis, comparison and control. The study confirmed a similar trend: electronic reporting systems in Ukraine not only increase the transparency of indicators but also shape a new management culture, where accounting becomes a source of strategic information for decision-making. At the same time, there is still a need to develop a culture of responsible disclosure, which is a key condition for trust in financial information.

The impact of the introduction of international financial reporting standards for SMEs on the properties of financial indicators and the cost of debt financing in private firms in Sweden was investigated by N. Hellman *et al.* (2022). The study determined that the application of standardised rules for the valuation of assets and liabilities reduces the volatility of indicators and improves the predictability of profitability. At the same time, the simplified reporting structure reduces the cost of preparing documents and facilitates access to bank lending. The study demonstrated a similar pattern: harmonising Ukrainian accounting regulations with international standards ensures better comparability of reporting, which is relevant for companies that attract external financing. This indicates a direct link between standardisation of reporting, reduction of information risk and increased investment attractiveness of businesses.

D. Cicchini *et al.* (2024) compared approaches to digital reporting in the EU and the US, emphasising the combination of financial and non-financial disclosures. The study concluded that disclosure standards in the EU are more flexible but of higher quality due to the integration of environmental and social aspects into financial reporting. The authors emphasised that the digitalisation of reporting has catalysed the transition from a narrow accounting approach to a comprehensive approach to corporate transparency. The study confirmed this thesis, as the Ukrainian experience of implementing digital formats also demonstrates a trend towards expanding disclosures and including non-financial indicators in reporting, which correlates with the European logic of “sustainable development reporting”. A. Reino *et al.* (2020) investigated the relationship between organisational culture and the financial performance of Estonian companies. The study concluded that organisational openness, innovation orientation and support for staff training contribute to better financial performance of enterprises. The study also emphasised that digital technologies are a tool for strengthening transparency and accountability, as they change corporate culture towards trust in data. The study confirmed a similar relationship: the success of the digitalisation of financial reporting in Ukraine is determined not only by the availability of technical infrastructure, but also by the willingness of business leaders to perceive accounting as a strategic element of management, rather than merely a regulatory requirement.

At the same time, P. Schorn *et al.* (2021) emphasised the development of integrated reporting in the German SME

sector. The experts demonstrated that combining financial, environmental and social information in reporting helps to increase trust on the part of investors and banks. The study also emphasised that the introduction of digital tools makes this process more efficient and economically viable even for small businesses. The study is consistent with these findings, as it proves that digital reporting platforms in Ukraine not only increase the transparency of financial indicators but also create the possibility of integrating non-financial data into a single information environment.

Based on panel data, emphasising that models that reflect time dynamics more accurately reflect the relationship between management structure, digital processes and financial results, M. Yousaf (2025) analysed methods for assessing the performance of enterprises. The study proved that in the current conditions of digitalisation, the efficiency of an enterprise depends not only on resources, but also on the ability to integrate data for strategic decision-making. The study confirmed this approach: analytical systems related to digital reporting formats create a basis for forecasting and strategic planning, which transforms financial reporting into a management tool rather than just a form of reporting to the state. Summarising the results of the analysis, it is possible to state that European studies confirm the key pattern identified in the conducted research: digitalisation, harmonisation of standards and the formation of a reporting culture are interrelated processes that enhance the quality of management decisions. European experience shows that the integration of IFRS for SMEs and XBRL digital formats creates a stable information ecosystem in which financial reporting becomes a mechanism for managing risks and increasing trust between business, government and investors. For Ukraine, further improvement of the financial reporting system requires the development of digital tools, updating the regulatory framework and forming a culture of transparency, which will be a prerequisite for integration into the European financial space.

Conclusions

The study provided a comprehensive overview of the financial reporting system for small and micro-enterprises in the context of NAS and IFRS for SMEs. The study proved that the quality of reporting is determined not only by the correct application of methods for valuing assets and liabilities, but also by the consistency of accounting policies, the completeness of explanatory notes and the level of digital maturity of accounting processes. The peculiarities of micro-enterprises are considered, for which simplified reporting needs to be supplemented with disclosures on the structure of assets, deferred expenses and related party transactions, which will increase the transparency of information and the reliability of analytical conclusions.

References

- [1] Akter, M., Kummer, T.F., & Yigitbasioglu, O. (2024). Looking beyond the hype: The challenges of blockchain adoption in accounting. *International Journal of Accounting Information Systems*, 53, article number 100681. [doi: 10.1016/j.accinf.2024.100681](https://doi.org/10.1016/j.accinf.2024.100681).

A conceptual model of the relationship between the level of digitisation of reporting and the quality of financial data has been developed, reflecting the logic of the transition from paper-based and fragmented forms of submission to an integrated electronic ecosystem. The model covers three interrelated blocks: regulatory – harmonisation of Ukrainian standards with EU directives and IFRS for SMEs; technological – implementation of XBRL, ERP systems and cloud platforms; analytical – assessment of the reliability, comparability and usefulness of financial data for management decisions. The study showed that harmonising Ukrainian standards with EU directives creates a basis for comparability of indicators and ensures transparency of financial flows. The study determined that the digital transformation of reporting through the introduction of XBRL taxonomies and ERP platforms contributes to increased reliability, efficiency and control over data. The study established that micro-enterprises that switch to electronic formats reduce the time spent on reporting and reduce the number of arithmetic errors by three times. Combined with analytical tools, this creates the conditions for a transition to the concept of “real-time reporting”. A comparison of practices in Ukraine and EU countries has shown that the key factor in improving the quality of reporting is digital standardisation and the integration of national formats into the European BRIS, e-Balance and SAF-T systems.

The recommendations based on the research results describe the implementation of standard digital reporting templates in micro and small enterprises with the possibility of automatic verification of XBRL structures, the creation of industry guidelines for the disclosure of explanatory notes following Directive No. 2013/34/EU, the introduction of internal audit systems emphasising verification of the consistency of financial, tax and management data, and the development of programmes to improve the digital competence of accountants to ensure the correct completion of electronic forms. Further research should conduct a quantitative assessment of the impact of digitalisation on reporting reliability indicators, comparison of the effectiveness of different accounting automation models, and a study of the long-term effect of harmonisation of Ukrainian standards with European ones in the context of integration into a single economic space.

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- [2] Al-Okaily, M., Alkayed, H., & Al-Okaily, A. (2024). Does XBRL adoption increase financial information transparency in digital disclosure environment? Insights from emerging markets. *International Journal of Information Management Data Insights*, 4(1), article number 100228. doi: 10.1016/j.jjime.2024.100228.
- [3] Annual report. (2024). Retrieved from <https://www.stat.ee/sites/default/files/2025-04/Annual%20report%202024.pdf>.
- [4] Banera, N.P., & Heley, O. (2021). Financial reporting of small businesses: Assessment and ways to increase the informativeness of indicators. *Scientific View: Economics and Management*, 1(71), 55-62. doi: 10.32836/2521-666X/2021-71-10.
- [5] Bautista-Mesa, R., Muñoz-Tomás, J.M., & Horno-Bueno, M.P. (2019). Does the IASB know the needs of SMEs? A comparative analysis between the IFRS for SMEs and full IFRS due processes. *Spanish Accounting Review*, 22(2), 203-217. doi: 10.6018/rcsar.382261.
- [6] Bucior, G., & Jaworska, E. (2023). Bidding farewell to paper financial reports – are Polish micro businesses coping with the phenomenon. *Procedia Computer Science*, 225, 3395-3403. doi: 10.1016/j.procs.2023.10.334.
- [7] Chicchini, D., Carello, L.A., & Cotona, M.L. (2024). Comparing digital sustainability reporting through the EU and US perspectives. In R. Lombardi (Ed.), *Mixing accounting regulation and corporate accountability in the era of non-financial information, intangibles and digitalization* (pp. 57-68). Rome: Sapienza Università. doi: 10.13133/9788893773065.
- [8] Czech Statistical Office. (2023). *Statistical yearbook of the Czech Republic – 2023*. Retrieved from <https://csu.gov.cz/produkty/statistical-yearbook-of-the-czech-republic-2023>.
- [9] Directive of the European Parliament and of the Council No. 2013/34/EU “On the Annual Financial Statements, Consolidated Financial Statements and Related Reports of Certain Types of Undertakings, Amending Directive 2006/43/EC of the European Parliament and of the Council and Repealing Council Directives 78/660/EEC and 83/349/EEC”. (2013, June). Retrieved from <https://eur-lex.europa.eu/eli/dir/2013/34/oj/eng>.
- [10] Directive of the European Parliament and of the Council No. 2014/95/EU “Amending Directive No. 2014/95/EU as Regards Disclosure of Non-Financial and Diversity Information by Certain Large Undertakings and Groups”. (2014, October). Retrieved from <https://eur-lex.europa.eu/eli/dir/2014/95/oj/eng>.
- [11] Dzhulii, L., Hrebinska, S., & Chenash, V. (2024). Features of accounting and taxation of small enterprises. *Economy and Society*, 70. doi: 10.32782/2524-0072/2024-70-164.
- [12] European Commission. (2023). *Implementation reports 2023*. Retrieved from https://commission.europa.eu/publications/implementation-reports-2023_en.
- [13] European Commission. (2024). *Annual activity report 2024: Directorate general for internal market, industry, entrepreneurship and SMEs*. Retrieved from https://commission.europa.eu/document/download/724e5745-c742-4242-b723-bcbf48de5fae_en?filename=GROW_AAR_2024_final.pdf.
- [14] Federal Statistical Office. (n.d.). *Industry, manufacturing*. Retrieved from https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Industrie-Verarbeitendes-Gewerbe/_inhalt.html.
- [15] Fomina, O., Semenova, S., & Berezovska, D. (2022). Transformation of financial reporting of small enterprises according to IFRS. *Foreign Trade: Economics, Finance, Law*, 123(4), 44-59. doi: 10.31617/3.2022(123)04.
- [16] Gogol, T., & Kolotok, V. (2020). Disclosure of non-financial information in small business reporting. *Problems and Prospects of Economics and Management*, 1(21), 174-182. doi: 10.25140/2411-5215-2020-1(21)-174-182.
- [17] Hellman, N., Nilsson, H., Tylaite, M., & Vural, D. (2022). The impact of an IFRS for SMEs-based standard on financial reporting properties and cost of debt financing: Evidence from Swedish private firms. *European Accounting Review*, 31(5), 1175-1205. doi: 10.1080/09638180.2022.2085758.
- [18] Incollingo, A., & Lionzo, A. (Eds.). (2023). *The European harmonization of national accounting rules: The application of Directive 2013/34/EU in Europe*. Cham: Springer. doi: 10.1007/978-3-031-42931-6.
- [19] Kaya, D., & Koch, M. (2014). Countries’ adoption of the international financial reporting standard for small and medium-sized entities (IFRS for SMEs) – early empirical evidence. *Accounting and Business Research*, 45(1), 93-120. doi: 10.1080/00014788.2014.969188.
- [20] Knuth, A., Saha, D., & Poluschkin, G. (2021). *Progress and challenges in the digital transformation of businesses in Ukraine – results from a representative business survey*. Retrieved from <https://www.german-economic-team.com/en/publication/progress-and-challenges-in-the-digital-transformation-of-businesses-in-ukraine-results-from-a-representative-business-survey-2/>.
- [21] Kostash, T. (2025). Modernisation of financial reporting of enterprises in the digital economy. *Actual Issues of Economic Sciences*, 15. doi: 10.5281/zenodo.17215812.
- [22] Kostyakova, A. (2025). Reporting without borders: Ukrainian realities in the context of IFRS. *Economy and Society*, 74. doi: 10.32782/2524-0072/2025-74-108.
- [23] Kostyuchenko, V., & Kovalova, A. (2020). *Adoption of IFRS for SME in Ukraine*. *Journal of Economics and Economic Education Research*, 21(6).

- [24] Kovalchuk, I. (2025). Harmonization of regulatory regulation of digitalization of state financial control in Ukraine: Challenges and prospects for adaptation to European Union standards. *Customs Scientific Journal*, 1, 23-29. doi: [10.32782/2308-6971/2025.1.3](https://doi.org/10.32782/2308-6971/2025.1.3).
- [25] Latif, S., Salleh, S.I.M., Ahmad, B., & Saif, F. (2025). ERP adoption and strengthening of management accounting and controls at a Pakistani manufacturing SME: A case study approach. *South Asian Journal of Business and Management Cases*, 14(2), 145-161. doi: [10.1177/22779779251349974](https://doi.org/10.1177/22779779251349974).
- [26] Law of Ukraine No. 996-XIV "On Accounting and Financial Reporting in Ukraine". (1999, July). Retrieved from <https://zakon.rada.gov.ua/laws/show/996-14?lang=en#Text>.
- [27] Lukianykhina, O., Suprunenko, S., Slavkova, A., Skorba, O., & Zavrzhnyi, K. (2024). Digital innovations in the fiscal policy of Ukraine: Promoting sustainable economic development. *International Journal of Economics and Financial Issues*, 14(4), 77-86. doi: [10.32479/ijefi.16202](https://doi.org/10.32479/ijefi.16202).
- [28] Ministry of Finance of the Republic of Poland. (n.d.). Retrieved from <https://www.gov.pl/web/finance>.
- [29] Mulyk, Y. (2021). Audit services market: The experience of Ukraine. *Green, Blue and Digital Economy Journal*, 2(3), 35-42. doi: [10.30525/2661-5169/2021-3-6](https://doi.org/10.30525/2661-5169/2021-3-6).
- [30] Nazarova, K., & Bondarenko, K. (2022). Vectors of XBRL reporting development in Ukraine. *Scientia Fructuosa*, 142(2), 81-93. doi: [10.31617/visnik.knute.2022\(142\)06](https://doi.org/10.31617/visnik.knute.2022(142)06).
- [31] Ngaruko, F. (2023). *Annual report 2023*. Washington: World Bank Group.
- [32] OECD. (2021). *The digital transformation of SMEs*. Paris: OECD Publishing. doi: [10.1787/bdb9256a-en](https://doi.org/10.1787/bdb9256a-en).
- [33] OECD. (2024). *Financing SMEs and Entrepreneurs 2024: An OECD scoreboard*. Paris: OECD Publishing. doi: [10.1787/fa521246-en](https://doi.org/10.1787/fa521246-en).
- [34] Polish Agency for Enterprise Development. (2024). *Report on the state of the small and medium-sized enterprise sector in Poland*. Retrieved from https://popw.parp.gov.pl/storage/publications/pdf/ROSS_2024.pdf.
- [35] Reino, A., Rõigas, K., & Müürsepp, M. (2020). Connections between organisational culture and financial performance in Estonian service and production companies. *Baltic Journal of Management*, 15(3), 375-393. doi: [10.1108/BJM-01-2019-0017](https://doi.org/10.1108/BJM-01-2019-0017).
- [36] Sarker, J. (2025). Cloud accounting system and financial reporting efficiency of SMEs. *International Journal of Science and Business*, 48(1), 75-91. doi: [10.58970/IJSB.2626](https://doi.org/10.58970/IJSB.2626).
- [37] Schorn, P., Tempel, A., Bauer, R., & Klapdor, R. (2021). SMEs and IR: Evidence from Germany. In J. Dyczkowska, A. Szirmai Madarasine & A. Tiron-Tudor (Eds.), *Development of integrated reporting in the SME sector: Case studies from European countries* (pp. 21-44). Cham: Springer. doi: [10.1007/978-3-030-81903-3_2](https://doi.org/10.1007/978-3-030-81903-3_2).
- [38] Semenova, S., & Shpyro, O. (2019). Accounting policies of small enterprises in Ukraine and Germany. In *Collection of scientific research papers State University of Infrastructure and Technologies Section "Economics and Management"*, 46, 95-108. doi: [10.32703/2664-2964-2019-46-95-108](https://doi.org/10.32703/2664-2964-2019-46-95-108).
- [39] Smith, J.A., Reid, G.C., & Cardao-Pito, T. (2022). Call for papers: Accounting and accountability in small-to medium-sized enterprises (SMEs). *European Journal of Management Studies*, 27(3), 341-345. doi: [10.1108/EJMS-11-2022-112](https://doi.org/10.1108/EJMS-11-2022-112).
- [40] Strategy of Ukrainian financial sector development until 2025. (n.d.). Retrieved from https://mof.gov.ua/storage/files/Strategy_FS_2025_eng.pdf.
- [41] Vakun, O., Horodysky, M., Grabchuk, I., & Solovyov, B. (2020). Problems of implementing the XBRL reporting standard. *Problems of Theory and Methodology of Accounting, Control and Analysis*, 2(46), 3-8. doi: [10.26642/pbo-2020-2\(46\)-3-8](https://doi.org/10.26642/pbo-2020-2(46)-3-8).
- [42] Verner, I. (Ed.). (2024). *Statistical yearbook of Ukraine for 2023*. Kyiv: State Statistics Service of Ukraine
- [43] Yang, L.C., & Ming, C.W. (2024). Digital transformation and its effects on the financial performance of Malaysian SMEs. *Journal of Digitainability, Realism & Mastery*, 3(8), 21-32. doi: [10.56982/dream.v3i08.263](https://doi.org/10.56982/dream.v3i08.263).
- [44] Yousaf, M. (2025). Determinants of firm performance: How to choose the best model among panel data models? *Central European Management Journal*, 33(3), 504-521. doi: [10.1108/CEMJ-05-2023-0229](https://doi.org/10.1108/CEMJ-05-2023-0229).

Особливості складання фінансової звітності малими підприємствами та мікропідприємствами: український та міжнародний досвід

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Анотація. Метою статті було обґрунтування теоретичних і прикладних засад удосконалення складання фінансової звітності малих підприємств і мікропідприємств в Україні з урахуванням міжнародного досвіду та цифрової трансформації облікових процесів. Методологічну основу становили порівняльний та контент-аналіз, узагальнення практик подання даних у форматі розширюваної мови бізнес-звітності та спостереження. Емпіричну базу сформовано на основі офіційних аналітичних та статистичних звітів. Отримані результати дали змогу ідентифікувати ключові відмінності між вимогами національних стандартів бухгалтерського обліку та міжнародних стандартів для малих підприємств у частині складу звітності, принципів оцінки активів і зобов'язань та розкриття інформації. Виявлено, що запровадження цифрових форматів звітності та гармонізація методичних підходів підвищують порівнянність і достовірність даних, скорочують час на підготовку звітів і знижують ризик арифметичних та класифікаційних помилок. Доведено, що використання інтегрованих інформаційних систем, зокрема систем планування ресурсів підприємства та хмарних платформ, сприяє формуванню єдиного інформаційного простору між обліковими, податковими й аналітичними підсистемами. У результаті сформовано структуровану модель взаємозв'язку між цифровим рівнем звітності та якістю фінансових даних, а також у рекомендаціях щодо гармонізації української системи фінансової звітності з європейськими стандартами. Запропонована модель включає узгодження форматів подання звітності, посилення вимог до пояснювальних приміток і розкриття інформації, впровадження внутрішніх контрольних процедур для забезпечення порівнянності та прозорості. Матеріали дослідження можуть бути використані під час розроблення державних стратегій модернізації фінансової звітності, удосконалення податкової політики та підвищення інвестиційної привабливості українських підприємств у процесі інтеграції до європейського економічного простору

Ключові слова: бухгалтерський облік; економічна прозорість; гармонізація стандартів; цифрові формати даних; управлінська аналітика; регуляторна конвергенція; якість інформаційних систем

Technology transfer as a foundation for starting a business in Ukraine

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Abstract. The relevance of innovation development activation in Ukraine is combined with the limited use of scientific results in entrepreneurial activities, which hinders the formation of a knowledge economy. The existing gap between academic research and commercial application determines the necessity to improve technology transfer mechanisms and create conditions for efficient implementation of university initiatives. In this context, study of technology transfer as a foundation for starting a business becomes relevant. The study aimed to identify mechanisms through which technology transfer can be used as a practical basis for starting a business, as well as to develop an applied model of interaction between scientific institutions, technology transfer offices, and the entrepreneurial sector. The methodology was based on analytical, comparative, and systemic research. A logical and content analysis of scientific sources from international databases such as Scopus, Web of Science, and university repositories was conducted. Generalisation of empirical data identified three directions of influence of technology transfer on business creation: scientific-technological, organisational-managerial, and socio-economic. The study addressed technology transfer as a factor in shaping entrepreneurial activity and developing innovation economy in Ukraine. The study determined that modern universities are becoming hubs for dissemination of scientific results, combining research, education, and entrepreneurial initiatives. The results showed that the effectiveness of technology transfer in Ukraine is lower than in developed countries, due to insufficient integration of science, education, and business. A model for the development of university entrepreneurship has been proposed, which combines the activities of technology transfer offices, incubators, start-up schools, and government support programs. Its implementation would contribute to increasing the commercialisation of research results, fostering an entrepreneurial culture among students and researchers, and attracting investment in the innovation sector. The practical value of this work lies in forming the analytical foundation for modernising the policy to support university-based start-ups and improving the commercialisation mechanisms for scientific developments

Keywords: start-up management; technology transfer; academic entrepreneurship; university start-ups; business planning; knowledge commercialisation; human capital development

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Introduction

In 2020-2025, Ukraine has prioritised commercial use of scientific research results, but the transition from technology creation to practical application remains fragmented and uneven. A significant portion of scientific developments does not reach the implementation stage due to insufficient coordination between scientific, innovative, and entrepreneurial activities of universities. This situation creates a gap between generation of new knowledge, economic implementation and slows formation of innovation market as well as development of academic entrepreneurship. University teams often face a lack of advisory, organisational, and financial support, which complicates the transition from idea to product development stage. Under such conditions, technology transfer represents a process that links scientific results with opportunities for commercial application; however, potential remains limited by organisational and legal constraints. Such issues caused further scientific research in analysis of technology transfer as a basis for university start-up implementation in Ukraine.

Conceptual foundations of academic entrepreneurship have evolved alongside development of entrepreneurship research. According to T.D. Barth & W. Schlegelmilch (2020), academic entrepreneurship refers to entrepreneurial activity emerging within universities and research institutions, where scientific knowledge becomes a source of economic value creation through technology transfer, spin-offs, and cooperation with external partners. H. Landström (2020) demonstrated that entrepreneurship has developed into an independent scholarly field, extending from individual business activity to institutional and ecosystem-level processes, including the role of universities in knowledge commercialisation and innovation development. These theoretical considerations create a framework for analysis of technology transfer as a mechanism embedded in the wider development of academic entrepreneurship.

Subsequent studies addressed institutional and organisational conditions influencing the functioning of technology transfer. S. El-Ferik & M. Al-Naser (2021), in analysis of trilateral interaction between universities, business, and the state, highlighted the role of knowledge and technology transfer in coordinating interests of participants involved in cooperation. Within this context, D. Prokop (2021) demonstrated that the nature of institutional support at universities affects both the number and the duration of spin-off entities based on research results.

Empirical research further underlines significance of organisational arrangements in supporting university-based entrepreneurial activity. A.I. Gaspar Pacheco *et al.* (2024) demonstrated that mentoring programmes, educational courses, and administrative support create favourable conditions for initiation of university start-ups. Furthermore, Y. Nikitin (2023) presented a model of an innovation ecosystem in which technology transfer processes arise from interaction between science, education, the economic sphere, government structures, society, and digital platforms. At the level of applied outcomes,

H. Martínez-Ardila *et al.* (2023) confirmed the presence of a relationship between university-industry cooperation and the creation of spin-off projects based on joint patenting.

In Ukrainian academic literature, institutional and regulatory issues related to technology transfer were prioritised. D. Tymchenko *et al.* (2020) examined the establishment of technology transfer offices in higher education institutions, describing their structural organisation and forms of interaction with participants in innovative activity. T. Yaroshevska (2022) analysed institutional factors of uneven economic use of scientific research results across sectors of Ukrainian economy, while I. Zrybnieva *et al.* (2023) addressed legal issues and difficulties arising during the implementation of technology transfer legislation in scientific institutions.

Related research demonstrated persistent gaps between implementation of research and subsequent economic use. L.V. Rozhkova (2024) examined commercial use of research results created with state funds, whereas V.V. Pyroh (2025) explored technology transfer as a source of funding for start-up projects in scientific sphere, highlighting investment mechanisms supporting entrepreneurial initiatives at universities. From a broader macroeconomic perspective, T. Zarkua *et al.* (2025) demonstrated that entrepreneurial initiatives are central in countries undergoing transformational processes in economic and scientific domains.

Despite extensive body of literature devoted to technology transfer offices, innovation ecosystems, and entrepreneurial activity, there remains a lack of studies explaining how technology transfer functions as a practical basis for the creation of university start-ups in Ukraine. Therefore, the study aimed to examine how technology transfer may serve as a foundation for starting a business in Ukraine and to develop an applied model of interaction between university teams, technology transfer offices, and innovation support structures.

Materials and Methods

The study was conducted using a combination of general scientific and special methods to analyse technology transfer in the launch of university start-ups. Methodology addressed reproducibility of research through description of data sources, analytical procedures, and sequence of research operations.

The study covered 2019 to 2024 including available comparable and complete statistics from open sources and analytical reports. Data for 2025 were excluded due to absence of verified and summarised metrics, which hindered comparison. To examine quantitative indicators on activity of technology transfer offices, statistical summarisation was applied. This procedure included aggregation of indicators reported in analytical publications, their conversion into comparable measurement units, and calculation of average values. The resulting data formed the basis for Table 1, which presents indicators for the United States (US), The United Kingdom (UK), Germany, Poland, and Ukraine.

The dynamics of university start-up creation in the European Union (EU), North America, Asia, Latin America, and Ukraine were analysed using generalisation of data reported in systematic reviews and analytical studies (Padilla Bejarano *et al.*, 2023; Ríos Yovera *et al.*, 2025). Analysis incorporated average annual number of newly created start-ups, share of projects that reached the stage of commercial use, and main sources of funding. Summarised quantitative data were structured in tabular form to support comparison between regions.

Furthermore, systematic and comparative analysis supported generalisation of theoretical findings and formation of integrated concept of technology transfer as a research process. Content analysis of publications by international and Ukrainian authors identified major research directions related to university entrepreneurship and use of scientific results. Combination of methods ensures scientific soundness of the study, adequate coverage of research topic, and

possibility of repeating the procedure using similar information sources and analytical sequences.

Results and Discussion

Technology transfer as a mechanism for shaping entrepreneurial initiatives

When analysing the role of technology transfer in launching entrepreneurial initiatives, it is useful to refer to quantitative metrics of the performance of technology transfer offices in different countries. Such metrics can be used to trace the transfer of scientific research results to the stage of practical application and to identify the institutional conditions that contributed to this process. For a comparative analysis of universities' capabilities in technology transfer, Table 1 presents indicators characterising average annual number of patents transferred, share of developments developed for use, and number of spin-off projects created in selected countries.

Table 1. Performance indicators of technology transfer offices in selected countries worldwide (2019-2024)

Country	Average number of patents transferred annually	Share of commercialised developments, %	Number of spin-offs created	Main forms of support
US	520	38.6	210	Grants, venture capital funds, business incubators
UK	310	35.2	175	University development funds, partnerships with businesses
Germany	285	33.1	160	Government programs, EXIST, innovation clusters
Poland	95	27.4	68	Regional hubs and technology parks
Ukraine	22	10.5	9	Academic laboratories, start-up schools at universities

Source: based on M. Guerrero & M. Menter (2024)

Metrics presented in Table 1 are analytically significant for assessment of functioning of technology transfer offices. The average annual number of patents transferred reflects intensity of research results transfer outside universities. Share of developments that have reached the stage of use indicates the ability of institutions to accompany these results at legal formalisation and implementation stages. Number of spin-off projects, in turn, characterises entrepreneurial activity based on scientific achievements. A comparison of indicators between countries reveals a significant difference in activities of technology transfer offices. European Union and North American countries had higher values for patent activity, share of developments used, and number of spin-off projects. Ukraine had significantly lower indicators, which could be caused by limited financial resources, less developed forms of interaction between scientific community and users of developments, as well as a lack of specialists in research transfer.

Similar observations are present in analysis by M. Guerrero & M. Menter (2024), noting that management capabilities of universities have a decisive influence on the development of academic entrepreneurship. C. Olvera *et al.* (2021) also demonstrated that organisational

conditions of institutions involved in technology transfer influenced nature of cooperation between universities and external partners.

Scientific publications showed that technology transfer was considered by researchers to be an important component in transforming research results into developments suitable for practical use. The analysed studies demonstrated a tendency towards strengthening role of technology transfer offices in supporting entrepreneurial activities of scientists and students, in particular through participation in commercial support of developments and establishment of interaction between academic community and potential users of technologies. This approach was reflected in studies by C.S. Hayter *et al.* (2023), N. Halilem *et al.* (2024), as well as Z. Chen *et al.* (2025). A summary of comparative analysis results suggested that technology transfer was substantial in shaping entrepreneurial initiatives both at support for individual researchers and students and at institutional development of universities. A comparison of the activities of technology transfer offices in different countries reveals a pattern whereby more structured interaction between the academic sector and users of developments was accompanied by higher rates of conversion of scientific ideas into applied solutions. These generalisations provide a basis for

further analysis of possibilities for developing technology transfer in Ukrainian universities in the context of launching start-ups based on scientific results.

University start-ups as a result of the commercialisation of scientific knowledge

A substantial aspect of entrepreneurial ecosystem is university spin-offs, which emerge based on research projects and represent a specific form of transferring scientific knowledge into economic activity. According to A. Civera *et al.* (2020), such entities arise when research outcomes are combined with organisational conditions for further development outside academic context.

E.E. Lehmann *et al.* (2021) emphasised that academic entrepreneurship is formed at intersection of innovation processes, institutional settings and individual initiative within universities. In this context, university spin-offs

function as organisational arrangements through which research results acquire an applied dimension. B.H. Jevnaker & B.A. Misganaw (2022) demonstrated that formation of spin-off projects is related to structure and coordination of entrepreneurial teams, as well as role of technology transfer offices in supporting researchers at early stages. From perspective of developing economies, M.M. Musleh *et al.* (2025) highlighted that university spin-offs often operate under conditions of limited resources, which increases the importance of coordinated institutional support and access to external networks.

To analyse dynamics of university start-up creation across different regions, data from international analytical studies were summarised. Results of comparative assessment are presented in Table 2, which reflects average indicators of start-up creation and progression to commercial application stage in selected regions between 2019 and 2024.

Table 2. Estimated dynamics of university start-up creation (2019-2024)

Region	Average number of new start-ups per year	Percentage of start-ups that have passed the commercialisation stage, %	Main source of funding
European Union	420	42.1	EU grants, venture capital
North America	510	47.3	Private investors, corporate partners
Asia	375	39.8	University funds, government programs
Latin America	165	24.7	International technical assistance
Ukraine	35	12.6	Donor support programs, government grants

Note: The figures shown reflect the average number of university start-ups that have passed the initial commercialisation stage, i.e. received initial funding (grant or investment) or brought a minimum viable product (MVP) to market between 2019 and 2024

Source: summary based on J.B. Padilla Bejarano *et al.* (2023), V.R. Ríos Yovera *et al.* (2025)

The data presented in Table 2 indicate notable differences in scale and progression of university start-up creation across regions. Higher average numbers of newly established projects and larger shares of initiatives reaching commercial application stage were noted in North America and the European Union, which reflects presence of more developed organisational arrangements supporting research-based projects. Lower indicators recorded for Ukraine suggest a more limited number of start-up initiatives and a smaller proportion of projects progressing outside early stages. Similar observations were reported by C.S. Hayter *et al.* (2023), emphasising that formation of academic entrepreneurship is associated with availability of educational programs, access to incubation infrastructure and institutional support for intellectual property. A summary of the analysis results shows that university start-ups had significant potential for developing scientific results, while emergence pace depended on available resources, institutional support and quality of interaction between participants in innovation system. For Ukraine, these conclusions determine the need to expand opportunities for teams working on scientific developments and to create conditions that facilitate the transition from research to commercial application.

Development of financial and organisational mechanisms to support start-ups

The analysis showed that creation of university start-ups correlated with availability of financial and organisational support, ensuring transfer of research results to business sector. In European Union countries, such support was based on a combination of public funding, venture capital investments and participation of private funds. As noted by M. Guerrero & M. Menter (2024), government grants and programmes, particularly within European Commission initiatives, were directed toward initial costs related to development, prototyping, and early stages of research application.

In Ukraine, government grants dominated, prioritising support of research and development projects. Participation of private investors and venture capital funds was sporadic. N. Halilem *et al.* (2024) confirmed that the main source of funding for start-ups remained government support through national programmes for young scientists and a start-up fund. For comparison, in 2024, the average amount of funding for start-ups in European Union countries was approximately 7.4 billion EUR, while in Ukraine it was 32 million EUR, which indicated a significant reserve for expanding investment field by integrating university projects into international support programmes. Structure of university start-up funding by source is presented in Table 3.

Table 3. Structure of university start-up funding by source, %

Source of funding	EU	US	Asia	Ukraine
Grants from governments and international organisations	42.3	28.7	33.5	61.0
Venture capital	31.5	47.8	29.4	12.4
Crowdfunding and private investors	8.6	12.2	18.1	7.8
University funding	10.4	6.1	11.3	9.6
Other sources (donations, corporate participation, etc.)	7.2	5.2	7.7	9.2

Source: summarised based on analytical data from international and national studies A. Civera *et al.* (2020), N. Halilem *et al.* (2024)

The indicators presented in Table 3 are central for analysis of effectiveness of financial mechanisms supporting university start-ups, as they can be used for an assessment of ratio between budgetary and extra-budgetary sources of funding. High share of grants from state and international organisations reflects the dependence of start-ups on budgetary support, while volume of venture financing and private investor participation characterises the level of interest of capital market in university projects.

Presented data show that financing of university start-ups in Ukraine was predominantly based on state programmes, as more than 60% of support was provided from budgetary sources. This funding structure limited opportunities for broader private capital involvement and distinguished Ukraine from European Union and United States, where venture capital funds and private investors were more influential, supporting faster project development and wider prospects for further expansion.

Predominance of budget-based support constrained development potential of university projects and highlighted the need for diversification of funding sources. In this context, reference to international experience in academic entrepreneurship provides a basis for analysis of alternative formats for combining financial and organisational support in development of university start-ups.

International practices in the development of academic entrepreneurship

A study of international experience showed that mechanisms supporting academic entrepreneurship in different countries share a common foundation, while specifics are shaped by economic opportunities and organisational characteristics of national systems. Despite these differences, researchers identified recurring patterns in university practices, including use of financial support, consulting assistance, interaction with investors, and creation of organisational arrangements aimed at supporting start-ups at early stages.

A distinct organisational configuration has been formed in Singapore. According to J. Hong *et al.* (2023), university accelerators in Singapore accompany projects until they reach market stage and create conditions for attracting private investors. This configuration relies on long-term mentoring and stable partnerships between research groups and economic structures, which supports continuity of assistance throughout entire development cycle.

European Union countries demonstrate a different format, prioritising integration of university developments

into regional development policy. J.A. Cunningham *et al.* (2022) showed that universities in Italy, Spain, and Finland receive tax incentives, grant support, and advisory assistance, which support project development at early stages and contributes to cooperation between academic institutions and regional partners. Scandinavian practice should also be mentioned. Y. Cai & A. Lattu (2022) emphasised that universities in these countries involve external partners in management of technology transfer offices, which supports trust among participants and facilitates assessment and further use of innovations.

Ukrainian commercialisation system remains at an early stage of formation. Most influential support mechanisms include international technical assistance programmes, particularly Horizon Europe (n.d.), as well as initiatives of the European Bank for Reconstruction and Development. Activities of state institutions, including the Ukrainian Start-up Fund and National Research Fund of Ukraine, support communication between scientists and investors, although scale of such support remains lower than that observed in European practice. Effects of interaction between universities, public authorities, and economic partners are also reflected in employment outcomes. M. Guerrero & M. Menter (2024) reported that a single university start-up in the United States creates, on average, between 6 and 12 jobs during first years of operation, which confirms role of academic entrepreneurship as a source of economic activity.

A summary of international experience indicates that several typical formats of support organisation for entrepreneurial activity based on technology transfer can be identified. One such format involves early selection of innovations, with specialised funds concentrating resources on promising developments at initial stages. In Singapore, a system of long-term support for start-up projects has been formed, with prioritising developments throughout entire cycle, from idea to market entry.

European Union countries are characterised by a regional format for development of entrepreneurial initiatives, which relies on combination of educational, financial, and organisational resources within territorial partnerships that include universities and other institutions. In Scandinavian countries, a system of partnership-based management of technology transfer offices prevails, in which coordination between participant's supports the use of scientific results and facilitates their further application.

These formats remain relevant for Ukraine; however, their efficient use requires gradual improvement in

funding availability, expansion of accelerator networks, and conditions that support private investment. A comparison of foreign experience indicates that Ukraine may move toward a configuration that combines state support with the development of independent institutions operating alongside universities. Such a configuration supports the transformation of university developments into projects capable of entering the market and underscores the growing role of digital solutions in coordinating technology transfer processes and start-up management.

Digitisation of technology transfer and use of data analytics in start-up management

Continuing analysis of technology transfer mechanisms in formation of entrepreneurial initiatives, this subsection considers the role of digital solutions in compilation of information on scientific results and coordination of interaction between participants involved in the further use.

Digital tools support systematisation of data on research outputs and facilitate communication between universities, investors, and users of developments. P. Karanikic *et al.* (2021) noted that use of digital knowledge management tools reduced time required to assess potential of scientific developments and supported faster establishment of professional contacts.

Further development of electronic technology transfer platforms has expanded these possibilities. Z. Chen *et al.* (2025) demonstrated that such platforms accumulate, systematise, and disseminate information on inventions, patents, and research results suitable for further use. These platforms supported remote submission of applications, execution of licence agreements, and partner search, which facilitated coordinated interaction between participants involved in transfer of scientific results. A generalised representation of this form of interaction is presented in Figure 1.

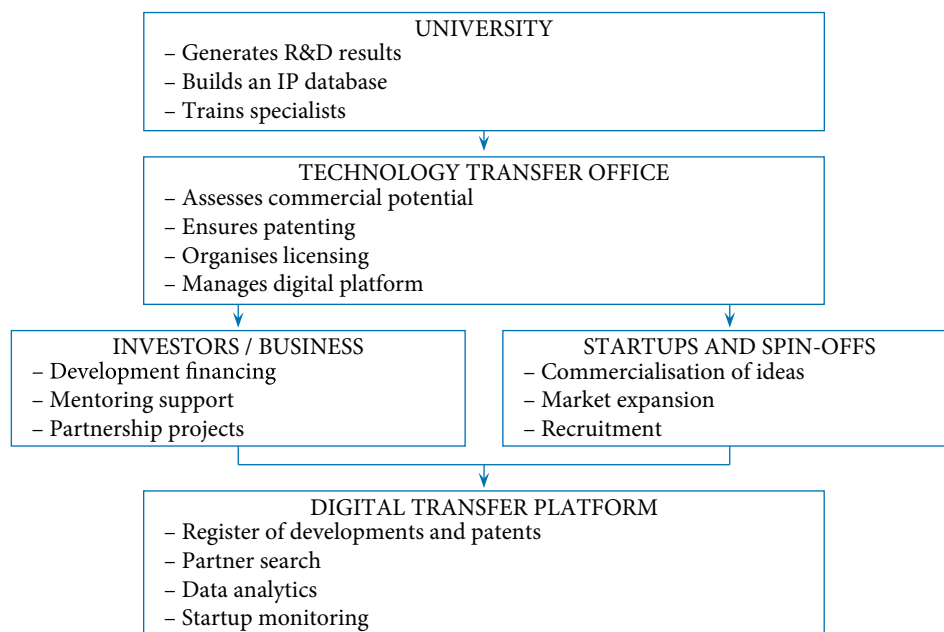


Figure 1. Model of digital interaction between participants in the technology transfer system

Source: compiled by the authors based on P. Karanikic *et al.* (2021), J.B. Padilla Bejarano *et al.* (2023), Z. Chen *et al.* (2025)

Figure 1 illustrates information exchange between universities, investors, users of developments, and organisational structures involved in transfer of research results. This interaction creates a basis for monitoring start-up projects and evaluation of their progress using analytical methods. Within this digital environment, analytical methods have become relevant in supporting start-up projects. According to M.F. Arroyabe *et al.* (2022), use of data analysis can be used to assess potential of developments more accurately, evaluate demand for innovative products, and allocate available resources more rationally during the selection of projects for funding.

A separate direction of digital development in technology transfer is associated with creation of national

electronic systems for intellectual property registration. Such systems simplify application procedures, reduce processing time, and expand interaction between universities and users of research results. Estonia is an illustrative example, where the e-IP electronic service introduced by national patent office can be used for remote submission and support of intellectual property applications (E-services: Electronic channels..., n.d.).

Ukraine has also introduced digital services in this field. According to official materials of the Ukrainian National Office of Intellectual Property and Innovation, online tools for submitting applications and managing rights have been gradually implemented, expanding opportunities for scientific institutions to register and transfer

research results (Ukrainian National Office for..., 2025). The main directions of digital development related to technology transfer and academic entrepreneurship are summarised in Table 4.

Table 4. Main directions of digitalisation in the field of technology transfer and academic entrepreneurship

Digitalisation direction	Main functions	Expected effect
Electronic technology transfer platforms	Publication of information about patents, agreements, start-ups	Expansion of the circle of potential investors
Data analytics and artificial intelligence	Assessing innovation potential, forecasting demand	Improving the accuracy of management decisions
Blockchain technologies	Accounting for license agreements and copyright protection	Reducing the risks of intellectual property infringement
Digital education platforms	Training specialists in the commercialisation of innovations	Developing entrepreneurial skills among scientists
Cloud services for joint development	Collaborative work on projects between universities and businesses	Accelerating the creation of prototypes and the launch of start-ups

Source: compiled based on P. Karanikic *et al.* (2021), M.F. Arroyabe *et al.* (2022), S. Proença (2025)

The directions presented in Table 4 reflect different areas of application of digital solutions in technology transfer and start-up project support. Their use supports structured handling of information on patents and developments, increases accuracy of analytical evaluation, and facilitates collaboration coordination. Digital solutions have also influenced organisational practices within technology transfer offices. Z. Chen *et al.* (2025) emphasised that digitalisation supported a transition from intermediary functions toward forms of organisation based on shared access to information and coordinated activity. In this context, digital tools strengthened correlation between scientific research and entrepreneurial initiatives and supported informed decision-making in start-up project management.

Fostering entrepreneurial culture in universities and developing human capital through technology transfer

Z. Chen *et al.* (2025) considered digitalisation as a factor in formation of innovative culture in universities, ensuring transition from forms of technology transfer organisation in which transfer office performed mainly intermediary functions to integrated interaction between participants in the process. Under these conditions, researchers, students, and investors gained access to shared digital services, which created opportunities for collaboration on data, accelerated information exchange, and coordination of decisions on further development of projects.

Digital platforms that support technology transfer are already widely used in international practice and significantly influence organisation of interaction between universities and external partners. For example, the AUTM Innovation Marketplace (AIM) (n.d.) platform in United States can be used to publish developments for licensing,

search for investors, and monitor status of commercialisation. Stanford University operates the Sophia system, through which descriptions of inventions are submitted and patent applications are managed. In Europe, similar functions are performed by digital platforms of the Technical University of Munich (TUM Patent and License Portal) and KU Leuven, which provide access to technology databases and support online communication with potential users of developments. These examples demonstrated how digital infrastructure supports practical implementation of technology transfer and creates conditions for its integration into the academic environment.

Role of digital solutions is not limited to facilitating technology transfer procedures. Their implementation also influences broader processes related to development of entrepreneurial activity in universities, as digital services increasingly become part of educational space and support preparation of students for implementation of personal projects. This connection between digital infrastructure and education defines the growing attention to entrepreneurial culture as an element of university development.

Academic entrepreneurship is not limited to establishment of start-ups. It includes teaching innovative thinking, development of competencies related to technology management, and encouraging initiative among students and early-career researchers. Scientific and pedagogical staff involved in entrepreneurial activity performs a substantial educational role by demonstrating practical applications of research results in real economic conditions. Comparative characteristics of the implementation of entrepreneurial education and its influence on human capital development in different university models are presented in Table 5.

Table 5. Comparing the role of academic entrepreneurship in the educational process in different university models

Country/university model	Characteristics of entrepreneurial education	Forms of interaction with business	Key effects on human capital
US (entrepreneurial university)	Entrepreneurship is integrated into curricula at all levels, and incubators operate at faculties	Mentoring, joint programs with venture capital funds, start-up competitions	Risk management skills development, team building, leadership
UK (innovative model)	Universities actively involve students in research projects with commercialisation potential	Partnerships with local businesses, technology hubs	Development of creative thinking and independent business planning skills
Germany (research and applied model)	Dual education programs that combine research and practice	Cooperation with industrial enterprises, joint laboratories	Deepening technical competencies, involving applicants in technology transfer
Ukraine (model in development)	Courses in innovation management and start-up education are being introduced, support centres are being created	Participation in international programs, grant projects, cooperation with start-up funds	Increasing the level of entrepreneurial activity among applicants and young scientists

Source: summarised based on S. Taskin *et al.* (2023), S. Proença (2025)

Formation of an entrepreneurial culture in universities is also related to changes in educational methods. R.A. Rahmatika & S.E. Rachma (2025) noted that universities in the United States, the Netherlands, and Sweden promote a model of learning by venturing, in which educational process is combined with implementation of research and entrepreneurial projects. Such learning formats familiarise students with technology transfer mechanisms through direct participation in project activities.

Similar conclusions were reached by E. Aromaa *et al.* (2024), demonstrating the value of combining educational and project-based activities for development of socially oriented entrepreneurship in cooperation between universities and external partners. M.A. Davila *et al.* (2024) also demonstrated that involving students in entrepreneurial initiatives during the educational process contributes to development of practical skills related to commercial use of research results.

From an institutional perspective, M.S. Loyola & C.J. Selby (2025) emphasised that expansion of access to entrepreneurial education in universities creates conditions for a more even distribution of academic entrepreneurship among different groups of students. At the

same time, O. Maliarchuk & V. Vostriakova (2024) highlighted that efficiency of such educational formats largely depends on coordinated interaction between technology transfer offices, educational units, and other participants in innovation-related activities.

Furthermore, M. Passarelli & G. Bongiorno (2025) showed that efficiency of start-up education is closely connected with interdisciplinarity of learning. The combination of engineering, economic, and social disciplines contribute to a comprehensive concept of innovation processes and trains specialists capable of operating under conditions of market uncertainty. Relationship between education, technology transfer, and human capital development is illustrated in Figure 2.

Thus, development of an entrepreneurial culture in universities represents one of the main directions for implementation of technology transfer in Ukraine. Formation of educational programmes that combine theoretical foundations of innovation management with project-based learning contributes to improved human capital of scientific sphere and supports new generations of entrepreneurs capable of implementing research results in production and economic activity.

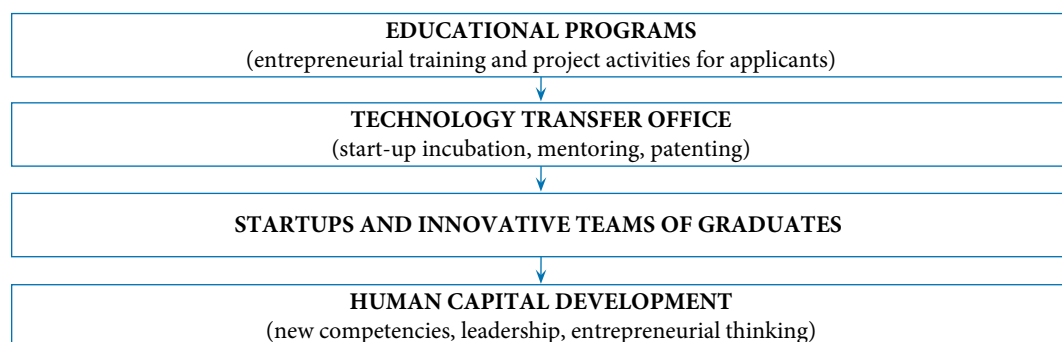


Figure 2. Schematic representation of the relationship between education, technology transfer, and human capital development

Source: summarised by the authors based on A.I. Gaspar Pacheco *et al.* (2024), M. Passarelli & G. Bongiorno (2025)

Problems and directions for improving the technology transfer system in Ukraine

The technology transfer system in Ukraine is still in early stages of development, and despite existence of a regulatory framework and state programmes to support innovation, a number of issues remain unresolved, including coordination between universities, technology transfer offices and institutions responsible for practical utilisation of scientific results. Scientific research showed that the effectiveness of interaction depends on the ability of universities to create conditions for the development of innovative initiatives, in particular by streamlining commercialisation processes and strengthening institutional capacity (Guerrero & Menter, 2024).

Ukraine has developed tools to support scientific developments and start-ups. These include programmes of the Ukrainian Start-up Fund aimed at financing early stages of project development, and grant competitions of the National Research Fund of Ukraine, which support scientific research with potential for practical application. However, scale of such support is still significantly inferior to European practices, which limits ability of universities to expand circle of partners and accelerate commercialisation of research results.

Development of institutional infrastructure remains a separate problem. There are a range of technology transfer offices operating in Ukraine, but most of them have limited financial and human resources, as well as insufficient experience in interaction with international partners. There is also no unified digital system that would integrate databases of intellectual property, patents and promising developments on a single platform, which complicates access to information and coordination between participants in innovation activities.

In this context, issue of low commercialisation of research results in state universities requires further consideration. Studies show that even in economically developed countries, only a fraction of academic developments reach market, and effective management of technology transfer process is a determining factor in innovative development (Halilem *et al.*, 2024). In Ukrainian context, the situation is complicated by lack of motivation among researchers, absence of specialised educational programmes in patent management, and limited opportunities for attraction of private capital. Table 6 summarises the main problems of technology transfer in Ukraine identified through analysis of academic literature and regulatory documents.

Table 6. Main problems of technology transfer in Ukraine and possible ways to solve them

Problem	Characteristics	Possible solutions
Insufficient digitisation of technology transfer	Lack of a unified national database of patents and scientific developments	Creation of a centralised electronic platform based on open data
Weak interaction between universities and business	Limited number of joint innovation projects	Introduction of joint incubation programs and regional clusters
Low motivation of scientists to commercialise	Lack of financial incentives and appropriate training	Improvement of the system of incentives, grants, and educational programs
Uncertainty of rights to research results	Complexity in the distribution of rights between the institution and the author	Harmonisation of legislation with EU standards and updating of licensing procedures
Lack of specialists in the field of technology transfer	Limited opportunities for training and professional development	Development of master's and postgraduate programs in the field of innovation management

Source: developed by the authors based on analysis of scientific and regulatory sources

Experience of European countries shows that efficiency of technology transfer system directly depends on state's participation in creating favourable conditions for interaction between scientific institutions and investors. Germany, Finland, and Spain have special government programs that support university start-ups by providing grants at prototyping stage.

In Ukraine, institutions were also gradually formed to support innovative initiatives at universities. In particular, at Lviv Polytechnic National University (n.d.), innovative projects were implemented through Tech Start-Up School, which functioned as a university platform for start-up development and included acceleration programmes, prototyping laboratories, and mentoring support, as evidenced by official university materials. The National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute" operated the Sikorsky Challenge Ukraine innovation ecosystem, which combined incubation and

acceleration formats, as well as a network of investors prioritising support of technology projects at various stages of their development, as confirmed by information published on project's official website (Sikorsky Challenge Ukraine, n.d.). Similar initiatives were implemented in other higher education institutions. For example, the Kyiv School of Economics (n.d.) introduced the Start-up Booster Program, aimed at supporting technology-oriented projects in cooperation with international partners, as reflected in institution's official materials. Odesa Polytechnic National University (n.d.) operated the Polytechnic Start centre, which was aimed at supporting student and scientific initiatives within university, as evidenced by information published on university's official website. These examples confirm gradual development of university support structures in Ukraine and convergence of their organisational capabilities with practices characteristic of leading European institutions.

These developments make it possible to draw broader conclusions regarding factors that influence efficiency of technology transfer systems across different countries. As shown by studies by J. Hong *et al.* (2023) and N. Halilem *et al.* (2024), improvement of efficiency of the system is possible if that network interaction is established between all participants – universities, research institutes, venture capital funds, business associations, and regional authorities. This format of cooperation ensures sustainable circulation of knowledge and contributes to

formation of a national innovation system in which technology transfer is a central element of entrepreneurship development. Therefore, creation of a national technology transfer ecosystem should be based on integration of three levels: educational (competence building), scientific (knowledge generation), and entrepreneurial (commercialisation of innovations). A generalised scheme of interaction between these levels is presented in Figure 3, which reflects proposed model for improving technology transfer system in Ukraine.

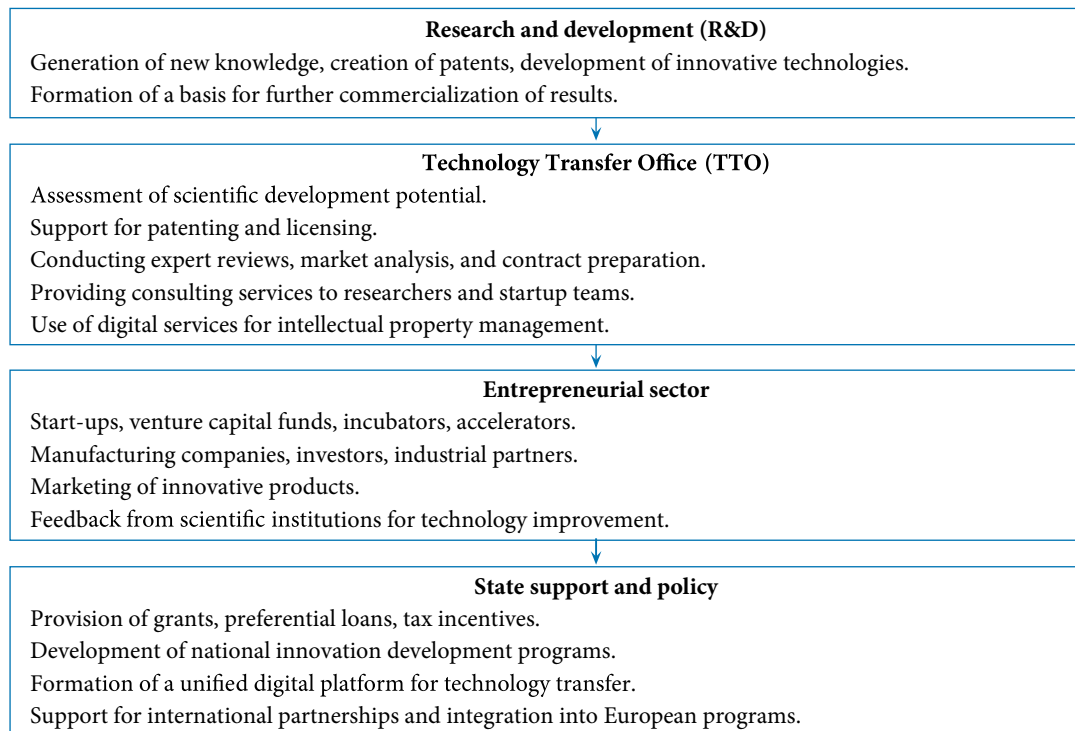


Figure 3. Generalised model for improving the technology transfer system in Ukraine

Source: developed by the authors based on J.A. Cunningham *et al.* (2022), M. Guerrero & M. Menter (2024)

As M. Guerrero & M. Menter (2024) noted, creation of an integrated technology transfer system can combine academic initiatives with market needs, promoting development of innovative entrepreneurship and formation of a competitive economy. Presented model reflects an interconnected system of participants in technology transfer process in Ukraine, combining scientific, organisational, entrepreneurial, and governmental levels. At the centre of this system is scientific research (R&D), which provides new knowledge, developments, and patents that form the basis for commercialisation. Next link is technology transfer office (TTO), which acts as an intermediary between universities, businesses, and government institutions. Activities of TTO include assessment of innovation potential, supporting patenting and licensing, analysing market opportunities, and supporting start-ups in early stages.

Interaction with business sector ensures implementation of developments in production, creation of new start-ups, and attraction of investments. At the final level,

state support and policy are aimed at stimulating the process through grant programs, tax incentives, development of digital infrastructure, and integration into the European innovation space. Thus, proposed model demonstrates consistent movement of technologies from laboratory research to market, where each level contributes to efficiency of national innovative development.

Conclusions

The study assessed state of technology transfer system in Ukraine and identified main development trends. The summary indicators show that Ukrainian universities lag significantly behind leading countries in terms of technology transfer and creation of innovative projects. Average number of patents transferred in Ukrainian institutions is only 22 per year, while in the United States this figure exceeds 520, and in Germany it is approximately 285. Only 10.5% of Ukrainian developments are commercialised, which is several times lower than in EU

countries. An analysis of university start-ups confirmed that around 35 projects are created in Ukraine each year, of which only 12.6% pass initial commercialisation stage, i.e., receive initial funding or receive enough development to become a minimally viable product. This demonstrated limited opportunities for transforming research results into ready-made technological solutions and highlights the need to strengthen support in early stages of innovation development.

A study of the structure of start-up financing showed that more than 61% of funds come from public sources, which creates significant dependence on budget and does not stimulate activity of private investors. For comparison, in European Union countries, share of venture capital exceeds 30%, and in the United States, it is approximately 48%, which creates much broader opportunities for intensive innovation development. Obtained results substantiated a model for improving technology transfer system, which is based on coordinated interaction of three interrelated levels: educational, which forms competencies in field of innovation; scientific, where new knowledge

is generated; and entrepreneurial, which ensures commercial implementation of developments. Systematic integration of these levels will contribute to an increase in the number of innovative projects, improve quality of scientific results assessment, and develop human resources capable of transforming scientific ideas into applied technologies. Prospects for further research include development of mechanisms for evaluation of effectiveness of technology transfer offices, modelling of relationships between universities and innovative enterprises, and determination of socio-economic impact of introducing scientific developments into entrepreneurial activity.

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Conflict of Interest

None.

References

- [1] Aromaa, E., Eriksson, P., Hirvonen, P., & Palo-Oja, O. (2024). Societal entrepreneurship and university-industry collaboration: A case study of an academic research community. In *Stimulating entrepreneurial activity in a European context: Reflections on programs, courses and cases* (pp. 28-47). Cheltenham: Edward Elgar Publishing Ltd. [doi: 10.4337/9781802200683.00010](https://doi.org/10.4337/9781802200683.00010).
- [2] Arroyabe, M.F., Schumann, M., & Arranz, C.F.A. (2022). Mapping the entrepreneurial university literature: A text mining approach. *Studies in Higher Education*, 47(5), 955-963. [doi: 10.1080/03075079.2022.2055318](https://doi.org/10.1080/03075079.2022.2055318).
- [3] AUTM Innovation Marketplace (AIM). (n.d.). Retrieved from <https://surl.li/udfqfe>.
- [4] Barth, T.D., & Schlegelmilch, W. (2020). Academic entrepreneur, academic entrepreneurship. In E.G. Carayannis (Ed.), *Encyclopedia of creativity, invention, innovation and entrepreneurship* (pp. 1-8). Cham: Springer. [doi: 10.1007/978-3-319-15347-6_456](https://doi.org/10.1007/978-3-319-15347-6_456).
- [5] Cai, Y., & Lattu, A. (2022). Triple helix or quadruple helix: Which model of innovation to choose for empirical studies? *Minerva*, 60(2), 257-280. [doi: 10.1007/s11024-021-09453-6](https://doi.org/10.1007/s11024-021-09453-6).
- [6] Chen, Z., Little, V.J., & Thuan, N.H. (2025). The evolving role of technology transfer offices in stakeholder relationships: Intermediaries or implementers? *Journal of Technology Transfer*, 50, 1060-1079. [doi: 10.1007/s10961-024-10123-4](https://doi.org/10.1007/s10961-024-10123-4).
- [7] Civera, A., Meoli, M., & Vismara, S. (2020). Opportunity and necessity academic entrepreneurship: Evidence from university spinoffs. *Research Policy*, 49(8). [doi: 10.1016/j.euroecorev.2020.103376](https://doi.org/10.1016/j.euroecorev.2020.103376).
- [8] Cunningham, J.A., Lehmann, E.E., & Menter, M. (2022). The organizational architecture of entrepreneurial universities across the stages of entrepreneurship: A conceptual framework. *Small Business Economics*, 59(1), 11-27. [doi: 10.1007/s11187-021-00513-5](https://doi.org/10.1007/s11187-021-00513-5).
- [9] Davila, M.A., Pantaleon, A.J.S., Caro, O.C., Reyes, E.I.B., & Ocampo, P.E. (2024). Entrepreneurship and entrepreneurial innovation of university students, Amazonas, Peru. *International Journal of Innovative Research and Scientific Studies*, 7(3), 901-913. [doi: 10.53894/ijirss.v7i3.2975](https://doi.org/10.53894/ijirss.v7i3.2975).
- [10] El-Ferik, S., & Al-Naser, M. (2021). University-industry collaboration: A promising trilateral co-innovation approach. *IEEE Access*, 9, 112761-112769. [doi: 10.1109/ACCESS.2021.3104096](https://doi.org/10.1109/ACCESS.2021.3104096).
- [11] E-services: Electronic channels for using the Estonian Patent Office services. (n.d.). Retrieved from <https://www.epa.ee/en/e-services>.
- [12] Gaspar Pacheco, A.I., Ferreira, J., Simoes, J., Mota Veiga, P., & Dabic, M. (2024). Mechanisms for facilitating academic entrepreneurship in higher education. *International Journal of Entrepreneurial Behaviour & Research*, 30(6), 1448-1479. [doi: 10.1108/IJEBR-04-2023-0333](https://doi.org/10.1108/IJEBR-04-2023-0333).
- [13] Guerrero, M., & Menter, M. (2024). Driving change in higher education: The role of dynamic capabilities in strengthening universities' third mission. *Small Business Economics*, 63, 1321-1337. [doi: 10.1007/s11187-024-00869-4](https://doi.org/10.1007/s11187-024-00869-4).
- [14] Halilem, N., Landry, R., & Amara, N. (2024). "Meet me at the backdoor": A multiple-case study of technology transfer office bypassing in academic entrepreneurship. *Research Policy*, 53(5), article number 104991. [doi: 10.1016/j.respol.2024.105156](https://doi.org/10.1016/j.respol.2024.105156).

- [15] Hayter, C.S., Link, A.N., & Schaffer, M. (2023). Identifying the emergence of academic entrepreneurship within the technology transfer literature. *Journal of Technology Transfer*, 48, 1800-1812. doi: [10.1007/s10961-023-10026-w](https://doi.org/10.1007/s10961-023-10026-w).
- [16] Hong, J., Cha, J.G.B., & Park, K. (2023). Evaluation framework for facilitating the technology transfers of universities: Focusing on the perspective of technology donors. *PLoS ONE*, 18(12), article number e0293951. doi: [10.1371/journal.pone.0293951](https://doi.org/10.1371/journal.pone.0293951).
- [17] Horizon Europe (n.d.). Retrieved from <https://surli.cc/lkctxh>.
- [18] Jevnaker, B.H., & Misganaw, B.A. (2022). Technology transfer offices and the formation of academic spin-off entrepreneurial teams. *Entrepreneurship & Regional Development*, 34(9-10), 977-1000. doi: [10.1080/08985626.2022.2080867](https://doi.org/10.1080/08985626.2022.2080867).
- [19] Karanikic, P., Bezic, H., & Redzepagic, S. (2021). Digitalization of the university technology transfer process. In *2021 44th international convention on information, communication and electronic technology (MIPRO)* (pp. 1431-1435). Opatija: IEEE. doi: [10.23919/MIPRO52101.2021.9596918](https://doi.org/10.23919/MIPRO52101.2021.9596918).
- [20] Kyiv School of Economics. (n.d.). Retrieved from <https://kse.ua>.
- [21] Landström, H. (2020). The evolution of entrepreneurship as a scholarly field. *Foundations and Trends in Entrepreneurship*, 16(2), 65-243. doi: [10.1561/03000000083](https://doi.org/10.1561/03000000083).
- [22] Lehmann, E.E., Meoli, M., & Paleari, S. (2021). Innovation, entrepreneurship and the academic context. *Industry and Innovation*, 28(3), 235-246. doi: [10.1080/13662716.2021.1904843](https://doi.org/10.1080/13662716.2021.1904843).
- [23] Loyola, M.S., & Selby, C.J. (2025). Democratizing academic entrepreneurship: An interpretive insight. *South Asian Journal of Business and Management Cases*, 14(1), 10-28. doi: [10.1177/22779779251326210](https://doi.org/10.1177/22779779251326210).
- [24] Lviv Polytechnic National University. (n.d.). Retrieved from <https://lpnu.ua/en>.
- [25] Maliarchuk, O., & Vostriakova, V. (2024). Models of partnership of the office of technology and knowledge transfer with stakeholders of the innovation entrepreneurship ecosystem. *Economy and Society*, 60. doi: [10.32782/2524-0072/2024-60-35](https://doi.org/10.32782/2524-0072/2024-60-35).
- [26] Martínez-Ardila, H., Castro-Rodríguez, Á., & Camacho-Pico, J. (2023). Examining the impact of university-industry collaborations on spin-off creation: Evidence from joint patents. *Heliyon*, 9(9), article number e19533. doi: [10.1016/j.heliyon.2023.e19533](https://doi.org/10.1016/j.heliyon.2023.e19533).
- [27] Menter, M. (2022). Entrepreneurial universities and innovative behavior: The impact of gender diversity. *Economics of Innovation and New Technology*, 31(1-2), 20-34. doi: [10.1080/10438599.2020.1843988](https://doi.org/10.1080/10438599.2020.1843988).
- [28] Musleh, M.M., Mohamed, I., Sallehudin, H., & Abushawish, H.F. (2025). University spin-off challenges and opportunities: A proposed framework of academic entrepreneurship in developing economies. *Cogent Education*, 12(1), article number 2530894. doi: [10.1080/2331186X.2025.2530894](https://doi.org/10.1080/2331186X.2025.2530894).
- [29] Nikitin, Y. (2023). The six-helix model of technology transfer innovation ecosystem. *International Science Journal of Management, Economics & Finance*, 2(5), 1-12. doi: [10.46299/j.isjmef.20230205.01](https://doi.org/10.46299/j.isjmef.20230205.01).
- [30] Odesa Polytechnic National University. (n.d.). Retrieved from <https://opu.ua/en>.
- [31] Olvera, C., Piqué, J.M., Cortés, U., & Nemirovsky, M. (2021). Evaluating university-business collaboration at science parks: A business perspective. *Triple Helix*, 8(3), 445-485. doi: [10.1163/21971927-bja10007](https://doi.org/10.1163/21971927-bja10007).
- [32] Padilla Bejarano, J.B., Zartha Sossa, J.W., Ocampo-López, C., & Ramírez-Carmona, M. (2023). Open innovation: A technology transfer alternative from universities. *Journal of Open Innovation: Technology, Market, and Complexity*, 9(3), article number 100090. doi: [10.1016/j.joitmc.2023.100090](https://doi.org/10.1016/j.joitmc.2023.100090).
- [33] Padilla Bejarano, J.B., Zartha Sossa, J.W., Ocampo-López, C., & Ramírez-Carmona, M. (2023). University technology transfer from a knowledge-flow approach: A systematic literature review. *Sustainability*, 15(8), article number 6550. doi: [10.3390/su15086550](https://doi.org/10.3390/su15086550).
- [34] Passarelli, M., & Bongiorno, G. (2025). Is it time to reshape entrepreneurship education? *International Entrepreneurship and Management Journal*, 21, article number 61. doi: [10.1007/s11365-025-01071-y](https://doi.org/10.1007/s11365-025-01071-y).
- [35] Proença, S. (2025). How to boost entrepreneurship and innovation in higher education institutions. *European Conference on Innovation and Entrepreneurship*, 20(1), 575-583. doi: [10.34190/ecie.20.1.3908](https://doi.org/10.34190/ecie.20.1.3908).
- [36] Prokop, D. (2021). University entrepreneurial ecosystems and spin-off companies: Configurations, developments and outcomes. *Technovation*, 107, article number 102286. doi: [10.1016/j.technovation.2021.102286](https://doi.org/10.1016/j.technovation.2021.102286).
- [37] Pyroh, V. (2025). Technology transfer as a hidden mechanism of venture investment in innovative startups. *Economy and Society*, 73, 374-383. doi: [10.32782/2524-0072/2025-73-77](https://doi.org/10.32782/2524-0072/2025-73-77).
- [38] Rahmatika, R.A., & Rachma, S.E. (2025). Entrepreneurship education in the context of minority groups: A systematic literature review. *Entrepreneurship Education*, 8, 497-520. doi: [10.1007/s41959-025-00162-9](https://doi.org/10.1007/s41959-025-00162-9).
- [39] Ríos Yovera, V.R., Ramos Farroñán, E.V., Arbulú Ballesteros, M.A., Calmet, V.G.V., Aguilar Armas, H.M., Soto Deza, J.M., Redolfo, R.L., Acosta, R.M., & Reyes-Pérez, M.D. (2025). Academic entrepreneurship evolution: A systematic review of university incubators and start-up development (2018-2024). *Sustainability*, 17(12), article number 5365. doi: [10.3390/su17125365](https://doi.org/10.3390/su17125365).
- [40] Rozhkova, L.V. (2024). Effectiveness analysis of technologies transfer, created at the expence of the state budget. *Science, Technology, Innovation*, 2(30), 35-42. doi: [10.35668/2520-6524-2024-2-05](https://doi.org/10.35668/2520-6524-2024-2-05).
- [41] Sikorsky Challenge Ukraine. (n.d.). Retrieved from <https://sikorskychallenge.com>.

- [42] Taskin, S., Javed, A., & Kohda, Y. (2023). Promoting entrepreneurial mindset for successful entrepreneurship. *Journal of Women's Entrepreneurship and Education*, 34, 122-142. doi: 10.28934/jwee23.34.pp122-142.
- [43] Tymchenko, D., Korogod, N., & Novorodovska, T. (2020). Project product management for establishing a technology transfer office in a higher education institution. *Bulletin of Cherkasy State Technological University*, 25(3), 48-57. doi: 10.24025/2306-4412.3.2020.214879.
- [44] Ukrainian National Office for Intellectual Property and Innovations (IP Office). (2025). Retrieved from <https://nipo.gov.ua/en/>.
- [45] Yaroshevska, T. (2025). Technology transfer as a component of innovative development of Ukraine. *Scientific Bulletin of the Dnipro State University of Internal Affairs*, 1, 46-53. doi: 10.31733/2078-3566-2022-1-46-53.
- [46] Zarkua, T., Heijman, W., Benesova, I., & Krivko, M. (2025). Entrepreneurship as a driver of economic development. *Entrepreneurial Business and Economics Review*, 13(1), 61-77. doi: 10.15678/EBER.2025.130104.
- [47] Zrybnieva, I., Suprunenko, S., Ivanenko, R., & Ashcheulova, O. (2023). Economic and legal aspects of technology transfer in Ukraine: Results, problems, prospects. *Academic Visions*, 18. doi: 10.5281/zenodo.7794827.

Трансфер технологій як підґрунтя відкриття власної справи в Україні

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Анотація. Потреба в активізації інноваційного розвитку в Україні поєднується з обмеженим рівнем використання наукових результатів в підприємницькій діяльності, що стримує формування економіки знань. Наявний розрив між академічними розробками та їх комерційним застосуванням засвідчує необхідність удосконалення механізмів передачі технологій і створення умов для ефективного реалізації університетських ініціатив. За таких умов особливої актуальності набуває дослідження трансферу технологій як основи започаткування власної справи. Метою дослідження було визначення механізмів, за допомогою яких трансфер технологій може стати практичною основою для започаткування власної справи, а також сформувати прикладну модель взаємодії між науковими установами, офісами трансферу технологій і підприємницьким сектором. Методологія ґрунтувалася на аналітичному, порівняльному та системному дослідженні. Проведено логіко-змістовний аналіз наукових джерел з міжнародних баз Scopus, Web of Science та університетських репозитаріїв. На основі узагальнення емпіричних даних визначено три напрями впливу трансферу технологій на створення бізнесу: науково-технологічний, організаційно-управлінський та соціально-економічний. У статті розглянуто роль трансферу технологій як фактора формування підприємницької активності та розвитку інноваційної економіки в Україні. Визначено, що сучасні університети перетворюються на осередки поширення наукових результатів, де поєднуються дослідження, освітній процес і підприємницькі ініціативи. Результати засвідчили, що ефективність трансферу технологій в Україні є нижчою, ніж у розвинених державах, що зумовлено недостатньою інтеграцією науки, освіти й бізнесу. Запропоновано модель розвитку університетського підприємництва, яка поєднує діяльність офісів трансферу технологій, інкубаторів, стартап-шкіл та державних програм підтримки, реалізація якої сприятиме підвищенню рівня комерціалізації результатів досліджень, формуванню підприємницької культури серед здобувачів і науковців, а також залученню інвестицій у сферу інновацій. Практична цінність роботи полягає у формуванні аналітичної основи для модернізації політики підтримки стартапів при університетах та вдосконалення механізмів комерціалізації наукових розробок

Ключові слова: стартап-менеджмент; трансфер технологій; академічне підприємництво; університетські стартапи; бізнес-планування; комерціалізація знань; розвиток людського капіталу

Architecture of digital innovations as a determinant of strategic resilience of an enterprise

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Abstract. The relevance of the study is determined by the need to increase the strategic resilience of enterprises in the context of digital transformation, where the architecture of digital innovations is a key factor in adaptability and competitiveness. The aim of the study was to substantiate the role of the architecture of digital innovations as a determinant of the strategic resilience of enterprises. The research methodology was based on the use of systemic-structural and comparative analysis methods to identify the parameters of digital architecture, as well as economic-mathematical modelling to develop a matrix of its functional role in ensuring the adaptive potential of business. It is accepted that in conditions of growing turbulence of exogenous factors and digital transformation of the economy, the architecture of digital innovations is a key determinant of the strategic resilience of an enterprise. The conceptual parameters of digital architecture (technological basis, adaptability, predictability) and their impact on the transformation of traditional management models are considered. The dynamics of the integration of digital components into the operational activities of Ukrainian enterprises are analysed, which has made it possible to identify risks that negate the strategic potential of digital architecture. Based on the analysis, a phased approach to the formation of a holistic architecture and a matrix of its functional role in ensuring the resilience of economic entities are proposed. It has been proven that only a comprehensive approach to combining technological drivers with strategic development goals can ensure the long-term adaptive stability and competitiveness of an enterprise in the global digital space. The practical value of the study lies in the possibility of applying the proposed architectural approach and innovative tools by senior managers, crisis managers and digital development specialists to design flexible management strategies that ensure high resilience of enterprises in critical conditions

Keywords: cyber resilience; technological drivers; adaptive management; digitalisation; business model reconfiguration

Introduction

The formation of digital innovation architecture constitutes a key factor in the contemporary transformation of business entities, significantly modifying the paradigm of strategic management and the criteria for assessing long-term business sustainability. The integration of complex digital

solutions, in particular artificial intelligence systems, big data architecture, cloud infrastructures and automated management platforms, is leading to profound reconfigurations of business models, organisational structures and predictive decision-making mechanisms. The relevance of

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this issue is due to the growing turbulence of the market environment, the acceleration of technological cycles, and the increasing demands on the adaptability of business systems in the global digital space. The transition to digitally oriented models of enterprise development is accompanied by a complex set of interrelated challenges.

On the one hand, the active implementation of digital innovations increases the vulnerability of enterprises to information and technological destabilisers and leads to an increase in cyber risks, which requires the formation of multi-level digital security mechanisms. On the other hand, increased competitive pressure from high-tech market players and dynamic consumer expectations are driving management to constantly reconfigure strategic business contours, which requires significant intellectual investment. Ensuring strategic resilience as the ability to quickly regenerate and maintain functionality in crisis conditions requires not only the implementation of individual technological solutions, but also the development of a comprehensive architecture of digital innovations, harmonised with long-term development goals. The successful functioning of an enterprise in an unstable environment requires the development of adaptive strategies based on the synergy of technological, organisational and managerial components, which will contribute to strengthening the systemic resilience of the business to exogenous shocks and ensure its sustainable development in a changing digital landscape.

A significant number of works are devoted to the study of the theoretical and practical aspects of the architecture of digital innovation and the strategic resilience of enterprises. M. Biluha (2025) considered the conceptual foundations of innovative development of enterprises in the context of digital transformation and crisis shifts. The author analysed in detail the potential of digital solutions to improve the efficiency of business processes and identified systemic barriers that hinder their implementation. The conclusions showed that the digitalisation of enterprises in Ukraine has great strategic potential, but requires a comprehensive approach to overcoming technological and organisational constraints, particularly in the context of cybersecurity and intellectual capital. N. Ivanova (2024) studied the impact of digitalisation on the national economy and the quality of life of the population in Ukraine. The author concluded that digital transformation contributes to the achievement of sustainable development goals by stimulating economic activity and improving the quality of public services, which is essential for ensuring systemic resilience at the meso and macro levels.

Researchers O. Kolodiziev *et al.* (2024) analysed the role of digital technologies and innovations in increasing the resilience and modernisation of the economy after periods of crisis. They applied a systematic approach, combining case studies and expert assessments, to identify the key factors of enterprise resilience. The study emphasised that digital tools and innovative solutions are crucial for the recovery and structural transformation of public and

private organisations in the post-war period. Y. Parkhuts & O. Ohdanska (2025) explored the issue of increasing the competitiveness of enterprises through digitalisation. The authors applied business process analysis and assessment of digital integration indicators for enterprises in various industries. The conclusions of the study indicate that enterprises that actively implement digital technologies demonstrate a higher level of adaptability and ability to withstand market crises by optimising costs and expanding sales channels. A. Kuzior *et al.* (2022) focused on assessing Ukraine's national innovation ecosystems in the context of sustainable development. Using comparative analysis and rating methods, the authors identified the key strengths and weaknesses of the country's innovation structures. The results of the study showed that effective digitalisation of ecosystems significantly increases their ability to support innovative projects and integrate into global technology chains, which strengthens national resilience. The dependence of organisational resilience on the development of the innovative potential of enterprises was examined by J.A.R. Awad & R. Martin-Rojas (2024). The study applied an analytical model for assessing the impact of innovative resources on the sustainability of organisations. The authors concluded that enterprises with a high level of innovative potential demonstrate a greater ability to recover quickly from crisis situations because they have mechanisms for flexible resource reallocation. G. Fletcher & M. Griffiths (2020) analysed digital transformations in the context of lockdowns and crisis periods. They used case study and comparative analysis methods to identify effective business adaptation strategies. The findings showed that companies that plan digital transformation systematically are able to adapt more quickly to external shocks and minimise losses compared to companies that use fragmented IT solutions.

Despite significant scientific attention to individual aspects of digitalisation, the issue of forming a holistic architecture of digital innovations as a systemic determinant of strategic resilience remains controversial. Most existing works focus either on the technological component or on general issues of crisis management, leaving aside the mechanisms of their architectural integration. A number of important aspects of the organisational, financial and informational support of digital transformation processes at the level of economic entities have been partially studied. Methodological approaches to the integrated assessment of the effectiveness of digital adaptation of enterprises through the prism of their strategic sustainability are insufficiently developed. The lack of a systematic vision of mechanisms for overcoming barriers to technological integration, minimising cyber risks and eliminating the shortage of digital competencies creates a scientific gap in the development of adaptive architectural management models. This necessitates clarification of the conceptual parameters of digital innovation architecture and a reconsideration of the role of the technological factor as a fundamental determinant of business viability

under contemporary exogenous shocks. Thus, the aim of the study was to theoretically substantiate the concept of digital innovation architecture and develop practical recommendations for its formation as a fundamental tool for strengthening the strategic resilience of Ukrainian enterprises. The following hypotheses were formulated within the framework of scientific research:

H1: The development and implementation of integrated digital architecture significantly increases the adaptability and strategic resilience of enterprises to exogenous shocks.

H2: Systemic integration of innovative digital platforms (artificial intelligence, digital copies of enterprises) has a direct positive impact on operational efficiency and competitiveness.

H3: Institutional barriers to technological integration and a shortage of digital skills among staff are critical factors limiting the effectiveness of digital adaptation by economic entities.

Materials and Methods

The research methodology was based on a comprehensive combination of general scientific and specialised methods, which ensured a high degree of objectivity and representativeness of the scientific results obtained. To achieve the set aim, a systematic approach was used, which allowed to consider the architecture of digital innovations not as an isolated technological process, but as a complex multi-component system integrated into the overall development strategy of the enterprise. The choice of methods was determined by the need for interdisciplinary analysis at the intersection of modern management, the digital economy and strategic planning.

Empirical methods, such as observation, comparison, and description, were used to study modern approaches to the digitalisation of enterprises in leading economic systems and to identify key global and national trends in the field of innovative development (Awad & Martin-Rojas, 2024; Ivanova, 2024; Biluha, 2025). In particular, the observation method allowed to evaluate practical models for implementing digital technologies in real business processes, comparison helped to identify critical differences and effective practices between different sectors of the economy, and description ensured the systematisation of existing approaches and their structured presentation for further analysis. The theoretical-cognitive method was used to conceptualise the architecture of digital innovations through the formalisation of basic ideas and testing of hypotheses regarding the impact of technological transformations on the strategic resilience of enterprises (Fletcher & Griffiths, 2020; Cui, 2025).

Logical methods were used to substantiate the conclusions: analysis, synthesis, induction, deduction, generalisation, and scientific abstraction. This made it possible to identify methodological problems and risks of digital transformation, as well as to determine the possibilities for its strategic optimisation in the national and international context (Kuzior *et al.*, 2022; Akib *et al.*, 2022; Parkhuts & Ohdanska, 2025). The information base of the study consisted of documentary and statistical sources. In particular, reports and publications of the National Bank of Ukraine (n.d.) were studied to assess the macroeconomic stability of the business environment. Analytical materials and global reviews by PwC Ukraine (n.d.) and KPMG Ukraine (2024) were necessary to identify strategic priorities and challenges of digitalisation. Official government statistics on the use of information and communication technologies (ICT) in the business sector (Ukrstat, n.d.) were analysed. Scientific works on trends in innovative progress and post-war reconstruction (Savras & Fedynets, 2023; Pizniak & Turchina, 2023) were also analysed.

Case studies and management scenario modelling were used to analyse the practical impact of digital innovations on business processes and the level of enterprise recovery in crisis conditions. This made it possible to verify the consistency of theoretical propositions with actual data on the functioning of economic entities in conditions of high turbulence (Kolodiziev *et al.*, 2024; Tkachenko, 2024). This multi-method approach provided a comprehensive assessment of the architecture of digital innovations as a key determinant of strategic resilience.

Results and Discussion

The formation of the architecture of digital innovations of business entities within this study was based on the analysis of a number of empirical and statistical data. In particular, the use of analytical reviews by PwC Ukraine (n.d.) and KPMG Ukraine (2024) made it possible to identify the key strategic priorities for the digitalisation of Ukrainian business, among which the development of flexible IT infrastructures occupies a leading place. An analysis of documentary sources from the National Bank of Ukraine (n.d.) helped to assess the macroeconomic stability of the business environment, while official government statistics (Ukrstat, n.d.) made it possible to determine the dynamics of the use of information and communication technologies in the business sector. In addition, the scientific findings of I. Savras & N. Fedynets (2023) and D. Pizniak & S. Turchina (2023) were taken into account when considering post-war reconstruction trends. Based on a synthesis of these sources, a system of key parameters of digital architecture was formed (Table 1).

Table 1. Conceptual parameters of digital innovation architecture as determinants of resilience

Analysis parameter	Characteristic	Impact on strategic resilience
Technological basis	Convergence of artificial intelligence (AI), industrial Internet of Things (IIoT) and digital copies of the enterprise into a holistic architectural ecosystem.	Creates conditions for instant identification and adaptive response to dynamic market anomalies and technological failures.

Continued Table 1

Analysis parameter	Characteristic	Impact on strategic resilience
Structural adaptability	Modular configuration of business architecture (Microservices), which ensures high speed of process reengineering without stopping operations.	Neutralises the negative effects of structural transformations in the economy and increases the flexibility of the operating model under pressure from risks.
Analytical predictability	Use of big data analytics methods for multi-variant scenario modelling.	Ensures the transition from reactive to proactive management through the preventive identification of potential crisis phenomena.
Cognitive integration	Synergy of digital competencies of human capital and innovative culture within a single intellectual information space.	Increases the systemic stability of the organisation to destabilising factors through intellectual flexibility and the speed of staff training.
Ecosystem openness	The ability of digital architecture to integrate with external platforms and stakeholders through open interfaces (API).	Builds network resilience for the business through diversification of partnerships and rapid access to external innovation resources.
Resource mobility	The use of cloud technologies (Cloud Computing) for the dynamic redistribution of computing and operational capacities.	Ensures business continuity under any conditions and optimises costs during periods of low market activity.

Source: developed by the authors based on research by I.Z. Savras & N.I. Fedynets (2023), J.A.R. Awad & R. Martin-Rojas (2024), KPMG Ukraine (2024), I. Tkachenko (2024)

The architecture of digital innovation is not just an inert system, but a dynamic phenomenon that initiates a radical evolution of business models. It reorients organisational structures towards the principles of intellectual adaptability, innovation and predictive resilience using modern digital tools and end-to-end data analytics. In this context,

architecture serves as the foundation on which an economic entity's ability to maintain functionality during exogenous shocks is based. The process of forming such architecture is iterative and multi-vector. The stages of developing the architecture of digital innovation as a determinant of an enterprise's strategic resilience are illustrated in Figure 1.

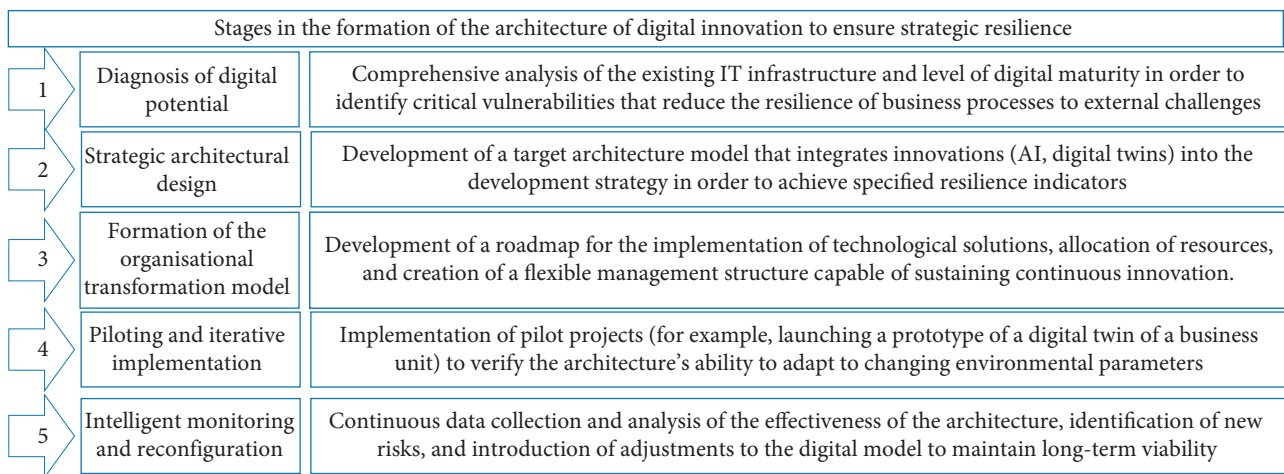


Figure 1. Stages in the formation of the architecture of digital innovation to ensure strategic resilience

Source: developed by the authors based on research by Y. Yan (2023), Strutynska *et al.* (2024), M. Biluha (2025), S. Masaev *et al.* (2025)

This sequence of stages reflects the logic of transition from diagnosing the initial state of the system to forming a predictive management model. At the same time, the development of digital innovation architecture allows a business entity to transform

disparate technological tools into a coherent mechanism for counteracting crisis phenomena. The relationship between the strategic potential of digital architecture and the relevant risks of its implementation is systematised in Table 2.

Table 2. Determinants of the realisation of the strategic potential of digital architecture and systemic challenges to its implementation

Architecture components	Functional purpose	Example of implementation	Systemic risks and limitations
Intelligent algorithms (AI & ML)	Demand forecasting and automatic resource manoeuvring in real time.	Walmart: automatic replenishment of scarce goods based on analysis of weather anomalies.	High dependence on the accuracy of input data; inefficiency in situations without historical analogues.

Continued Table 2

Architecture components	Functional purpose	Example of implementation	Systemic risks and limitations
Digital copies (Digital Twins)	Stress testing of business processes and failure modelling without risk to assets.	Siemens: virtual testing of production lines during emergency power outages.	Significant development costs; risk of discrepancies between the digital model and reality.
Cloud ecosystem (Hybrid Cloud)	Ensuring operational continuity and territorial invariance of the business.	Capital One: complete relocation of banking operations to the cloud to continue working during local server failures.	Dependence on external providers; data confidentiality issues on third-party resources.
Cyber resilience (Zero Trust)	Forming a secure perimeter for safe access to strategic data.	Google (BeyondCorp): secure remote work for staff with critical data without using VPN.	Need for constant investment; risks of human error and social engineering.
Cognitive culture (Knowledge Mgmt)	Scaling adaptive experiences and rapid diffusion of anti-crisis solutions.	Toyota: global digital knowledge bases for instant replication of engineering solutions between factories.	Information overload for specialists; difficulty maintaining team spirit when working remotely.

Source: developed by the authors based on research by I. Trunina *et al.* (2023), I.Z. Savras & N.I. Fedynets (2023), D. Pizniak & S. Turchina (2023), O. Kolodiziev *et al.* (2024)

A summary of the above data allows to conclude that the architecture of digital innovations is not only a technological foundation but also a stabilising mechanism that minimises the impact of destabilising factors on the enterprise’s activities. The key advantage of implementing such an architecture is the transition from static protection to dynamic adaptability, where digital copies and intelligent algorithms allow crises to be predicted even before they physically manifest themselves. At the same time, the identified systemic risks point to the need for a balanced approach: the technological complexity of the architecture must be accompanied by an appropriate level of cyber protection and the development of the cognitive abilities of personnel.

Thus, the strategic resilience of an enterprise in the digital age is determined not only by the availability of advanced technologies, but also by the ability to integrate them into a flexible and secure architectural model capable of continuous self-improvement. An analysis of the functional orientation of digital architecture (Table 2) confirmed that technological transformation is not only a requirement of the times, but also a key condition for ensuring the continuity of operational activities. To assess the real impact of these processes on the strategic stability of organisations, it is advisable to analyse the dynamics of the integration of key components of digital architecture into the operational activities of Ukrainian enterprises during 2022-2024 (Fig. 2).

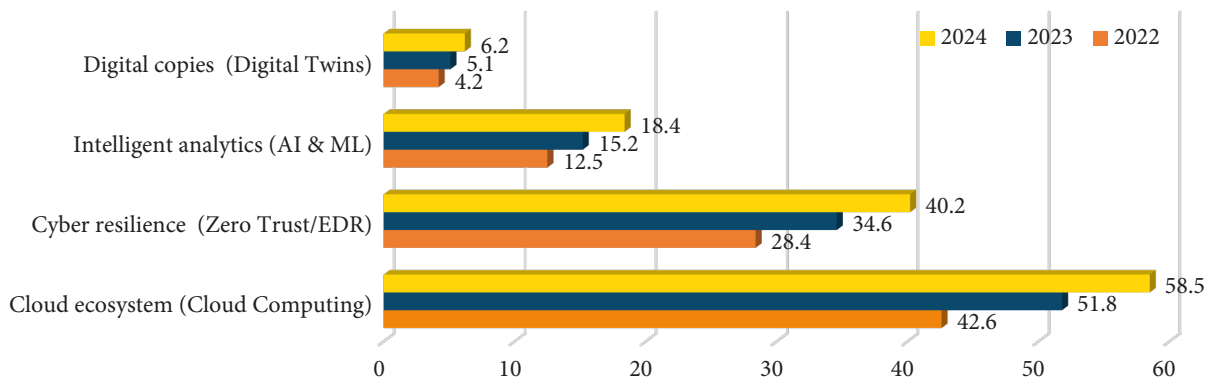


Figure 2. Dynamics of integration of digital architecture components into the operational activities of Ukrainian enterprises in 2022-2024, %

Source: developed by the authors based on research by Ukrstat (n.d.), KPMG Ukraine (2024), National Bank of Ukraine (n.d.), Y. Voloshchuk *et al.* (2025)

The data presented in Figure 2 clearly illustrate that, under conditions of high turbulence, Ukrainian businesses have chosen the path of consistent development of digital architecture. The most stable positive dynamics were demonstrated by the segments of intellectual analytics (+47.2%) and digital copies (+47.6%), which is explained by the gradual adoption of scenario modelling tools to

minimise management risks. At the same time, the growth in the share of cloud technology use to 58.5% in 2024 indicates the systematic formation of territorial invariance of business. This has allowed organisations to ensure the preservation of operational memory and the continuity of processes regardless of physical threats to local infrastructure. Thus, the presented statistical indicators confirm the

role of digital architecture as a stabilising mechanism that transforms technological investments into strategic stability and adaptability of economic entities.

An analysis of the dynamics of indicators characterising the effectiveness of digital architecture implementation (Fig. 2) allows to assess both the positive effects and hidden challenges for enterprises in the period 2022-2024. Positive trends that directly affect the level of strategic resilience include: optimisation of operating costs: the integration of automated management systems and the transition to cloud services have enabled enterprises to reduce the costs of maintaining physical infrastructure, which has partially offset the negative impact of inflationary processes; faster recovery of business processes: the use of predictive analytics and digital twins has enabled rapid modelling of logistics chains and production cycles in the event of disruption; Strengthening digital immunity: systematic investments in cybersecurity architecture have minimised direct financial losses from the growing number of cyberattacks, ensuring the integrity of corporate data.

At the same time, the process of intensive digitalisation is accompanied by a number of destabilising factors that need to be taken into account in strategic management: Temporary decline in net profitability: significant capital investments in updating digital architecture (CapEx) in the

early stages create additional pressure on profitability, requiring a review of investment policy; increased costs of retaining specialists: a shortage of personnel with a high level of digital competencies forces companies to increase their payroll, which affects the overall structure of operating expenses; risk of technological dependence: high concentration on solutions from global cloud providers creates potential threats in the event of technical failures on the part of the supplier or changes in licensing conditions.

Despite these challenges, the results of the analysis show that digital architecture in turbulent conditions is becoming a basic asset that determines not only current competitiveness, but also the ability of an enterprise to survive and adapt in the future. The data obtained confirm the hypothesis about the advisability of transforming IT infrastructure costs into strategic investments in security and resilience. In addition to internal economic factors, the period of intensive transformation of the architecture of digital innovation is driven by the need for Ukrainian businesses to adapt to new regulatory norms and global technological standards. In particular, institutional drivers such as integration into the European Union (EU) Single Digital Market, the introduction of open banking standards, and stricter personal data protection requirements have significantly changed the vector of digital solutions development (Table 3).

Table 3. Impact of strategic and regulatory drivers on the architecture of digital innovation in enterprises

Factor/category	Description	Impact on resilience	Implementation challenges
Harmonisation with the Digital Single Market (EU)	Implementation of General Data Protection Regulation (GDPR), electronic Identification, Authentication and Trust Services (eIDAS) and digital reporting standards.	Simplification of cross-border cooperation, entry into the EU market, increased investor confidence.	High costs of technical and legal compliance.
Special regime "Dii.City"	Preferential tax treatment and English law for IT assets.	Stimulation of in-house product development, capitalisation of intellectual assets.	The need for strict adherence to transparency and audit criteria.
National Cybersecurity Strategy	Critical infrastructure resilience requirements, Zero Trust model.	Formation of a systematic defence against hybrid threats, ensuring business continuity (BCP).	Shortage of qualified specialists, complex security audit procedures.

Source: developed by the authors based on research by A. Kuzior *et al.* (2022), N. Ivanova (2024), P. Zhang & Y. Wang (2024), National Bank of Ukraine (n.d.)

The systematisation of the factors presented in Table 3 provides grounds to assert that the regulatory environment in Ukraine serves as an external institutional basis for the formation of the architecture of digital innovation. On the one hand, the implementation of European standards has stimulated innovative activity and facilitated the integration of enterprises into the global digital space. On the other hand, adaptation to EU standards forces businesses to abandon fragmented software products in favour of unified integrated ecosystems, which minimises the risks of data fragmentation and strengthens the foundation for strategic resilience.

The introduction of the "Dii.City" regime has created more favourable financial and institutional conditions for the development of the technology sector, enabling enterprises to reallocate resources to scale complex

architectural solutions. At the same time, the role of digital innovation architecture as a determinant of strategic resilience directly depends on the level of cognitive readiness of management to operate in the updated legal environment. In this context, it is important to develop the dynamic adaptability of management teams to converge the technological potential of architecture into the functional contours of strategic planning and preventive risk management. Thus, the formed architecture of digital innovations is not just a technical basis, but a holistic strategic system within which regulatory compliance is combined with technological flexibility. This creates the preconditions for the transition to an intellectually adaptive management model capable of self-learning in response to external challenges. For the practical implementation of this concept, it is necessary to define a

hierarchical structure of interaction between the components of the architecture, which allows transforming technological tools into an effective mechanism for ensuring strategic resilience (Fig. 3).

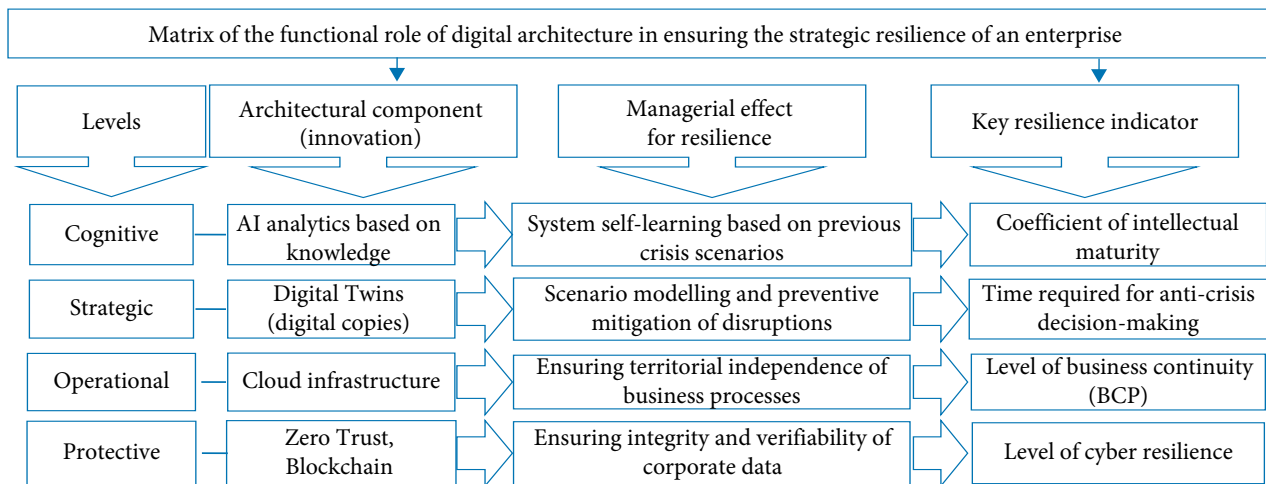


Figure 3. Matrix of the functional role of digital architecture in ensuring the strategic resilience of an enterprise

Source: developed by the authors based on research by H. Akib *et al.* (2022), R.G. Kula & C. Treude (2022), J.A.R. Awad & R. Martin-Rojas (2024), I. Tkachenko (2024)

The presented matrix clearly demonstrates the role of digital architecture as a key determinant defining an enterprise’s capacity to withstand external shocks. Due to continuous feedback loops between the protective and cognitive levels, the system acquires self-organising properties. This means that the enterprise does not simply respond to changes in regulatory norms or security threats, but uses them as input data for automatic updating of management algorithms. Thus, the matrix presented in Figure 3 illustrates a hierarchical model of transforming digital innovations into strategic assets, where each level of architecture performs a specific function in ensuring the effective functioning and long-term resilience of the enterprise.

Despite the high strategic potential of the developed matrix (Fig. 3), its practical implementation is complicated by the influence of a number of destructive factors identified in the course of the study. Typologisation of these obstacles allows to specify the content of the problem field and determine the mechanisms for their elimination. The key

obstacle is the fragmented implementation of digital solutions. The creation of “digital islands” (separate programmes without integration) leads to a break in information flows, which makes it impossible to form a single resilience contour. The solution to this problem lies in the transition to a microservice architecture that ensures the seamless integration of all business processes. Secondly, the development of architecture is accompanied by specific cyber risks, which, in conditions of global turbulence, transform from technical threats into strategic challenges. The implementation of the Zero Trust model, embedded in the protective layer of the author’s matrix, allows for a change in the security paradigm: from perimeter protection to the protection of each individual operation. Thirdly, there is an acute shortage of digital competencies. Even the most sophisticated architecture remains inert without specialists capable of managing innovation cycles. This requires companies to transform their human resource management systems towards the formation of a “cognitive culture” (Table 4).

Table 4. Mechanisms for overcoming destabilising factors in the formation of digital architecture

Problem	Essence of destructive influence	Architectural solution (overcoming mechanism)	Effect on resilience
Fragmentation of solutions	Duplication of data and delays in managerial responses.	Implementation of unified ecosystems and integration through API interfaces.	System integrity and the speed of strategic manoeuvring.
Cyber risks	Risk of complete business disruption as a result of external attacks.	Transition to a multi-layered Zero Trust model and blockchain-based verification.	BCP and protection of assets.
Competence deficit	Inability to effectively operate intelligent systems.	Development of managerial “digital intelligence” and self-learning systems.	Increased adaptability to technological upgrades.
Misalignment with strategic objectives	A disconnect between IT expenditure and strategic outcomes.	Convergence of digital architecture into functional planning frameworks.	Transformation of digital innovation into a sustainable competitive advantage.

Source: developed by the authors based on research by G. Fletcher & M. Griffiths (2020), R.G. Kula & C. Treude (2022), D. Pizniak & S. Turchina (2023), J. Cui (2025)

The proposed comprehensive approach assumes that the architecture of digital innovation should be formed not as an isolated technological structure, but as a determining factor of systemic stability integrated into the organisational structure. This accelerates innovation cycles – from threat identification to adaptive response generation – which is important for maintaining stability in the dynamic global digital space. Thus, the strategic resilience of an enterprise is directly determined by the depth of integration of digital innovations into the management system. Only by overcoming these barriers can digital architecture become an effective tool for ensuring competitiveness, allowing an economic entity not only to maintain functional stability during shocks, but also to use digital transformation as a driver of exponential strategic development. It should be noted that even with intensive expansion of digital potential, financial and economic indicators of activity in the short term may show some volatility. This is due to the following factors: temporary depression of profitability: significant capital investments in digital infrastructure and support for cloud ecosystems create a burden on net profit, but such expenses are investments in strategic security; the cost of technological convergence: the process of combining disparate products into a single model requires significant resources to overcome data fragmentation; exogenous destruction: external shocks and energy instability lead to increased operational risks, which temporarily negate the expected economic effect. To transform architecture into an effective determinant of resilience, it is necessary to implement a strategic algorithm covering the following functional vectors:

1. Conceptual design: development of a target innovation model relevant to dynamic business goals.
2. Cognitive transformation: development of digital intelligence of personnel and innovative culture.
3. Optimisation of the operational contour: automation of routine processes to free up resources for strategic manoeuvring.
4. Cyber resilience: building a perimeter based on Zero Trust.

The implementation of these strategic vectors ensures a qualitative transformation of the enterprise management system into an intelligent adaptive model, where the use of API interfaces and blockchain technologies guarantees the necessary ecosystem openness. This allows for the optimisation of innovation cycles, enabling the organisation to not only adapt to market anomalies, but also to set new standards for industry leadership. The systematic integration of technological solutions positions the architecture of digital innovation as a fundamental determinant of strategic resilience, ensuring the long-term stability and competitiveness of a business entity in the global digital space (Beverungen *et al.*, 2022).

It has been established that the architecture of digital innovation acts as a multi-level framework that integrates the technological basis (artificial intelligence, big data, cloud infrastructures) with organisational and managerial

contours. This allows digitalisation to be transformed from a budget expense into a strategic asset that generates added value even in periods of turbulence. Unlike the fragmented automation of individual functions, the architecture approach provides end-to-end visibility of business processes, which is critical for rapid decision-making. A central role in this process is played by digital twins of enterprises. Systematic digitalisation helps to strengthen the anti-crisis immunity of an enterprise. The integration of cloud computing ensures the mobility of work processes, and automated management systems allow the functionality of production chains to be maintained even with limited access to physical resources. Thus, digital architecture becomes the foundation for implementing a “dynamic capabilities” strategy.

The generalisation of the data obtained confirmed the key scientific hypotheses of the study: The results of the study fully confirmed hypothesis H1, as a direct relationship was established between the level of integrity of the digital architecture and the speed of regeneration of the enterprise’s functions after critical exogenous shocks. The confirmation of hypothesis H2 is based on an analysis of operational efficiency: the implementation of systems based on predictive analytics and digital twins allows management to perform real-time simulation modelling of risks. The results also confirmed hypothesis H3: the architecture of digital innovations is identified as a key determinant of strategic resilience, ensuring the flexibility of business models in highly turbulent conditions.

Discussion of the obtained results within contemporary scientific discourse makes it possible to more fully reveal the theoretical and practical value of the study. It has been established that the need for deep reconfiguration of management systems under the influence of digitalisation fully corresponds to the position of M. Biluha (2025). The author rightly pointed out the systemic barriers faced by Ukrainian enterprises; however, this study expands that approach by proposing digital innovation architecture as a concrete methodological instrument for overcoming such obstacles. Supporting M. Biluha’s (2025) thesis that technological inertia constitutes a major impediment to development, the present research demonstrates that overcoming it is possible only through a shift in the managerial paradigm towards adaptability. This requires not merely the replacement of software, but a reconsideration of organisational hierarchy, where digital flows become the foundation for decision-making at all management levels.

The analysis of the impact of digital innovations on corporate efficiency resonates with the empirical findings of J. Cui (2025), who identified a direct relationship between process digitalisation and productivity growth through the integration of artificial intelligence. This study aligns with the conclusion that the positive effects of technology emerge only under conditions of full systemic integration. It is demonstrated that the isolated use of, for example, artificial intelligence without coherent linkage to a comprehensive data architecture does not ensure the desired increase in resilience. Such synergy confirms the non-linear nature

of digital transformation effectiveness: maximum returns are achieved only after crossing a critical threshold of systemic integration. The vision of digital architecture as an ecosystem is also consistent with the work of I. Trunina *et al.* (2023). However, while those authors concentrated on the threats associated with Industry 5.0, the present study proposes solutions through the construction of strategic security contours, enabling risk neutralisation already at the stage of architectural design.

An important area of debate concerns the role of digital twins. The strategic approach of S.N. Masaev *et al.* (2025), who conceptualised digital twins as complex dynamic systems, is supported. Nevertheless, this study introduces a different emphasis: it argues that a digital twin is not merely a monitoring instrument, but a mechanism for ensuring strategic manoeuvrability of enterprises under wartime conditions, which corresponds with the conclusions of I. Tkachenko (2024) regarding the critical role of innovation during periods of military conflict. Complementing this perspective, the research substantiates that digital architecture performs the function of an intellectual “shell” that minimises the impact of physical destruction on the managerial stability of a business entity.

With regard to post-war recovery processes, the article shares the optimism of D. Pizniak & S. Turchina (2023) concerning the catalytic role of technology. However, unlike their macroeconomic approach, the focus of the present study is placed at the micro level – the individual enterprise. The results confirm the conclusions of I. Strutynska *et al.* (2024) that for small and medium-sized enterprises digitalisation constitutes a non-alternative means of survival. Given that such enterprises are the most vulnerable, the proposed architecture is characterised by modularity. This enables phased implementation, thereby addressing the problem of limited financial capacity discussed by I. Savras & N. Fedynets (2023). Such a stepwise approach makes digital transformation accessible even to entities with constrained investment resources, transforming financial limitations from an insurmountable barrier into a factor for prioritising change.

The issue of public investment, raised by Y. Voloshchuk *et al.* (2025), is particularly relevant in the current context. This study supports the thesis regarding the necessity of state stimulation of innovation. However, the analysis revealed a certain contradiction: external financing without an internal transformation of managerial architecture proves to be insufficiently effective. In this regard, the position of H. Akib *et al.* (2022) appears more convincing, emphasising the primacy of combining organisational and technological components. It has been demonstrated that adaptive management strategies integrated into a digital foundation create immunity to unpredictable market fluctuations, thereby increasing an enterprise’s attractiveness for long-term investment.

In assessing the vulnerability of digital systems, it is appropriate to refer to the work of R. Kula & C. Treude (2022) on the impact of geopolitics on software ecosystems. The

current findings confirm their concerns regarding the growth of cyber risks. Business stability now critically depends on the resilience of digital infrastructure, which substantiates the necessity of embedding cybersecurity directly into the architecture of innovation. This expands the traditional understanding of resilience by incorporating digital security as a mandatory determinant.

Summarising the results of the discussion, it is important to emphasise that the systemic analysis of opportunities and threats presented by Y. Yan (2023), along with the findings of P. Zhang & Y. Wang (2024), confirms that the academic community recognises digitalisation as a key factor in strategic management. The present research logically advances this argument by demonstrating that the architectural approach represents the highest form of realising innovation potential, as conceptualised by J.A.R. Awad & R. Martin-Rojas (2024). The proposed concept enables enterprises not merely to react to crises, but to build anticipatory resilience through continuous technological self-renewal. The conceptualisation of the results allows to conclude that the proposed digital innovation architecture forms a reliable foundation for the long-term survival of businesses under conditions of global instability. This confirms the expediency of transitioning from fragmented IT solutions to comprehensive digital ecosystems. Thus, an enterprise’s strategic resilience is derived from the quality and integrity of its digital architecture.

Conclusions

The results of the study show that the formation of the architecture of digital innovations in the current turbulent conditions is a complex and multi-level process that combines technological, organisational and managerial components. The architecture of digital innovation is not just a set of individual technologies, but a holistic management system that ensures the adaptation of economic entities to global challenges, transforming traditional business models, optimising internal structures and creating conditions for dynamic resilience to exogenous shocks. The study confirmed that the systematic integration of digital copies of enterprises (Digital Twins), intellectual analytics and cloud computing allows a transition from passive response to crisis situations to predictive modelling of development scenarios. This ensures the continuity of business processes, increases the flexibility of management decisions and minimises the destructive impact of risks on the functioning of the organisation. An analysis of the dynamics of Ukrainian business digitalisation for 2022-2024 showed a positive correlation between the development of digital architecture and the level of strategic resilience of enterprises. Despite the temporary burden on financial indicators, investments in digital infrastructure form the basis for maintaining market positions and rapid recovery of potential in the post-war period.

It has been found that the process of digital architecture formation is determined not only by technological factors, but also by institutional drivers, such as

harmonisation with the EU Digital Single Market and the introduction of special legal regimes (Diia.City). Strategic resilience is ensured through the synergy of protective, operational, strategic and cognitive levels, with the key indicator of effectiveness being the system's ability to self-organise and make rapid anti-crisis decisions. The main vectors of architecture development in the context of Industry 5.0 are cyber resilience, openness of ecosystems through API solutions, and the development of digital intelligence of human capital. To realise their strategic potential, enterprises must apply a systematic approach that includes conceptual design, overcoming data fragmentation and cognitive transformation of management. Promising areas for further research include studying the

impact of quantum computing on the cyber resilience of enterprises, developing methods for assessing the return on investment in digital resilience, and researching the role of artificial intelligence in the automatic re-engineering of business architectures in real time.

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Conflict of Interest

None.

References

- [1] Akib, H., Furkan, F., Sumarno, S., Budidarma, A., Salam, R., & Hadi, S. (2022). Business resilience in the digital transformation era. *Pinisi Discretion Review*, 6(1), 95-102. doi: [10.26858/pdr.v6i1.37708](https://doi.org/10.26858/pdr.v6i1.37708).
- [2] Awad, J.A.R., & MartinRojas, R. (2024). Digital transformation influence on organizational resilience through innovation capability. *Journal of Innovation and Entrepreneurship*, 13(1), article number 69. doi: [10.1186/s13731-024-00405-4](https://doi.org/10.1186/s13731-024-00405-4).
- [3] Beverungen, D., Hess, T., Köster, A., Lehrer, C. (2022). From private digital platforms to public data spaces: Implications for the digital transformation. *Electronic Markets*, 32, 493-501. doi: [10.1007/s12525-022-00553-z](https://doi.org/10.1007/s12525-022-00553-z).
- [4] Biluha, M. (2025). Innovative business development under digital transformation and crisis: Potential, barriers, and prospects for Ukraine. *Marketing and Digital Technologies*, 9(3), 136-157. doi: [10.15276/mdt.9.3.2025.10](https://doi.org/10.15276/mdt.9.3.2025.10).
- [5] Cui, J. (2025). Empirical analysis of digital innovations impact on corporate ESG performance: The mediating role of GAI technology. *ArXiv*. doi: [10.48550/arXiv.2504.01041](https://doi.org/10.48550/arXiv.2504.01041).
- [6] Fletcher, G., & Griffiths, M. (2020). Digital transformation during a lockdown. *International Journal of Information Management*, 55, article number 102185. doi: [10.1016/j.ijinfomgt.2020.102185](https://doi.org/10.1016/j.ijinfomgt.2020.102185).
- [7] Ivanova, N. (2024). Digital transformation of Ukraine: Impact on the economy, quality of life and achievement of sustainable development goals. *Economics of Systems Development*, 6(1), 100-111. doi: [10.32782/2707-8019/2024-1-9](https://doi.org/10.32782/2707-8019/2024-1-9).
- [8] Kolodiziev, O., Shcherbak, V., Kostyshyna, T., Krupka, M., Riabovolyk, T., Androshchuk, I., & Kravchuk, N. (2024). Digital transformation as a tool for creating an inclusive economy in Ukraine during wartime. *Problems and Perspectives in Management*, 22(3), 440-457, doi: [10.21511/ppm.22\(3\).2024.34](https://doi.org/10.21511/ppm.22(3).2024.34).
- [9] KPMG Ukraine. (2024). *Ukrainian business through the eyes of managers and executives 2024*. Retrieved from <https://kpmg.com/ua/uk/home/insights/2024/11/kpmg-ceo-outlook-2024.html>.
- [10] Kula, R.G., & Treude, C. (2022). In war and peace: The impact of world politics on software ecosystems. *ArXiv*. doi: [10.48550/arXiv.2208.01393](https://doi.org/10.48550/arXiv.2208.01393).
- [11] Kuzior, A., Pidorycheva, I., Liashenko, V., Shevtsova, H., & Shvets, N. (2022). Assessment of national innovation ecosystems of the EU countries and Ukraine in interests of sustainable development. *Sustainability*, 14, article number 8487. doi: [10.3390/su14148487](https://doi.org/10.3390/su14148487).
- [12] Masaev, S.N., Vingert, V.V., Bogdanov, A.V., & Salal, Y.K. (2025). A strategic planning of a digital copy (an enterprise) as a task of control a dynamic system. *Journal of Physics: Conference Series*, 1679, article number 032010. doi: [10.1088/1742-6596/1679/3/032010](https://doi.org/10.1088/1742-6596/1679/3/032010).
- [13] National Bank of Ukraine. (n.d.). Retrieved from <https://bank.gov.ua/>.
- [14] Parkhuts, Y.D., & Ohdanska, O.D. (2025). Ensuring the competitiveness of an enterprise based on digital transformation models. *European Journal of Management Issues*, 33(2), 75-87. doi: [10.15421/192507](https://doi.org/10.15421/192507).
- [15] Pizniak, D., & Turchina, S. (2023). The use of digital technologies in the process of postwar reconstruction of Ukraine. *Modern Economics*, 40, 44-51. doi: [10.31521/modecon.V40\(2023\)06](https://doi.org/10.31521/modecon.V40(2023)06).
- [16] PwC Ukraine. (n.d.). *Banking sector*. Retrieved from <https://www.pwc.com/ua/uk/industry/banking.html>.
- [17] Savras, I.Z., & Fedynets, N.I. (2023). Digitalization and innovative development of enterprises: Trends, problems and prospects. *Herald of LUTE. Economic Sciences*, 74, 108-114. doi: [10.32782/2522-1205-2023-74-14](https://doi.org/10.32782/2522-1205-2023-74-14).
- [18] Strutynska, I., Dmytrotso, L., Sorokivska, O., & Kozbur, H. (2024). [Features of digital development of small and medium business in Ukraine, EU, and G7 countries](https://doi.org/10.31909/1pp125-135). In *Transformation of business for sustainable future: Research, digitalization and innovation* (pp. 411-427). Ternopil: FOP Palyanytsya.
- [19] Tkachenko, I. (2024). Resilience of Ukrainian business: How to support production and innovations in the conditions of war. *Economic Bulletin of the Dniprovsk State Technical University*, 2(9), 125-135. doi: [10.31319/2709-2879.2024iss2\(9\).319091pp125-135](https://doi.org/10.31319/2709-2879.2024iss2(9).319091pp125-135).

- [20] Trunina, I., Bilyk, M., & Yakovenko, Y. (2023). Artificial intelligence from Industry 5.0 perspective: Threats and challenges. In *IEEE 5th international conference on modern electrical and energy system (MEES)*. Kremenchuk: IEEE. doi: [10.1109/MEES61502.2023.10402468](https://doi.org/10.1109/MEES61502.2023.10402468).
- [21] Ukrstat. (n.d.). *Use of information and communication technologies at enterprises*. Retrieved from <https://stat.gov.ua/en/datasets/use-information-and-communication-technologies-enterprises>.
- [22] Voloshchuk, Y., Lavruk, N., Derlytsia, A., Havryliuk, V., & KuliiDemianiuk, Y. (2025). The role of public investment in innovative projects during martial law. *Economics of Development*, 24(1), 45-56. doi: [10.63341/econ/1.2025.45](https://doi.org/10.63341/econ/1.2025.45).
- [23] Yan, Y. (2023). Opportunities and challenges of enterprise digital transformation. *BCP Business & Management*, 44, 631-637. doi: [10.54691/bcpbm.v44i.4903](https://doi.org/10.54691/bcpbm.v44i.4903).
- [24] Zhang, P., & Wang, Y. (2024). Digital transformation: A systematic review and bibliometric analysis from the corporate finance perspective. *SSRN*. doi: [10.2139/ssrn.5053864](https://doi.org/10.2139/ssrn.5053864).

Архітектоніка цифрових інновацій як детермінанта стратегічної резильєнтності підприємства

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Анотація. Актуальність дослідження обумовлена необхідністю підвищення стратегічної резильєнтності підприємств у контексті цифрової трансформації, де архітектоніка цифрових інновацій виступає ключовим фактором адаптивності та конкурентоспроможності. Метою дослідження було обґрунтувати роль архітектоніки цифрових інновацій як детермінанти стратегічної резильєнтності підприємств. Методологія дослідження ґрунтувалася на використанні методів системно-структурного та компаративного аналізу для ідентифікації параметрів цифрової архітектури, а також економіко-математичного моделювання для розробки матриці її функціональної ролі у забезпеченні адаптивного потенціалу бізнесу. Акцентовано, що в умовах зростаючої турбулентності екзогенних чинників та цифрової трансформації економіки архітектоніка цифрових інновацій виступає ключовою детермінантою стратегічної резильєнтності підприємства. Розглянуто концептуальні параметри цифрової архітектоніки (технологічний базис, адаптивність, предиктивність) та їхній вплив на трансформацію традиційних моделей управління. Проаналізовано динаміку інтеграції цифрових компонентів в операційну діяльність підприємств України, що дозволило виявити кореляцію між рівнем технологічного потенціалу та швидкістю відновлення бізнесу після кризових шоків. Встановлено, що фрагментарність впровадження рішень, кіберризик та дефіцит цифрових компетенцій є дестабілізуючими факторами, які нівелюють стратегічний потенціал цифрової архітектури. На основі проведеного аналізу запропоновано етапність формування цілісної архітектоніки та матрицю її функціональної ролі у забезпеченні резильєнтності суб'єктів господарювання. Доведено, що лише комплексний підхід до поєднання технологічних драйверів із стратегічними цілями розвитку дозволяє забезпечити довгострокову адаптивну стійкість та конкурентоспроможність підприємства в глобальному цифровому просторі. Практична цінність дослідження полягає у можливості застосування запропонованого архітектурного підходу та інноваційного інструментарію керівниками вищої ланки, антикризовими менеджерами та фахівцями з цифрового розвитку для проектування гнучких стратегій управління, що забезпечують високу резильєнтність підприємств у критичних умовах

Ключові слова: кіберстійкість; технологічні драйвери; адаптивне управління; цифровізація; реконфігурація бізнес-моделей



Digital transformation of energy allocation: From data transparency to socio-economic justice

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Abstract. The relevance stems from the fact that, under the conditions of war and post-war recovery in Ukraine, the digital transformation of energy governance is becoming a key instrument for overcoming energy poverty, regional disparities, and a crisis of trust in energy policy. The organisation of digital energy allocation determines the social legitimacy of the energy transition and the recovery model. The purpose of the article was to substantiate the concept of digitally fair energy allocation and to develop a methodological framework for assessing the impact of digital tools on social justice and economic efficiency in distribution systems. The study systematised contemporary approaches to energy justice, analysed digital technologies in the energy sector, and applied comparative and systems analysis methods. On this basis, a conceptual “data-trust-justice” framework was developed, and a quasi-experimental design for evaluating digital allocation policies at the feeder level was formulated. The research established that the traditional centralised model of energy allocation, built on fragmented data and low transparency, reproduces regional disparities, energy poverty, and distrust towards regulatory decisions. Within the study, a new concept of “digitally fair energy allocation” was developed, combining economic efficiency and transparency with guaranteed access to basic energy services for vulnerable groups. The role of intelligent metering systems, big data analytics, artificial intelligence methods, and blockchain-based registries in forming an integrated “data-trust-justice” chain was analysed. A structure of digital allocation scenarios based on different principles of distributive justice was proposed, and measurable targets of implementation for distribution system operators were defined. The results showed that integrating justice criteria into digital allocation models helps to avoid socially regressive outcomes and strengthens the legitimacy of energy policy. The findings can be used by regulators, distribution system operators, central and local authorities, and energy and infrastructure project managers to design, monitor, and evaluate digital reforms in energy allocation, while considering principles of social equality and economic security

Keywords: economic efficiency; energy poverty; artificial intelligence; blockchain; energy ecosystem; concept of fair distribution

Introduction

The transformation of energy systems became one of the central dimensions of global economic modernisation in the 2010s and early 2020s. Between 2010 and 2024, reforms aimed at decarbonisation, decentralisation, and digitalisation of the energy sector were launched in many countries,

and digital technologies played a critical role by enabling real-time monitoring of energy flows, automated network control, and new forms of interaction between producers and consumers. The energy transition raised questions of social justice regarding the distribution of energy

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resources, the protection of vulnerable consumers, and spatial equity across regions.

Ukraine inherited a highly centralised energy infrastructure, significant asset depreciation, and institutional fragmentation in the governance of energy markets, which contributed to uneven access to reliable and affordable energy services across urban and rural areas, industrial centres, and peripheral territories, as well as across different income groups. After the full-scale Russian invasion in 2022, significant damage to generation, transmission, and distribution infrastructure occurred, supply interruptions became more frequent, and the need for emergency rationing increased. Under these conditions, digital transformation was considered not merely the introduction of modern information technologies into existing energy processes, but a systemic redesign of energy governance intended to reconcile efficiency, resilience, and social equity through advanced metering infrastructure, cloud-based data platforms, big data analytics, and artificial intelligence (AI) tools.

In the Ukrainian context, I.O. Pavlova (2025) formulated a paradigm of inclusive rural-urban development as a theoretical and applied model for post-war recovery and demonstrated that territorial disparities in infrastructure and access to basic services, including energy, constrained inclusive growth; the author concluded that reconstruction policies had to combine physical rebuilding with institutional and social reforms so that rural communities and secondary cities did not remain structurally disadvantaged. I. Rojek *et al.* (2025) investigated novel AI methods for energy-intensive industries and concluded that predictive maintenance, demand forecasting, and process optimisation significantly increased energy productivity and supported industrial transformation.

Additionally, researchers focused on blockchain and distributed ledger technologies (DLT) as elements of the digital energy and financial infrastructure. O.V. Sikorska *et al.* (2024) explored blockchain applications in the Ukrainian energy sector and argued that tamper-resistant registries and automated settlements could enhance transparency and reduce opportunistic behaviour in energy trading. O. Nakonechna & S. Gorodnichenko (2025) analysed DLT as a methodological foundation for control and accounting-analytical support in the digital economy. The researchers demonstrated that distributed ledgers enabled a shift towards triple-entry accounting and continuous auditing by ensuring immutability, cryptographic security, and real-time transaction verification, but also identified systemic challenges, such as shortages of DLT-competent staff, integration problems with legacy IT systems, and regulatory uncertainty. The authors' conclusions indicated that DLT-based registries could serve as a trusted digital infrastructure for recording and allocating economic resources, directly relevant to the design of digital energy-allocation mechanisms.

A substantial part of the research addressed renewable energy, circularity, and cooperative models, particularly in the agro-industrial complex (AIC). V. Brych *et al.* (2025) quantified the economic potential of renewable energy for

business in Ukraine and Europe. The authors argued that the deployment of renewables was economically rational and strategically necessary for climate neutrality, energy security, and post-war recovery. The authors' work explicitly linked renewable investments to circular-economy principles, including resource efficiency and new value chains. N.I. Horbal & I.V. Plish (2021) examined circular business models for Ukrainian enterprises. The researchers showed that repeated use of materials, energy recovery from residues, and cooperative ownership structures increased resilience and reduced dependence on imported resources.

Most studies on energy justice and energy-system modelling added an explicit normative dimension to discussions of digitalisation and renewables. P. Lehmann *et al.* (2024) analysed spatial distributive justice in the siting of renewable-energy infrastructure. The authors showed that alternative justice principles led to different spatial distributions of generation capacity and burdens across regions. C. Lohr *et al.* (2024) integrated disamenity costs and equality considerations into energy-system optimisation models. The researchers demonstrated that fairness-aware formulations tended to reallocate generation and network investments away from already burdened territories.

However, earlier works rarely examined how feeder-level digital allocation mechanisms in a war-affected country could be explicitly designed and evaluated through a spectrum of justice perspectives, while simultaneously incorporating indicators of circularity and cooperation in the agri-food sector. In light of these gaps, this research aimed to elaborate a concept of digitally fair energy allocation for Ukraine and to construct a feeder-level evaluation framework that links digital allocation mechanisms with distributive-justice criteria and indicators of circular development in the agro-industrial complex.

Materials and Methods

The research adopted a theoretical-analytical and design-oriented approach that combined conceptual analysis, a structured literature review, comparative and systems analysis, and elements of quasi-experimental and scenario design. The overall aim of the methodological strategy was to construct a coherent framework for digitally fair energy allocation in Ukraine without relying on a single empirical dataset or econometric model. The conceptual analysis of energy allocation in Ukraine was carried out. For this purpose, national analytical reports (Ukraine energy market observatory..., 2025; National energy and climate..., 2025), regulatory documents, and sectoral statistics (State Statistics Service of Ukraine, 2023) were examined. These materials were used to identify typical patterns of regional disparities, infrastructure depreciation, institutional fragmentation, and social vulnerability that condition the operation of distribution systems in wartime and post-war contexts, and the patterns are presented in the results section on socio-economic problems.

A structured literature review was then conducted in order to systematise academic contributions. The search

was conducted for the period 2000-2025 using combinations of relevant keywords. The selection focused on international and Ukrainian publications that addressed digitalisation and inclusive development (Košovská *et al.*, 2022; Pavlova, 2025). The selection also included studies examining artificial intelligence and digital technologies in energy systems (Sukhodolia, 2022; Rojek *et al.*, 2025). Particular attention was given to publications analysing blockchain and distributed ledger technologies (Sikorska *et al.*, 2024; Nakonechna & Gorodnichenko, 2025). In addition, the selection covered research on circular and cooperative models in the agro-industrial complex (Dovgal, 2020; Dovgal & Potryvaieva, 2024; Brych *et al.*, 2025). Furthermore, the review incorporated studies addressing energy justice and fair allocation principles (Sovacool & Dworkin, 2015; Jenkins *et al.*, 2016; Lohr *et al.*, 2024). This provided the conceptual building blocks for the subsequent stages of the study. Based on these materials, comparative, and systems analysis were applied to map the relationships between data transparency, institutional trust, and social justice outcomes. This work resulted in the formulation of the “Data-Trust-Justice” analytical framework, in which digital energy data were treated as a foundational element for both managerial efficiency and equitable access to energy services.

The methodological design further included the development of a quasi-experimental evaluation scheme for digital allocation policies at the feeder level. Feeder-level units with advanced metering infrastructure and analytical tools were defined conceptually as “treated”, while comparable feeders without such deployment were defined as “control”. The design relied on staggered rollout, seasonal controls, and robustness checks against weather shocks and con-

flict-related disruptions. Although no empirical estimates were reported in this research, the scheme was formulated in a manner that allows implementation by distribution system operators and researchers.

Scenario design was used to incorporate distributive-justice regimes into the digital allocation model. Three perspectives were distinguished: a needs-based regime prioritising feeders and communities with the highest levels of energy poverty and infrastructure damage; a responsibility-based regime giving precedence to actors investing in low-carbon generation, demand-side flexibility, and energy efficiency; and a capacity-based regime favouring consumers and territories with greater fiscal and institutional capacity to co-finance infrastructure. For each regime, the conceptual model specified how changes in the spatial distribution of generating and network assets could be evaluated, with particular attention to feeders supplying the agro-industrial complex and to indicators of circularity and resilience in local food systems. The study’s limitations should be acknowledged. The framework and scenarios remain conceptual and design-oriented and have not yet been tested empirically on real feeders. The magnitude of economic effects, such as reductions in losses, improvements in reliability, or changes in energy-poverty rates under different justice regimes, remains to be quantified.

Results

Socio-economic problems of energy resource allocation in Ukraine

The study systematised the main socio-economic problems of energy resource allocation in Ukraine under conditions of digital transformation, war, and post-war recovery (Table 1).

Table 1. Socio-economic problems of energy resource distribution in the context of digital transformation and the impact on the security and stability of the state’s development

Socio-economic problem	Content of the problem / manifestation	Impact on the security and stability of the country’s development
Uneven access to energy resources	Concentration of energy capacities in large cities, deficit in communities, energy poverty	Worsening regional disparities, increasing social tension, decreasing economic sustainability
Outdated energy infrastructure	High energy losses, worn-out networks, lack of modern control technologies	Increasing risks of man-made accidents, threat to energy security, increasing production costs
Lack of transparent energy accounting mechanisms	Insufficient digitalisation of data, duplication of regulatory functions, closed statistics	Corruption risks, loss of trust in energy policy, slowing down reforms
Low energy efficiency of industry and agro-industrial complex	Excessive energy consumption, lack of motivation to modernise	Overspending of resources, reduction in competitiveness, increasing dependence on energy imports
Energy poverty of the population	Inability of households and SMEs to invest in energy-saving technologies	Social stratification, growing dissatisfaction, risk of community destabilisation
Insufficient digital infrastructure for energy management	Lack of a single platform for data collection, analysis, and monitoring	Slow response to crises, ineffective state regulation
Human and technological deficit	Lack of specialists in the field of energy management, cybersecurity, data analysis	Decreased level of manageability of energy systems, vulnerability to external threats
Insufficient integration of socio-economic and technological reforms	Discontinuity between politics, business and science, weak intersectoral interaction	Loss of development synergy, risk of inefficient use of investments

Source: prepared by the authors

These problems were grouped into four interrelated clusters: spatial inequalities, infrastructural constraints, governance deficits, and social vulnerability. Spatial inequalities were manifested in the concentration of generation capacity and high-quality network infrastructure in large industrial agglomerations. At the same time, many rural and peripheral communities relied on weak feeders with high outage rates. Such disparities translated into differences in production costs, investment attractiveness, and quality of life across territories, contradicting the principles of inclusive rural-urban development. Enterprises located on vulnerable feeders faced higher implicit costs for backup solutions and lost output, whereas firms in more robust grids operated under more predictable conditions.

Infrastructural constraints arose from the ageing of generation, transmission, and distribution assets, high technical losses, and limited integration of renewable energy sources. Outdated equipment and damage from military actions contributed to frequent supply interruptions, voltage fluctuations, and an increased risk of large-scale failures. For industrial and agri-food producers, these constraints increased operating costs, disrupted cold chains, and reduced competitiveness in domestic and export markets.

Governance deficits were associated with fragmented institutional responsibilities, incomplete or non-transparent data, and insufficient digitalisation of operational processes. The absence of unified, high-quality statistics on outages, losses, and consumption hampered effective regulation, complicated public oversight, and weakened trust in tariff and investment decisions. Fragmented information systems prevented the construction of an integrated energy balance and limited the ability to provide targeted support to vulnerable regions and consumer groups. Social vulnerability was reflected in energy poverty, the inability of households and small businesses to secure adequate energy services without sacrificing other basic needs. Energy poverty was particularly acute in communities characterised by low incomes, degraded housing, and unreliable supply. In combination, spatial inequalities, infrastructural constraints, governance deficits, and social vulnerability produced a pattern of a socially unjust energy system, in which the burdens of unreliability, high tariffs, and wartime disruptions fell disproportionately on low-income households, rural communities, and small agri-food producers.

These diagnostic conclusions are consistent with official statistical and policy documents. The statistical compendium “Ukraine in Figures 2022” documented persistent regional differences in income levels, infrastructure quality, and electricity consumption, confirming that rural and war-affected regions face higher risks of energy poverty and service interruptions (State Statistics Service of Ukraine, 2023). The report National energy and climate plan of Ukraine 2025-2030 (2025) identified ageing networks, high distribution losses, and uneven integration of renewables as key constraints for the energy transition

and emphasised the need to modernise distribution infrastructure and improve data transparency. The report Ukraine energy market observatory: Quarterly report Q2 2025 (2025) further recorded increased losses, deteriorating reliability indicators, and severe damage to distribution assets in frontline and de-occupied regions. These findings provided the empirical background against which the problem clusters summarised in Table 1 were formulated.

In the contemporary Ukrainian context, these problems acquire a precise justice dimension. Energy systems and transition policies can be considered socially unjust where war-affected regions, low-income households, rural communities, and critical agri-food producers bear a disproportionate share of outages, losses, and tariff burdens, while benefiting least from modernisation. International research on energy justice (Sovacool & Dworkin, 2015; Jenkins *et al.*, 2016) highlighted that the choice between distributional, recognition-based, and procedural perspectives substantially alters the diagnosis of who is “vulnerable” and what constitutes a fair allocation of energy services. When these perspectives are absent from planning and modelling, the analytical horizon narrows to purely techno-economic indicators, risking recommendations that are misaligned with the lived experiences and values of different Ukrainian communities and stakeholders.

Digital technologies and artificial intelligence as drivers of transformation

The analysis of the latest practice and literature showed that digital technologies, including artificial intelligence, have the potential to reshape energy-allocation mechanisms at system and feeder levels. Advanced metering infrastructure, automated monitoring, and AI-based analytics increased the accuracy of demand forecasts, enabled predictive maintenance, and supported real-time optimisation of flows and network configurations. In distribution networks, this translated into reduced technical and non-technical losses, improved reliability indicators, and greater flexibility for integrating distributed renewable generation.

In the agri-food sector, digital tools and AI-supported simulations enabled more precise management of energy-intensive operations, such as irrigation, storage, and processing. Optimised load profiles and better coordination between energy and production cycles created opportunities to lower costs per unit of output, reduce spoilage, and strengthen resilience to climate variability and wartime supply disruptions. At the regional level, feeders with higher levels of digitalisation and analytical capacity could become platforms for concentrating investment in processing, logistics, and storage. In contrast, feeders without such development risked further marginalisation.

At the same time, the study confirmed that artificial intelligence is not neutral with respect to social outcomes. The design of algorithms, the availability of representative data, and the choice of optimisation criteria critically influence how burdens and benefits are allocated. If vulnerable groups are under-represented in datasets or if only

cost-minimisation objectives are used, automated decision systems for tariffs, outage management, or eligibility for support may unintentionally disadvantage those groups. This observation motivated the incorporation of explicit justice regimes and transparency requirements into the proposed digital allocation framework.

The “Data-Trust-Justice” framework

The third contribution of the article was the development of the “Data-Trust-Justice” conceptual framework (Fig. 1). The framework is built on the assumption that digital energy data, when collected and used appropriately, can become a key asset for both efficient management and social justice.

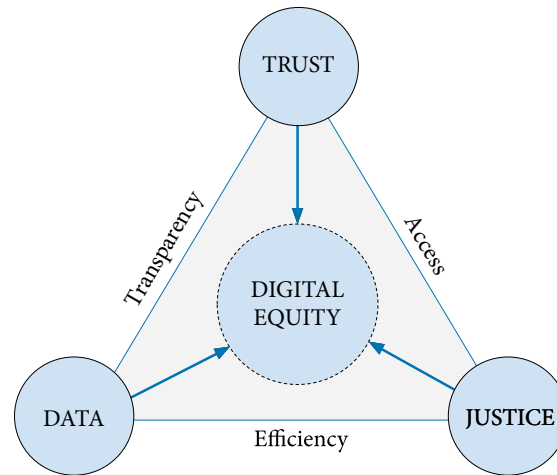


Figure 1. “Data-Trust-Justice” conceptual framework with edge labels Efficiency, Transparency, and Access, plus a centre “Digital Equity” (balance point)

Source: prepared by the authors

The vertex “Data” represents the availability, quality, and accessibility of information on generation, flows, losses, outages, tariffs, and the coverage of vulnerable groups. The vertex “Trust” captures the confidence of consumers, regulators, and market participants in the integrity of energy institutions, the fairness of allocation rules, and the reliability of technological solutions. The concept of “Justice” embodies the normative goal of ensuring that all citizens, particularly vulnerable households, have access to basic energy services and that the costs and benefits of energy transformation are distributed fairly.

The edges connecting the vertices are labelled “Efficiency”, “Transparency”, and “Access”. Efficiency refers to the ability of digital systems to enhance the technical and economic performance of energy networks, including through loss reduction and improved investment planning. Transparency refers to open access to non-sensitive energy data and clear communication of allocation rules, which support public accountability and evidence-based policy debates. Access highlights the guarantee of minimum energy services and the targeted support necessary to protect households facing energy poverty. At the intersection of these relationships lies the notion of “Digital equity”: a state in which digital transformation does not deepen existing inequalities but instead mitigates these inequalities by empowering consumers, enabling more precise targeting of support, and reducing information asymmetries. The framework emphasises that digitalisation is not inherently equitable; instead, equity results from deliberate design choices and governance arrangements.

The proposed “Data-Trust-Justice” triangle can be further specified by explicitly integrating circular-economy and food-system-resilience considerations. At the “Data” vertex, this includes disaggregated information on rural feeders, agricultural processors, storage facilities, and irrigation loads, as well as on distributed renewables and waste-to-energy projects in the AIC. At the “Trust” vertex, meaningful participation of farmers’ organisations, cooperatives, and local communities in the design of allocation rules strengthens recognition and procedural justice. Finally, at the “Justice” vertex, distributive criteria can be extended beyond standard welfare or cost metrics to include indicators of food security, employment in rural areas, and circular resource use, aligning with broader water-energy-food (WEF) nexus and sustainable food-ecosystem approaches.

Quasi-experimental design for evaluating digital allocation policies.

The fourth result concerned the design of a quasi-experimental evaluation methodology for digital allocation policies. Studies predominantly described technological architectures, pilots, and platform-level case evidence rather than rigorous causal evaluation of distributional and social outcomes. For example, F.M. Enescu *et al.* (2025) and V. Valsan *et al.* (2025) discussed AI- and blockchain-enabled micro market and IoT-based solutions for local balancing and consumer participation. However, these contributions provided limited guidance on quasi-experimental designs that would quantify the impact of feeder-level

digital interventions on both technical indicators and equity-related outcomes.

The proposed evaluation design used a feeder (a distribution line serving a defined group of consumers) as the unit of analysis (Fig. 2). Feeders that introduced advanced metering infrastructure and analytical tools formed the treatment group. Feeders with similar pre-treatment characteristics that did not receive the intervention constituted the control group. Matching criteria included baseline loss

levels, load profiles, customer composition, and climatic conditions. Key outcome indicators include: changes in feeder-level losses, measured as percentage points of energy input; changes in reliability indices, such as System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI); changes in the share of households in the service area that meet a defined criterion of energy poverty; coverage of vulnerable households by targeted tariffs or benefits linked to the digital system.

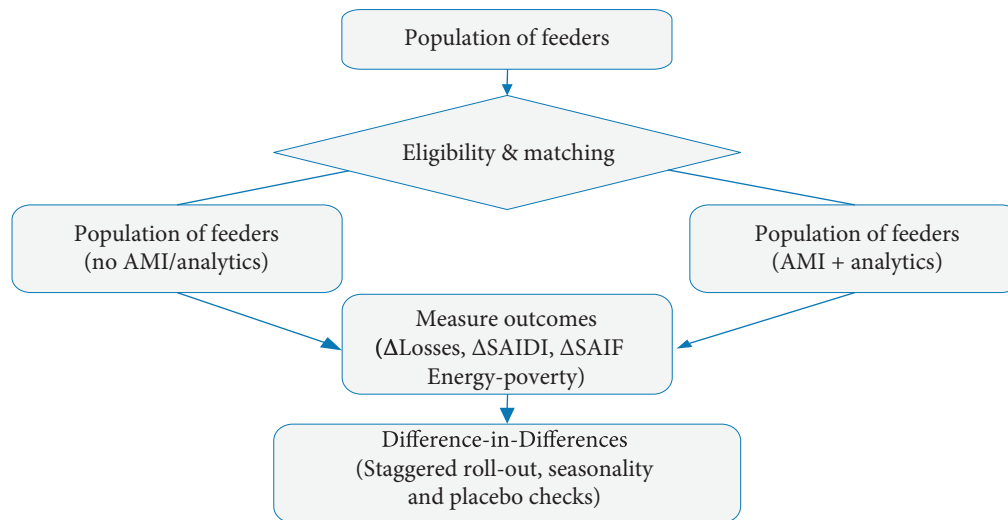


Figure 2. The design of the quasi-experimental evaluation

Source: prepared by the authors

The design relies on a staggered rollout of digital solutions across feeders, enabling difference-in-differences estimation with seasonality controls. Weather data and information on conflict-related damage are incorporated as covariates to control for confounding. Placebo periods, in which no treatment occurred, are used to test parallel trends assumptions. At the same time, the methodology acknowledges potential data-quality issues, including incomplete activation of metering points and inconsistencies in outage logging, and recommends sensitivity analyses. This design approach reflects international best practices in policy evaluation but is adapted to Ukraine's specific institutional and infrastructural context. It offers a pragmatic way for regulators and distribution system operators to assess whether digital interventions deliver promised improvements in efficiency, reliability, and social outcomes. At the same time, it draws on established evaluation techniques used in infrastructure and energy reform studies, particularly staggered rollouts and difference-in-differences methods (Lehmann *et al.*, 2024; Lohr *et al.*, 2024).

Within this quasi-experimental design, the evaluation also compares alternative justice regimes and circularity settings. For each treated feeder, outcome indicators (losses, SAIDI/SAIFI, tariff burdens, connection of renewables, stability of supply for critical agri-food loads) are estimated under three allocation logics: needs-based, responsibility-based, and capacity-based. Moreover, the spatial

distribution of generating and network assets is mapped across urban, peri-urban, and rural territories, with particular attention to feeders that serve agro-industrial clusters, storage and processing facilities, and irrigation systems. This allows assessing how equality-oriented versus disamenity-sensitive or cost-minimising scenarios shift burdens and benefits between regions and social groups, as suggested by the latest work on integrating equality considerations and local disamenity costs into energy system optimisation (Lehmann *et al.*, 2024; Lohr *et al.*, 2024). In turn, this provides an empirical basis for designing digital allocation policies that support a climate-neutral energy transition in the AIC while remaining socially acceptable.

Policy implications and implementation priorities

The results of the analysis yield a set of policy implications and implementation priorities for Ukraine's digital energy transformation. Firstly, digital reforms should explicitly incorporate social objectives, such as reducing energy poverty and ensuring territorial equity, rather than focusing exclusively on efficiency. This requires setting measurable targets, for example: reducing technical and non-technical losses on treated feeders by at least two percentage points; achieving coverage of at least 80% of customers with advanced metering infrastructure on urban feeders and 50% on rural feeders; reducing interruption duration by at least ten per cent relative to matched controls; and ensuring that

no less than 90% of registered vulnerable households are covered by targeted tariff or benefit delivery.

Building trust requires a robust open-data strategy. Non-sensitive data on outages, losses, tariffs, and planned coverage should be made available in user-friendly formats, enabling civil society, local governments, and researchers to monitor progress and identify bottlenecks. This approach is consistent with broader trends in digital governance and enhances accountability. Regulatory frameworks must address questions of data governance, privacy, and algorithmic fairness. Clear rules are needed to define which actors can access which types of data, under what conditions, and how decisions supported by artificial intelligence may be contested or revised. Dedicated institutions or units within existing regulators may be required to oversee these processes. Digital transformation must be accompanied by investments in human capital, including training for engineers, data scientists, regulators, and local officials. Without such investments, the potential of advanced technologies cannot be fully realised, and the risk of misinterpretation or misuse of data increases. International partners can play a crucial role by supporting pilot projects, co-financing digital infrastructure, and facilitating knowledge exchange with other countries that have implemented similar reforms. Such cooperation can accelerate learning and help avoid common pitfalls.

Justice perspectives and net-zero electricity futures for Ukraine's agri-food sector

Research on energy-system optimisation demonstrated that the choice of distributive-justice principle has a first-order effect on the resulting design of net-zero power systems (Lehmann *et al.*, 2024; Lohr *et al.*, 2024). When models seek only to minimise total system costs, the models tend to favour spatial concentration of generation in locations with the cheapest resources and lowest connection costs, even if this entails higher local disamenities or neglects peripheral regions. By contrast, models that incorporated equality constraints, social-welfare functions, or fairness-aware allocation rules often redistributed generation and grid investments more evenly across territories, prioritising regions with higher historical underinvestment or higher vulnerability to energy poverty (Lehmann *et al.*, 2024; Lohr *et al.*, 2024). In other words, different justice logics, utilitarian, egalitarian, capability-based, responsibility-based, or opportunity-oriented, can generate markedly different maps of future energy systems, even when the overall technical and climate targets (such as net-zero emissions by 2050) are held constant.

For Ukraine, this has direct implications for the design of alternative, zero-emission electricity systems extending to 2050. A purely cost-optimal scenario could, for example, concentrate most new renewable capacity, storage, and digital control in a few industrial and metropolitan hubs, while leaving AIC-dominated regions dependent on ageing infrastructure and exposed to more frequent curtailments or outages. An egalitarian or capability-oriented scenario,

by contrast, would explicitly treat reliable and affordable electricity for irrigation, storage, and primary processing as a critical capability for food security and rural livelihoods. This would justify greater investment in distributed renewables, storage, and digital control on feeders serving cooperatives, small- and medium-sized agri-food enterprises, and rural communities, even if such investments modestly increase aggregate system costs.

These justice-sensitive constructions directly influence the spatial distribution of generating infrastructure, the pattern of grid reinforcements, and the incidence of local externalities. When coupled with indicators of circularity, such as the utilisation of agricultural residues and biogas, waste-heat recovery in processing plants, or cooperative ownership structures in renewable projects, such approaches align energy system design with the broader objective of building a resilient, low-waste food-energy ecosystem as a pillar of Ukraine's post-war reconstruction model. In this sense, the "Data-Trust-Justice" framework, combined with justice-aware digital modelling, can help prevent the emergence of unjust or socially regressive designs for future energy systems, notably when models might otherwise implicitly encode normative assumptions without transparent justification. Making these justice perspectives explicit broadens the analytical horizon and increases the likelihood that model-based assessments will resonate with the values and lived experiences of diverse communities and stakeholders.

Economic, managerial, and regulatory implications of the proposed approach

The integrated analysis of socio-economic problems, digital tools, conceptual framework, and evaluation design led to several important implications for regional development, business decisions, and public policy. From an economic standpoint, a fair digital allocation at the feeder level can reduce technical and non-technical losses, shorten outages, and stabilise voltage quality, thereby lowering operating costs and investment risks for enterprises. For agri-food businesses, improved reliability and more predictable tariffs reduce spoilage of perishable products, facilitate long-term contracts, and support the development of higher-value-added processing and storage facilities in regions that previously suffered from chronic underinvestment. For territorial development, targeting digital and physical upgrades towards structurally weak feeders creates conditions for more balanced growth between urban centres and rural areas.

In managerial terms, the framework supports concrete decision-making processes. Distribution system operators can use feeder-level indicators within the "Data-Trust-Justice" framework to prioritise network reinforcement, transformer replacement, and the integration of distributed renewables, while balancing efficiency and justice criteria. Local governments and regional development agencies can identify where digital investments will yield the most significant combined impact on the business climate,

employment, and energy-poverty reduction. Agri-food cooperatives and energy communities can rely on the same information to design cooperative investment schemes and negotiate connection conditions for local generation and storage projects.

The regulatory and institutional implications concern the need to define standards for digital data, establish open-data practices, and embed fairness criteria into tariff and allocation rules. Regulators are required to mandate the publication of anonymised feeder-level data, specify procedures for the use of AI-based tools, and provide mechanisms for contesting unjust allocation decisions. Co-ordination among energy regulators, ministries responsible for regional and agrarian policy, and local authorities is essential to ensure that digital energy allocation reforms align with broader post-war recovery priorities. Overall, the results show that digitally fair energy allocation should be understood as both an energy-sector reform and a lever for wider socio-economic reconstruction. When combined with circular and cooperative trajectories in the agro-industrial complex, the proposed approach contributes to the formation of a resilient, low-waste, and socially balanced food-energy ecosystem for post-war Ukraine.

Discussion

The results of this study are closely related to the latest work on inclusive development and digital transformation. I.O. Pavlova (2025) developed a paradigm of inclusive rural-urban development for post-war Ukraine and demonstrated that disparities in infrastructure and access to basic services that are prerequisites for reliable energy service provision constrained inclusive growth. The present research confirmed this diagnosis but moved from the strategic level to the operational level of energy allocation. In contrast to I.O. Pavlova (2025), who focused on general reconstruction policy, the digitally fair allocation framework specifies feeder-level indicators and justice-aware scenarios to target investments and tariff measures in precisely the territories I.O. Pavlova (2025) identified as structurally disadvantaged.

The findings also engage with studies of the digital economy and electronic information systems. I. Košovská *et al.* (2022) analysed the electronification of accounting processes in the Slovak Republic and showed that digitalisation strengthened transparency, standardisation, and transaction traceability, thereby improving the quality of managerial decisions. The “Data-Trust-Justice” framework extends this logic to the energy sector. While I. Košovská *et al.* (2022) focused on financial accounting, the current study argues that similar data-centric architectures support not only efficiency but also social legitimacy when applied to energy allocation, as these architectures provide auditable evidence of how outages, losses, and tariff burdens are distributed across different consumer groups.

Technological research on artificial intelligence in the energy sector has so far stressed mostly efficiency gains. I. Rojek *et al.* (2025) reported that AI-based predictive

maintenance and optimisation tools improved energy productivity and supported industrial transformation. O.M. Sukhodolia (2022) examined the opportunities and risks of AI deployment in Ukraine’s energy sector and highlighted the importance of robust data governance and consumer rights protection. The integration of justice regimes into allocation scenarios directly addresses O.M. Sukhodolia’s (2022) concern about social risks. It illustrates how AI and advanced metering can be embedded in rules that consider needs, responsibility, or capacity rather than pure cost minimisation.

Another important strand of literature concerns blockchain and distributed ledger technologies. O.V. Sikorska *et al.* (2024) analysed blockchain-based applications for the Ukrainian energy sector and argued that tamper-resistant registries and smart contracts could enhance transparency in energy trading and settlements. O. Nakonechna & S. Gorodnichenko (2025) investigated distributed ledgers as a basis for control and accounting-analytical support in the digital economy. The authors demonstrated the feasibility of triple-entry accounting and continuous auditing, while also highlighting staffing shortages and institutional challenges. The present study builds on these insights by interpreting DLT-based registries as a component of the infrastructure for digitally fair energy allocation. Beyond recording transactions, such registries can track service levels and cost exposure across different categories of consumers, thereby enabling distributional analysis and monitoring of justice indicators within the energy system.

V. Valsan *et al.* (2025) proposed an AI-integrated blockchain micro market logic for local balancing and coordination and argued that automated verification and data-driven settlement can reduce transaction frictions and expand consumer participation in decentralised flexibility arrangements. This aligns with the present study’s interpretation of digital allocation as an institutional mechanism, not merely a technical tool, because micro market architectures make allocation rules explicit, auditable, and comparable across feeders. The proposed approach also interacts with research on renewable energy, circular economy, and cooperative models, particularly in the agro-industrial complex. V. Brych *et al.* (2025) quantified the economic potential of renewable energy for business in Ukraine and Europe. The researchers argued that investments in renewables were both economically rational and strategically necessary for climate neutrality and post-war recovery.

N.I. Horbal & I.V. Plish (2021) and O. Dovgal & N. Potryvaieva (2024) showed that circular business models, repeated use of materials, bioenergy from agricultural residues, and cooperative ownership structures increased resilience and reduced dependence on imported resources in the AIC. Related evidence from the Ukrainian agrarian context indicated that alternative and renewable energy solutions can strengthen resource conservation and competitiveness in the agricultural sector, especially when linked to local biomass streams and decentralised generation options (Parkhomets *et al.*, 2020). The concept of a

sustainable food-energy ecosystem adopted in this article is consistent with these results. Still, it emphasises that realisation of the economic potential described by these authors depends on feeder-level allocation rules. These considerations are aligned with analyses of how enterprises adapted the financial strategies to wartime and post-war challenges, which highlighted the need to combine short-term liquidity and risk management with investment in resilience-enhancing assets and infrastructure (Zhigar & Petryniak, 2025). Without justice-aware digital tools, renewable and circular projects may continue to bypass rural communities and smaller agri-food enterprises. In contrast, the allocation framework proposed here directs digital and physical investments precisely to those feeders where such investments can generate combined effects on energy security, food security, and rural employment.

Insights from the water-energy-food nexus literature add another perspective. J.G. Segovia-Hernández *et al.* (2023) reviewed optimisation approaches to the WEF nexus and highlighted the need to evaluate synergies and trade-offs jointly rather than within isolated sectoral models. The present study converged with this view by embedding indicators of circularity and food-system resilience, such as the share of renewable and bioenergy in processing facilities or the stability of cold chains, into the evaluation of energy-allocation scenarios. At the same time, WEF-nexus models have typically focused on physical and environmental constraints, whereas the framework developed here centres on distributive justice and wartime vulnerability. In this sense, the study offers a complementary angle rather than a competing one.

The normative dimension of energy systems is treated explicitly in the energy-justice literature. B.K. Sovacool & M.H. Dworkin (2015) conceptualised energy justice through distributional, procedural, and recognition components. The authors argued that energy systems are socially unjust depending on who bears the costs and who receives the benefits of energy production and transition. K. Jenkins *et al.* (2016) synthesised this field and defined energy justice as a framework for identifying, analysing, and remedying energy-related inequalities. The latest modelling work, such as that of P. Lehmann *et al.* (2024) and C. Lohr *et al.* (2024), demonstrated that different justice principles, such as cost minimisation, equality of outcomes, equality of opportunities, or consideration of local disamenity costs, led to markedly different spatial configurations of net-zero energy systems. The present research is fully aligned with these conclusions and operationalises these findings by implementing justice regimes as alternative objective functions or constraints in feeder-level digital allocation models. The needs-based, responsibility-based, and capacity-based regimes proposed in this article can be seen as specific instantiations of the broader justice logics discussed in these works.

Taken together, these comparisons indicated that the concept of digitally fair energy allocation does not contradict existing evidence but reorganises it around the

specific problem of justice in wartime and post-war conditions. Research on digitalisation, AI, and blockchain has tended to accentuate efficiency and security; this article adds a structured distributive-justice perspective and shows how efficiency-focused technologies can be embedded in rules that protect vulnerable households and agri-food producers. Studies on renewables and circular AIC models have documented substantial economic opportunities; the present work explains how allocation rules and digital data can either unlock or block these opportunities in practice. Energy-justice scholarship and fairness-aware modelling have demonstrated that justice principles shape system design; the framework developed here translates that insight into concrete feeder-level scenarios, linked to a quasi-experimental evaluation design and to agri-food-system indicators.

Conclusions

The study demonstrated that the digital transformation of energy allocation in Ukraine cannot be reduced to the technical introduction of new information technologies. Under wartime and post-war conditions, digital tools were shown to reshape the structure of socio-economic problems by influencing how shortages, losses, and reliability risks are distributed between regions, consumer groups, and sectors. The systematisation of spatial inequalities, infrastructural constraints, governance deficits, and social vulnerability revealed that existing allocation practices tend to reproduce energy poverty and territorial disparities, especially for rural communities and agri-food producers.

On this basis, the concept of digitally fair energy allocation was formulated. The “Data-Trust-Justice” framework clarified how energy data, institutional trust, and distributive outcomes are interconnected through efficiency, transparency, and access. Justice-aware regimes of allocation were specified, including needs-based, responsibility-based, and capacity-based approaches, and the conceptual embedding of these regimes into feeder-level scenarios was demonstrated. The corresponding quasi-experimental design provided a structured framework for evaluating digital allocation policies, using changes in losses, reliability, and energy-poverty indicators as outcome measures.

From an economic and managerial perspective, the proposed approach indicated that targeted digital investments at the feeder level can reduce losses, stabilise supply, and create more predictable conditions for business activity, particularly in the agro-industrial complex. At the same time, the framework highlighted that digitalisation must be accompanied by explicit fairness criteria, clear data-governance standards, and coordinated regulatory decisions if it is to support inclusive regional development and a sustainable food-energy ecosystem in the post-war recovery.

Future research should focus on empirical testing of the proposed evaluation scheme on real distribution feeders, including the estimation of actual economic gains and social effects under different justice regimes. Further

work is also needed to refine indicators of circularity and resilience for agri-food-dominated feeders, and to explore how cooperative and community-based energy projects respond to digitally fair allocation rules. In addition, comparative studies across regions and countries would help to determine the transferability of the framework and to identify institutional conditions under which digitally fair energy allocation can be most effective.

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References

- [1] Brych, V., Shuvar, A., Moroz, V., & Pankevych, V. (2025). Economic potential of renewable energy for business: Strategies of decarbonisation and climate adaptation in Ukraine and Europe. *Economic Analysis*, 35(3), 180-194. [doi: 10.35774/econa2025.03.180](https://doi.org/10.35774/econa2025.03.180).
- [2] Dovgal, O. (2022). Organizational and economic principles of creation and implementation of a circular business model of development. *Ukrainian Black Sea Region Agrarian Science*, 26(4), 40-50. [doi: 10.56407/2313-092X/2022-26\(4\)-4](https://doi.org/10.56407/2313-092X/2022-26(4)-4).
- [3] Dovgal, O., & Potryvaieva, N. (2024). Practical study of the implementation of circular economy at agricultural enterprises of Ukraine. *Ukrainian Black Sea Region Agrarian Science*, 28(1), 9-18. [doi: 10.56407/bs.agrarian/1.2024.09](https://doi.org/10.56407/bs.agrarian/1.2024.09).
- [4] Enescu, F.M., Drăgușin, S.-A., Boștinariu, R.-N., Marica, M.-C., Nicolăescu, C.-G., Frîncu, N.-C., & Bizon, N. (2025). Energy market: A review of current solutions, trends, issues, and future directions based on the blockchain, internet of things and artificial intelligence. *Results in Engineering*, 28, article number 107736. [doi: 10.1016/j.rineng.2025.107736](https://doi.org/10.1016/j.rineng.2025.107736).
- [5] Horbal, N.I., & Plish, I.V. (2021). Circular business models for sustainable development of Ukrainian enterprises. *Journal of Lviv Polytechnic National University. Series of Economics and Management Issues*, 5(1), 15-29. [doi: 10.23939/semi2021.01.015](https://doi.org/10.23939/semi2021.01.015).
- [6] Jenkins, K., McCauley, D., Heffron, R., Stephan, H., & Rehner, R. (2016). Energy justice: A conceptual review. *Energy Research & Social Science*, 11, 174-182. [doi: 10.1016/j.erss.2015.10.004](https://doi.org/10.1016/j.erss.2015.10.004).
- [7] Košovská, I., Hallová, M., Váryová, I., Šilerová, E., Hennyeyová, K., & Cihelka, P. (2022). The digital economy in the context of digital transformation and their impact on the electronification of accounting processes in the Slovak Republic. *AGRIS on-line Papers in Economics and Informatics*, 14(4), 53-65. [doi: 10.7160/aol.2022.140405](https://doi.org/10.7160/aol.2022.140405).
- [8] Lehmann, P., Gawel, E., Meier, J.-N., Reda, M.J., Reutter, F., & Sommer, S. (2024). Spatial distributive justice has many faces: The case of siting renewable energy infrastructures. *Energy Research & Social Science*, 118, article number 103769. [doi: 10.1016/j.erss.2024.103769](https://doi.org/10.1016/j.erss.2024.103769).
- [9] Lohr, C., Peterssen, F., Schlemminger, M., Bensmann, A., Niepelt, R., Brendel, R., & Hanke-Rauschenbach, R. (2024). Integration of disamenity costs and equality considerations regarding onshore wind power expansion and distribution into energy system optimization models. *Energy, Sustainability and Society*, 14, article number 58. [doi: 10.1186/s13705-024-00489-6](https://doi.org/10.1186/s13705-024-00489-6).
- [10] Nakonechna, O., & Gorodnichenko, S. (2025). Distributed ledger technologies for control and accounting-analytical support in the digital economy. *Ukrainian Journal of Applied Economics and Technology*, 4, 215-221. [doi: 10.36887/2415-8453-2025-4-42](https://doi.org/10.36887/2415-8453-2025-4-42).
- [11] National energy and climate plan of Ukraine 2025-2030. (2025). Retrieved from https://www.energy-community.org/dam/jcr:9d144283-08ed-410b-a670-7fd15c7782f2/1_NCEP_EnMachineTranslation.pdf.
- [12] Parkhomets, M., Putsenteilo, P., & Uniiat, L. (2020). Intensification of the use of renewable energy sources – the objective need to improve resource conservation and increase the competitiveness of production of products of the agrarian sector of Ukraine. *Innovative Economy*, 5-6, 122-132. [doi: 10.37332/2309-1533.2020.5-6.16](https://doi.org/10.37332/2309-1533.2020.5-6.16)
- [13] Pavlova, I.O. (2025). [The essence of inclusive development of rural-urban agglomerations](#). In *Theoretical and methodological foundations and practical aspects of inclusive development of rural-urban agglomerations in Ukraine* (pp. 39-65). Odesa: Astroprint.
- [14] Rojek, I., Mikołajewski, D., & Prokopowicz, P. (2025). The impact of novel artificial intelligence methods on energy productivity, industrial transformation and digitalization within the framework of energy economics, efficiency and sustainability. *Energies*, 18(19), article number 5138. [doi: 10.3390/en18195138](https://doi.org/10.3390/en18195138).
- [15] Segovia-Hernández, J.G., Contreras-Zarazúa, G., & Ramírez-Márquez, C. (2023). Sustainable design of the water-energy-food nexus: A literature review. *RSC Sustainability*, 1, 1332-1353. [doi: 10.1039/d3su00110e](https://doi.org/10.1039/d3su00110e).
- [16] Sikorska, O.V., Samsoniuk, D.Yu., & Bohatova, A.S. (2024). [The use of blockchain technologies in the energy sector](#). In *Materials of the LIII scientific and technical conference of VNTU departments*. Vinnytsia: Vinnytsia National Technical University.
- [17] Sovacool, B.K., & Dworkin, M.H. (2015). Energy justice: Conceptual insights and practical applications. *Applied Energy*, 142, 435-444. [doi: 10.1016/j.apenergy.2015.01.002](https://doi.org/10.1016/j.apenergy.2015.01.002).

- [18] State Statistics Service of Ukraine. (2023). *Ukraine in figures, 2022*. Kyiv: State Statistics Service of Ukraine.
- [19] Sukhodolia, O.M. (2022). *Artificial intelligence in the energy sector*. Kyiv: National Institute for Strategic Studies. doi: 10.53679/NISS-analytrep.2022.09.
- [20] Ukraine energy market observatory: Quarterly report Q2 2025. (2025). Retrieved from https://euneighbourseast.eu/wp-content/uploads/2025/08/q2_2025_observatory-report.pdf.
- [21] Valsan, V., Vuppala, N.S.K., Koganti, S.S.H., Kalla, L.S.E., Pappala, K.A., Kanakasabapathy, P., & Ramesh, M.V. (2025). Conceptual study – artificial intelligence-integrated blockchain micromarkets for sustainable energy. *Renewable and Sustainable Energy Reviews*, 214, article number 115482. doi: 10.1016/j.rser.2025.115482.
- [22] Zhigar, N., & Petryniak, A. (2025). Adaptation of financial strategies of enterprises to the challenges of wartime and post-war recovery. *Economic journal of Lesya Ukrainka Volyn National University*, 2(42), 82-89. doi: 10.29038/2786-4618-2025-02-82-89.

Цифрова трансформація розподілу енергоресурсів: від прозорості даних до соціально-економічної справедливості

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Анотація. Актуальність зумовлена тим, що в умовах війни та повоєнного відновлення України цифрова трансформація управління енергетикою стає ключовим інструментом подолання енергетичної бідності, регіональних диспропорцій та кризи довіри до енергетичної політики. Від організації цифрового розподілу енергії залежить соціальна легітимність енергетичного переходу та моделі відновлення. Метою статті було обґрунтувати концепцію справедливого розподілу енергії та розробити методологічні засади оцінювання впливу цифрових інструментів на соціальну справедливість і економічну ефективність систем розподілу. У дослідженні було систематизовано сучасні підходи до енергетичної справедливості, проаналізовано цифрові технології в енергетиці та застосовано методи порівняльного й системного аналізу. На цій основі було розроблено концептуальну рамку «дані-довіра-справедливість» і сформовано дизайн квазіекспериментального оцінювання політики цифрового розподілу енергії на рівні фідерів. Було встановлено, що традиційна централізована модель розподілу енергії, побудована на фрагментованих даних і низькій прозорості, відтворює регіональні диспропорції, енергетичну бідність і недовіру до рішень регулятора. У межах дослідження було розроблено концепт «цифрового справедливого розподілу енергії», який поєднує економічну ефективність, прозорість та гарантований доступ вразливих груп споживачів до базових енергетичних послуг. Було проаналізовано роль інтелектуальних систем обліку, аналітики великих даних, методів штучного інтелекту та блокчейн-реєстрів у формуванні цілісного ланцюга «дані-довіра-справедливість». Було запропоновано структуру сценаріїв цифрового розподілу, що ґрунтуються на різних принципах дистрибутивної справедливості, та сформульовано вимірювані цільові орієнтири на перші 24 місяці впровадження для операторів систем розподілу. Показано, що інтеграція критеріїв соціальної справедливості у цифрові моделі розподілу дає змогу уникати соціально регресивних рішень та посилює легітимність енергетичної політики. Отримані результати можуть бути використані регуляторами, операторами систем розподілу, органами державної влади та місцевого самоврядування, а також менеджерами енергетичних й інфраструктурних проектів для проектування, моніторингу та оцінювання цифрових реформ у сфері розподілу енергії з урахуванням принципів соціальної рівності та економічної безпеки

Ключові слова: економічна ефективність; енергетична бідність; штучний інтелект; блокчейн; енергетична екосистема; концепція справедливого розподілу

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