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Том 3, № 2, 2025

SMART ECONOMY, ENTREPRENEURSHIP AND SECURITY

Vol. 3, № 2, 2025

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ЗМІСТ

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ANALYSIS OF THE GLOBAL AUDIT SERVICES MARKET: EMPIRICAL EXPERIENCE OF LEADING INTERNATIONAL AUDIT COMPANIES

Abstract. *The development of the global stock market, the legislative protection of investors, stock exchange requirements and the provision of consulting and taxation services all place demands on the market for auditing services provided by auditing companies around the world. This requires an analysis of the market for auditing services provided by the world's leading companies in this field.*

This article aims to analyse the global market for auditing services provided by leading companies.

Analytical reviews and information from international institutions and professional accounting and auditing organisations regarding the market for auditing services and the activities of auditing companies around the world provide the empirical basis for ensuring the validity of theoretical propositions, the reliability of conclusions and recommendations.

The research methodology consists of general scientific and special methods for studying interconnected and developing processes and phenomena, namely the dialectical method, synthesis, induction and deduction, generalisation, the method of associations and analogies, comparative analysis, forecasting and tabular and graphical methods.

The analysis showed that the Big Four — PwC, EY, KPMG and Deloitte — account for around 90% of revenue in the global audit market, thanks to their global networks, the scale of their operations and the wide range of services they offer. Deloitte leads in terms of revenue and number of employees, confirming its strategic focus on consulting and digital solutions.

Revenue growth for the Big Four from 2009 to 2024 was gradual, accelerating from 2021 to 2024 due to digitalisation, increased demand for new types of consulting and greater global focus on business transparency. The forecast for 2025–2027 suggests that this positive trend will persist, with an expected average annual growth rate of around 7%.

Keywords: *analysis, business analysis, audit, international audit, audit in foreign countries, audit services, consulting, audit consulting, Big Four, audit companies, audit services market.*

1. Introduction

The growth of the global stock market, stronger legislative protection for investors, increasing stock exchange requirements, and high demand for consulting and tax services are creating new challenges and opportunities for the audit services market. These transformational factors are leading to higher expectations regarding audit quality, corporate governance standards and reporting transparency. Therefore, a comprehensive analysis of the auditing services market, as provided by leading international networks, is necessary in order to determine their readiness to meet current requirements, as well as to identify areas for improving efficiency.

This article aims to analyse the global market for auditing services provided by leading companies. To achieve this goal, the following research objectives have been set: 1) analyse the world's leading audit companies in terms of revenue from audit services; 2) characterise the revenue structure of the world's leading audit companies by service type; 3) forecast the total revenue of the four largest audit companies in the world; 4) estimate the number of employees of the four largest audit companies in the world.

Contemporary scientific research pays significant attention to issues related to the development of the global audit services market, covering both the theoretical foundations of international auditing and the practical aspects of regulating and transforming audit company activities.

Ukrainian researchers, in particular, focus on the essence of the concept of 'international auditing' as a key tool for ensuring institutional transparency [1].

The Ukrainian context, as analyzed by K. Bezverkhyi and V. Novikov [2], illustrates the integration of global auditing companies into transitional economies. Their findings underline the importance of international audit firms in enhancing financial discipline, promoting international standards, and increasing investor trust in local markets. This aligns with broader research showing that the presence of global audit firms contributes to the professionalization of audit practices and accelerates convergence with international regulatory frameworks.

The scientific literature also examines the peculiarities of institutional supervision of international audit companies' activities, particularly in the context of audits carried out by the Public Company Accounting Oversight Board (PCAOB), which emphasises the importance of audit quality for investor protection [3].

A significant body of research is devoted to improving the quality and public significance of international auditing standards [4]. In this context, works applying game-theoretic approaches to regulating the auditing services market and revealing the balance of interests between market participants and regulators are also relevant [6]. Researchers also emphasise the role of audit firms' market power in shaping the competitive environment and accessibility of audit services [7].

Contemporary research pays particular attention to the impact of the digital economy on the development of international auditing and the transformation of its organisational forms [8], as well as internal auditing practices in specific economic sectors, particularly state-owned banks [9]. Current challenges include the influence of cultural, political and religious factors on the functioning of international audit companies in different countries [19].

Researchers are also analysing the evolution of global networks of audit companies, which have become strategic networks of professional services [12]. At the same time, contemporary publications focus on the new challenges of auditing in the context of globalised trade and the need to harmonise international practices [20].

The literature also reflects regional aspects of the development of the audit services market. For example, the audit services market has been studied in Ukraine [13], Latvia [16] and Germany [17], enabling the specifics of how this market functions in different economic environments to be compared.

Contemporary scientific thought therefore comprehensively studies global and national trends in the development of auditing services, paying attention to issues such as regulation, quality, organisational transformations and the influence of the external environment. However, despite the significant number of publications, the comparative analysis of leading audit companies' revenue dynamics, personnel policies and market development forecast trends remains insufficiently researched, which makes this study relevant.

2. Materials and Methods

The empirical basis for ensuring the validity of theoretical propositions and the reliability of conclusions and recommendations was provided by analytical reviews, as well as information from international institutions and professional accounting and auditing organisations, concerning the audit services market and the activities of audit companies worldwide.

The research methodology consists of general scientific and specialised methods for studying interconnected processes and phenomena. When studying the income levels of leading international audit companies, for example, dialectical methods such as synthesis, induction and deduction, as well as generalisation, the method of associations and analogies were employed. A comparative analysis was employed to examine the income structure of the world's leading auditing companies by service type. To estimate the number of employees working in international auditing companies, an analytical scientific research method was employed. The forecasting method was employed to predict the total income of the four largest auditing companies worldwide for the period 2025–2027. Tabular and graphical methods were employed to visualise the research results.

3. Results and Discussion

The world's leading audit companies by revenue from audit services are listed in Table 1.

A 2022 analysis of the global audit market structure based on leading companies' revenues shows that

Table 1

Leading audit firms in the world by audit revenue in 2022

№	Name of the auditing company	Revenue, million US dollars
1	PwC	17154
2	EY	13600
3	KPMG	11460
4	Deloitte	10500
5	BDO	4927,8
6	Grant Thornton	2699,5
7	RSM	2612,3
8	Crowe	1778,7
9	Nexia International	1625,2
10	Baker Tilly International	1514,8
11	Moore Global	1282,9
12	Mazars	1232,4
13	HLB	1102
14	Kreston International	895,7

Source: compiled by the author based on [11]

PwC remains the undisputed leader, with audit service revenues exceeding $17 billion. EY ranks second with revenues of USD13.6 billion, followed by KPMG with revenues of USD11.46 billion. Together with Deloitte, these four companies form the so-called 'Big Four', accounting for an overwhelming 90.00% share of the global audit market.

Among the second-tier international networks, BDO ($4.9 billion), Grant Thornton ($2.7 billion) and RSM ($2.6 billion) have the highest revenues. Other companies — Crowe, Nexia International, Baker Tilly International, Moore Global, Mazars, HLB and Kreston International — occupy less significant but stable positions in the market, creating a competitive environment in the field of auditing.

Next, we will examine the revenue structure of the world's leading auditing companies by type of service provided (Fig. 1).

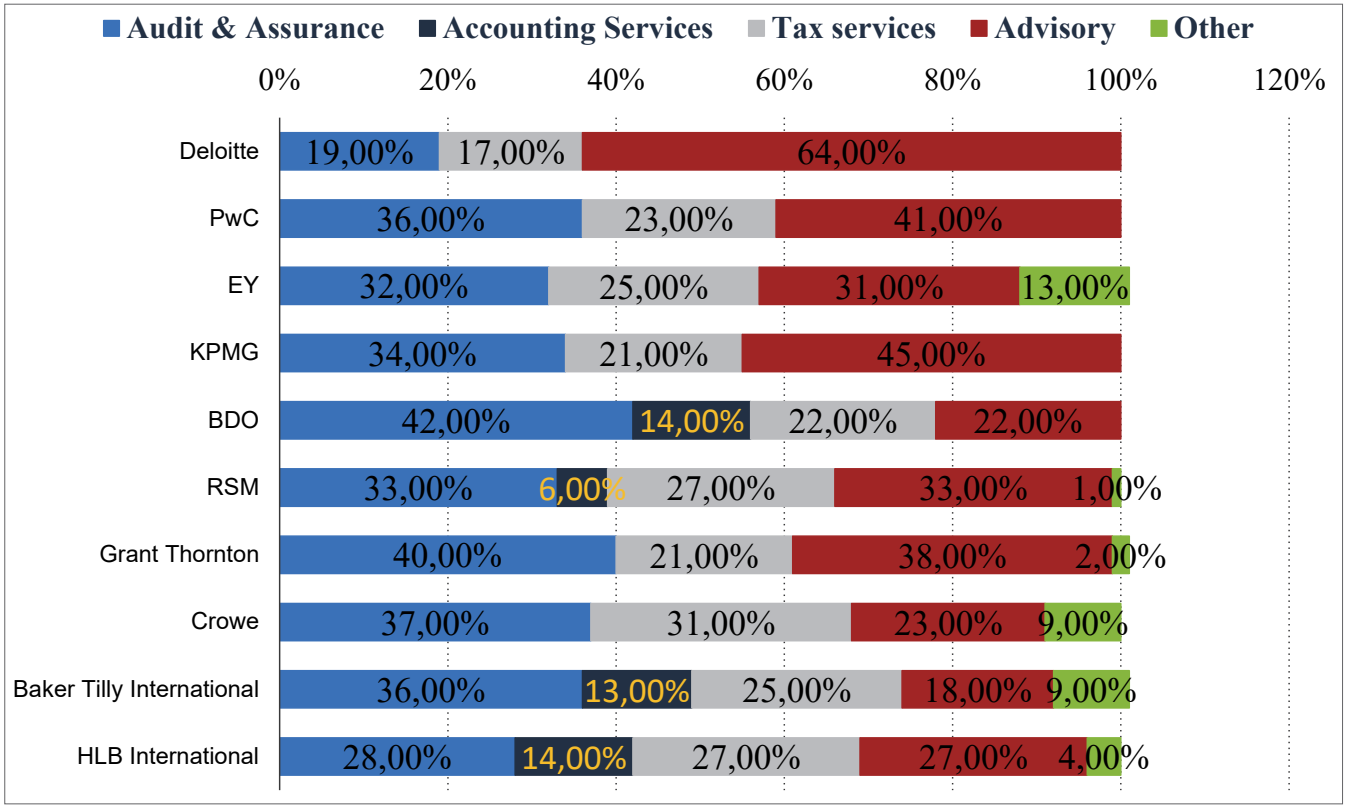

Figure 1. Share of fee income of the leading accounting firms in the world in 2022, by service line, %

Source: [16]

Fig. 1 shows that Deloitte's main focus is consulting (64% of revenue), with auditing accounting for only 19%. This indicates the company's transformation into a diversified consulting giant. Meanwhile, PwC, EY and KPMG have a more balanced structure, with auditing remaining a key source of revenue (32–36%), while tax and consulting services also play a significant role.

Among the 'medium-sized networks', BDO shows the greatest focus on auditing (42%), with accounting services accounting for a significant proportion (14%) of revenue.

Meanwhile, RSM, Grant Thornton, Crowe and Baker Tilly demonstrate a more diversified model, with significant positions in taxation and consulting.

HLB International stands out with fairly equal revenue distribution between auditing (28%), tax services (27%), and consulting (27%).

Based on the above, the Big Four are gradually reducing their dependence on auditing, expanding their consulting and taxation services, and diversifying their activities. Meanwhile, second-tier international networks (e.g. BDO, RSM and Grant Thornton) are trying to maintain auditing's dominance, while also developing related areas to compete for a wider range of services.

Next, we will consider the total revenue of the four largest auditing companies in the world (see Table 2).

The revenue dynamics of the world's leading audit firms from 2009 to 2024 show a steady growth trend, with certain phases of slowdown reflecting the impact of global economic and social factors.

1. 2009–2013 (post-crisis recovery). During this period, the combined revenue of the Big Four increased from $93.8 billion to $113.7 billion. Although growth rates were relatively moderate at around 4–5% annually, this indicates a gradual restoration of confidence in audit and consulting services following the global financial crisis of 2008.

2. 2014–2018 (active phase of development). This stage was characterised by dynamic revenue growth, with revenue increasing from $120.3 billion to $148.28 billion. Demand for audit and consulting services grew as a result of: 1) the adoption of International Financial Reporting Standards (IFRS); 2) business globalisation; and 3) greater focus on transparency and corporate governance.

3. 2019–2020 (slowdown due to the pandemic). Revenues actually stabilised, with 154.75 billion being recorded in 2019 versus 157.05 billion in 2020. The pandemic led to a slowdown in economic growth and a decline in demand for certain traditional audit services. However, it also accelerated the digitalisation of auditing and the adoption of remote service delivery models.

4. Period: 2021–2024 (digitalisation and a new wave of growth).

Revenue grew rapidly — from $167.2 billion to $212.2 billion (+27% in three years). The main drivers were: 1) the development of consultancy services in cybersecurity, artificial intelligence and digital business transformation; 2) the growing importance of Environmental, Social and Governance (ESG) reporting and sustainable

Table 2

Combined revenue of the Big Four audit firms worldwide from 2009 to 2024 (in billion U.S. dollars)

№ з/п	Years	Total revenue of the world's four largest audit firms, billions of US dollars
1	2009	93,8
2	2010	95,1
3	2011	103,6
4	2012	110,3
5	2013	113,7
6	2014	120,3
7	2015	123,66
8	2016	127,75
9	2017	134,28
10	2018	148,28
11	2019	154,75
12	2020	157,05
13	2021	167,2
14	2022	189,44
15	2023	203,79
16	2024	212,2
17	***2025***	***228,23****
18	***2026***	***241,86****
19	***2027***	***255,50****

* — forecast indicator calculated by the author using an exponential smoothing quantitative model in MS Excel

Source: [5]

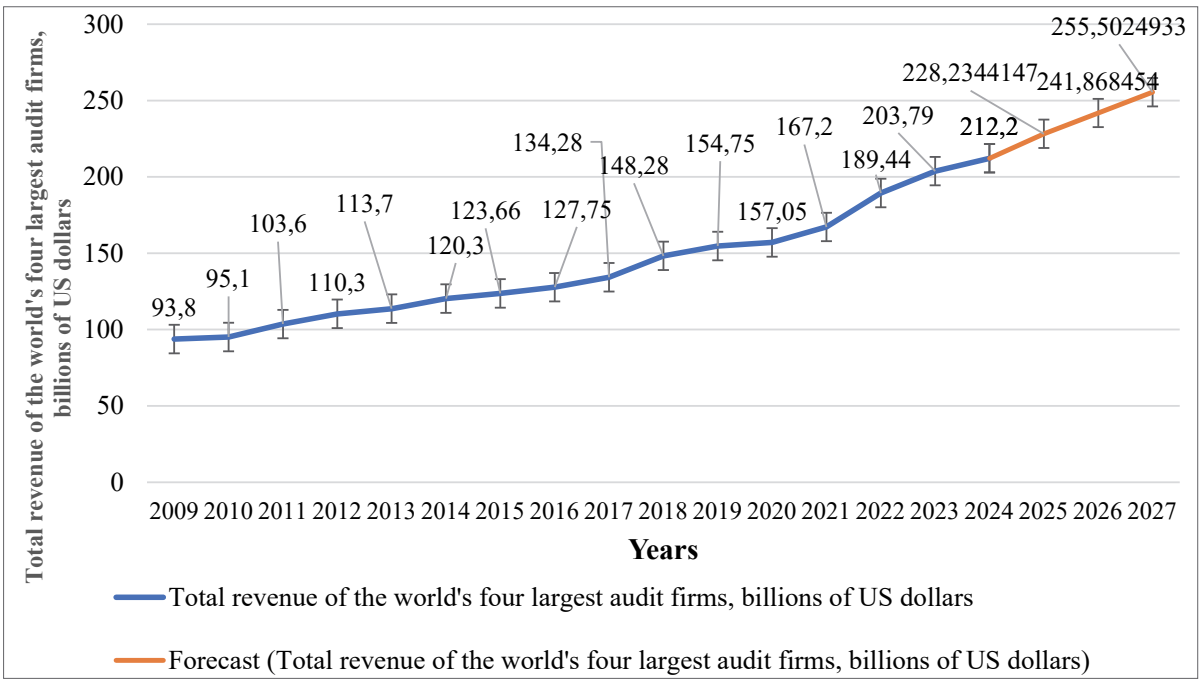

Figure 2. Forecast* of total revenue for the world's four largest audit firms
* — calculated based on the quantitative model of exponential smoothing in MS Excel
Source: generated by the author using Excel software based on the Table 2

development; and 3) increased demand for analytical and management services amid economic turbulence.

Based on Table 2, a forecast of the total revenue of the four largest audit companies in the world was constructed (see Fig. 2).

According to the forecast (see Fig. 2), steady, positive growth in the aggregate revenue of the world's four largest audit firms is expected to continue from 2024 to 2027. The estimated average annual growth rate for this period is around 6.9%, which confirms the high potential for the further development of the global audit and consulting services market.

Fig. 3 shows the revenue of the world's four largest audit firms.

Figure 3 shows that Deloitte remains the leader among the Big Four, with a lead of more than $11.8 billion over its closest competitor, Pw C. Meanwhile, PwC and EY are neck and neck in the race for second place. KPMG lags behind the other companies, but still accounts for nearly a fifth of the group's total revenue.

The revenue structure indicates relative stability in market share among the companies. Deloitte is strengthening its leadership position by actively developing its consulting and digital services.

Figure 4 shows the number of employees of the four largest auditing companies in the world.

As Fig. 3 shows, Deloitte is the market leader in terms of both revenue and headcount, with more than 67,000 additional employees than its closest competitor, EY. EY and PwC have similar staffing levels, confirming their direct competition in the global market. KPMG ranks last among the Big Four in terms of

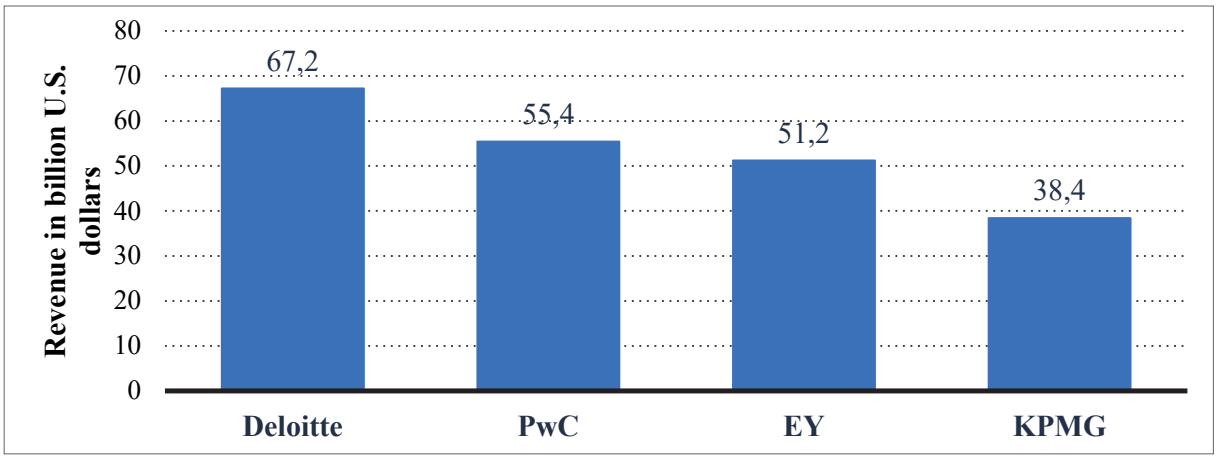

Figure 3. Revenue of the Big Four accounting/audit firms worldwide in 2024 (in billion U.S. dollars)
Source: [14]

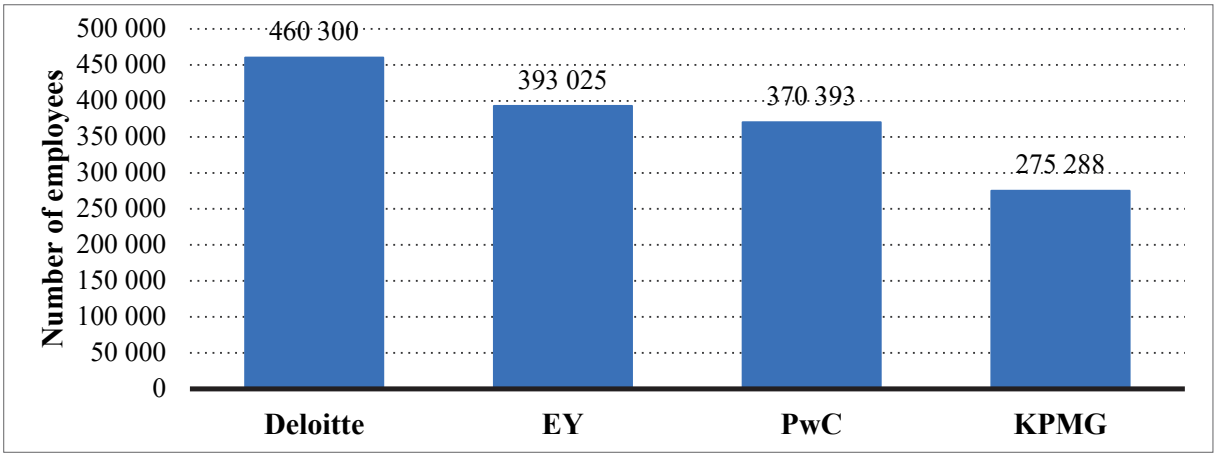

Figure 4. Number of employees of the Big Four accounting/audit firms worldwide in 2024
Source: [14]

number of employees, but still has almost 275,000 employees, indicating the scale of its operations. The total number of employees highlights the significant influence of the Big Four on the auditing and consulting services market, as these are essentially global corporations with a workforce comparable in size to that of medium-sized countries.

4. Conclusions

Analysing the global audit services market enables us to draw several general conclusions and practical observations.

PwC, EY, KPMG and Deloitte together account for around 90% of global audit market revenue. They maintain their leading positions thanks to their global networks, the scale of their operations and the wide range of services they offer. Deloitte leads in terms of revenue and number of employees, confirming its strategic focus on consulting and digital solutions.

In recent years, leading companies have become less dependent on auditing and more dependent on consulting, tax, and digital services. This aligns with the growing needs of businesses in areas such as cybersecurity, ESG reporting, and digital transformation.

While BDO, Grant Thornton, RSM and other international networks remain focused on auditing, they are also actively diversifying their activities and competing for segments of tax and consulting services. Their role in shaping the competitive environment is an important stabilising factor for the market.

The revenue dynamics of the Big Four from 2009 to 2024 show gradual growth, accelerating from 2021 to 2024. This is associated with digitalisation, the demand for new types of consultancy, and the global focus on business transparency. The forecast for 2025–2027 indicates that these positive dynamics will continue, with an average annual growth rate of around 7%.

The human resources potential of leading companies amounts to hundreds of thousands of employees, emphasising their importance as global corporations and determining the high level of competition for qualified specialists.

The results of our analysis of the global audit services market enable us to make a number of recommendations to increase the competitiveness of Ukrainian audit companies and integrate them into the global professional space:

1. It is important to reduce dependence on traditional financial statement audits gradually by expanding activities in areas such as tax consulting, corporate governance, risk management and the digital transformation of clients.

2. Innovative technologies such as artificial intelligence, big data analytics, automated audit procedures and remote audit tools should be introduced to improve the quality and efficiency of audits.

3. Ukrainian companies should expand their expertise in auditing and verifying sustainability reports, given the growing international requirements and prospects for integration into EU markets.

4. Investing in staff training, obtaining international certifications (ACCA, CPA, etc.) and creating a system to motivate and retain young professionals can give companies a competitive advantage.

5. Strengthening the application of International Standards on Auditing (ISAs) and International Financial Reporting Standards (IFRSs) will help to increase the confidence of foreign investors and expand opportunities for raising capital.

6. In order to strengthen market positions, it is advisable to develop partnerships with second-tier international audit networks such as BDO, RSM and Grant Thornton. These partnerships will provide access to modern methodologies and practices.

7. In light of the challenges posed by the ongoing conflict, Ukrainian auditors should enhance their risk management, crisis management and business restructuring services to promote the sustainability of national enterprises.

Therefore, developing audit services in Ukraine requires a combination of innovative approaches, international integration and improving the quality of human capital. This will enable Ukrainian audit

companies to strengthen their position in the domestic market and reach a new level of competitiveness in the global environment.

Further scientific research into the audit services market in Ukraine, with a view to identifying trends and directions for its development, is a promising area.

5. References

[1] Bezverkhyi, K., Poddubna, N, Pryimak, N. & Melnyk, A. (2023). Defining the essence of "international audit" as one of the key toolsfor the transparency of institutional activities. *Investytsiyi: praktyka ta dosvid,* Volume 12, Pp. 79–83. https://doi.org/10.32702/2306-6814.2023.21.79

[2] Bezverkhyi, K. & Novikov V. (2023). Activities of international auditing companies in Ukraine. *International Scientific Journal "Internauka". Series: "Economic Sciences".* Volume 9(77). Issue 2. Pp. 74–81. https://doi.org/10.25313/2520-2294-2023-9-9206

[3] Bishop, C.C., Hermanson, D.R. & Houston, R.W. (2013). PCAOB inspections of international audit firms: initial evidence. *International Journal of Auditing*, Volume 17, p. 1–18. https://doi.org/10.1111/j.1099-1123.2012.00453.x

[4] Christine E. Earley, Karen L. Hooks, Jenifer R. Joe, Paul W. Polinski, Zabihollah Rezaee, Pamela B. Roush, Kerri-Ann Sanderson & Yi-Jing Wu (2017). The Auditing Standards Committee of the Auditing Section of the American Accounting Association's Response to the International Auditing and Assurance Standard's Board's *Invitation to Comment: Enhancing Audit Quality in the Public Interest*. *Current Issues in Auditing,* 11 (1), Pp.1–25. https://doi.org/10.2308/ciia-51565

[5] Combined revenue of the Big Four accounting/audit firms worldwide from 2009 to 2024 (in billion U.S. dollars) URL: https://www.statista.com/statistics/473959/big-four-accounting-firms-global-combined-revenue

[6] Eleftheriou, K., Komarev, I. & Klumpes, P. (2023). Regulating the Market for Audit Services: A Game Theoretic Approach. *Abacus,* Volume 59, Issue 3, Pp. 697–734. https://doi.org/10.1111/abac.12278

[7] Gu, T.T., Simunic, D.A., Stein, M.T., Ye, M., & Zhang, P. (2020). The market for audit services: The role of market power. *Journal of International Accounting Research*, 19(3), Pp. 3–8. https://doi.org/10.2308/JIAR-2020-068

[8] Hajiyev, F., Babayev, N., & Gasimov, F. (2025). Organisation and areas of development of international audit in the digital economy. *Scientific Bulletin of Mukachevo State University. Series "Economics"*, 12(2), 23–33. https://doi.org/10.52566/ msu-econ2.2025.23

[9] Kaya, Y., & Utku, M. (2021). Internal Audit in Public Banks in the Framework of InternationalInternal Audit Standards: The Case of Turkey. In Contemporary Issues in Public Sector Accounting and Auditing. Emerald Publishing Limited. https://doi.org/10.1108/S1569-375920200000105014

[10] Kurnaz, N., Kestane, A. (2024). *Current Issues in Accounting*. Berlin, Germany: Peter Lang Verlag. https://doi.org/10.3726/b22748

[11] Leading accounting firms worldwide in 2022, by revenue from audit and assurance services URL: https://www.statista.com/statistics/784409/global-accounting-firms-audit-accounting-revenue

[12] Lenz, H., James, M.L. (2007). International Audit Firms as Strategic Networks — The Evolution of Global Professional Service Firms. In: Cliquet, G., Tuunanen, M., Hendrikse, G., Windsperger, J. (eds) Economics and Management of Networks. Contributions to Management Science. Physica-Verlag HD. https://doi.org/10.1007/978-3-7908-1758-4_17

[13] Nazarova K., Negodenko V. & Minjajlo V. (2021). Audit services market in Ukraine. *Tovary i rynky.* Volume 4. Pp. 4–15. DOI: https://doi.org/10.31617/tr.knute.2021(40)01

[14] Number of employees of the Big Four accounting/audit firms worldwide in 2024 URL: https://www.statista.com/statistics/250503/big-four-accounting-firms-number-of-employees

[15] Revenue of the Big Four accounting/audit firms worldwide in 2024 URL: https://www.statista.com/statistics/250479/big-four-accounting-firms-global-revenue

[16] Rozgina, L. (2018). The Latvian audit services market: Current issues and challenges. *Forum Scientiae Oeconomia,* Volume 6(4), Pp. 7–21. https://doi.org/10.23762/FSO_VOL6_NO4_1

[17] Semenova, S., Shpyrko, O., & Ziabchenkova, G. (2023). The market of audit services of the Federal Republic of Germany. *Foreign trade: economics, finance, law,* 126(1), Pp. 108–126. https://doi.org/10.31617/3.2023(126)09

[18] Share of fee income of the leading accounting firms in the world in 2022, by service line URL: https://www.statista.com/statistics/784452/global-accounting-firms-fee-income-breakdown/

[19] Sian, S., Agrizzi, D., Wright, T., & Alsalloom, A. (2020). Negotiating constraints in international audit firms in Saudi Arabia: Exploring the interaction of gender, politics and religion. *Accounting, Organizations and Society*, *84*, 101103. https://doi.org/10.1016/j.aos.2020.101103

[20] Vickneswaran, A. (2025). The Future of Auditing — Aligning International Audit Practices With Global Trade Needs. In L. Vardari & I. Qabrati (Eds.), *Aligning Financial Reporting Standards With Global Trade Needs* (pp. 287–316). IGI Global Scientific Publishing. https://doi.org/10.4018/979-8-3373-0887-6.ch010

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АНАЛІЗ СВІТОВОГО РИНКУ АУДИТОРСЬКИХ ПОСЛУГ: ЕМПІРИЧНИЙ ДОСВІД ПРОВІДНИХ МІЖНАРОДНИХ АУДИТОРСЬКИХ КОМПАНІЙ

Анотація. *Розвиток світового фондового ринку, законодавчий захист інвесторів, вимоги фондових бірж, надання консалтингових послуг та послуг у сфері оподаткування ставлять певні вимоги до ринку аудиторських послуг, які надають у всьому світі аудиторські компанії. Вищевказане потребує аналізу ринку аудиторських послуг, які надаються провідними аудиторськими компаніями світу.*

Метою статті є аналіз світового ринку аудиторських послуг провідними аудиторськими компаніями.

Емпірічною базою забезпечення доказовості теоретичних положень, достовірності висновків та рекомендацій стали аналітичні огляди та інформація міжнародних інституцій та професійних бухгалтерських та аудиторських організацій щодо ринку аудиторських послуг та діяльності аудиторських компаній у світі.

Методологію дослідження становлять загальнонаукові і спеціальні методи вивчення процесів і явищ у їх взаємозв'язку і розвитку, а саме: діалектичний метод, синтез, індукцію і дедукцію, узагальнення, метод асоціацій та аналогій, компаративний аналіз, прогнозування, табличний та графічний методи.

Аналіз показав, що «велика четвірка» — PwC, EY, KPMG і Deloitte — забезпечує приблизно 90% доходів світового ринку аудиту, зберігаючи свої лідируючі позиції завдяки глобальним мережам, масштабам діяльності та широкій диверсифікації послуг. Deloitte лідирує за доходами та кількістю співробітників, підтверджуючи свою стратегічну орієнтацію на консалтинг і цифрові рішення.

Динаміка доходів «великої четвірки» у 2009–2024 роках показує поступове зростання з прискоренням у 2021–2024 роках, що зумовлено цифровізацією, попитом на нові види консалтингу та глобальною увагою до прозорості бізнесу. Прогноз на 2025–2027 роки вказує на те, що позитивна тенденція продовжиться, із середнім щорічним зростанням близько 7%.

Ключові слова: *аналіз, аналіз господарської діяльності, аудит, міжнародний аудит, аудит в зарубіжних країнах, аудиторські послуги, консалтинг, аудиторський консалтинг, велика четвірка, аудиторські компанії, ринок аудиторських послуг.*

JEL: G01, G21, E32

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FINANCIAL SECURITY OF BANKS AND THEIR SENSITIVITY TO ACCELERATING ECONOMIC CYCLICALITY

Abstract. *The modern economy is characterized by accelerating cyclicality, which increases risks for the banking sector, which is the key to macroeconomic stability. For Ukraine, in the context of constant economic turmoil and martial law, the issue of financial security of banks and their sensitivity to cyclical fluctuations is particularly acute. Studies linking the financial security of banks to the dynamics of the economic cycle are fragmentary, which necessitates a comprehensive analysis.*

The study uses linear VAR modeling, Granger causality test, Kilian bootstrap method, and GIRF impulse response decomposition. Quarterly statistical data for the period 2009q1–2025q1 were used for the modeling, including the financial cycle indicator, the share of loans to GDP, profitability, the share of non-performing assets, and the loan-to-deposit ratio.

The modeling showed that the direct impact of the acceleration of cyclicality on the safety and efficiency of banking activities is mixed. In the short term (up to one year), financial cycle shocks depress bank profitability, while in the long term (after one and a half years) they contribute to its recovery. An increase in the share of loans in GDP temporarily worsens the liquidity of the banking system. The most sensitive to cyclical fluctuations were the return on assets and capital, as well as the share of non-performing assets.

The scientific novelty lies in the construction and empirical modeling of a system of relationships between the financial cycle and financial security indicators of Ukrainian banks, which allowed to quantify their sensitivity to macroeconomic fluctuations and identify the nonlinear nature of their impact.

The results of the study can be used by the NBU to improve its macroprudential policy, in particular to calibrate the countercyclical capital buffer. Banking institutions can apply the findings to develop more effective risk management strategies and increase their resilience to cyclical shocks. Prospects for further research include the development of an integrated stress-testing model taking into account macroeconomic cycles, analysis of the impact of FinTech and ESG factors on the cyclical stability of banks, as well as a comparative analysis of strategies to improve financial security in countries with different levels of development.

Keywords: *financial security, banking sector, economic cyclicality, VAR modeling, macroprudential policy, stress testing, bank sensitivity, financial cycle.*

1. Introduction

The banking sector is critical to the functioning of any economy. Its financial security is key to macroeconomic stability, ensuring the smooth functioning of financial markets and supporting economic growth. Today's global economy is characterized by accelerating and intensifying economic cycles, which makes banks, as the main financial intermediaries, particularly vulnerable.

Global experience (e.g., the 2008 crisis or the effects of COVID-19) has clearly shown that problems in the banking sector can quickly transform into systemic crises with devastating consequences for the real economy and households' welfare. In response to previous crises, international and national regulators have continuously reviewed and tightened capital, liquidity and risk management requirements for banks.

For Ukraine, as an emerging economy with a history of periodic economic shocks, exacerbated by the prolonged martial law, the issue of financial security of banks in the context of cyclicality is particularly acute and requires constant monitoring and analysis.

The purpose of the article is to substantiate the mechanisms for enhancing the financial security of banks in the context of accelerating economic cyclicality by assessing their sensitivity to macroeconomic fluctuations and developing recommendations for adaptation.

Modeling the assessment of the level of financial security of banks and determining their sensitivity to the acceleration of economic cyclicality is not a widespread topic in modern scientific research. sources. The scientific community pays more attention to the methodology of integrated assessment of the financial security of the state through the influence of the monetary system, macroprudential analysis and forecasting, assessment of financial stability indicators, formation of algorithms for determining the level of financial security of individual banking institutions, etc. However, their scientific works are appropriate for the realization of the goal in the presented study.

Thus, the scientific work of Arefiev *et al.,* [1], by calculating key financial stability ratios, investigates how financial stability and the ability to innovate can be integrated into the security and development strategies of banking institutions. The authors prove how the application of a security-oriented business model allows banks not only to maintain their sustainability in a competitive environment, but also to effectively integrate innovative development strategies. Noteworthy is the study conducted by Guzman-Garzon, *et al.,* [2], which presents the CAMEL Partial Triad Analysis (CPTA) model, which combines the CAMEL methodology with the Partial Triad Analysis (PTA) to assess financial indicators to determine the levels of risk of losing a safe level of banking business. Guzman-Garzon, *et al.,* [2], on the example of Ecuador, evaluated banking scenarios in the context of financial turbulence. The presented model revealed significant fluctuations in three key periods: pre-pandemic, pandemic, and the territorial crisis between russia and Ukraine. Gungoraydinoglu and Öztekin, [3], measuring "financial cyclicality", proved that countercyclicality occurs in debt, and procyclicality in securities issuance and debt maturity. The authors emphasize that financial countercyclicality due to debt is more pronounced in countries with weaker banking regulation. Kovalenko, *et al.,* [4], considered the impact of economic cyclicality on the financial security of the state through the impulses of changes in monetary policy. The authors proposed to determine this impact based on the calculation of the financial stress index. Based on the results of the economic and mathematical modeling, it was found that the most influential indicators of the monetary component on the financial stress index are the consumer price index; producer price index; gross domestic product to monetary aggregate M2; cash to GDP; share of foreign currency in monetary aggregate M3; NBU discount rate (average annual); NPL level.

If we consider publications that relate specifically to the assessment of financial security of banks, we should note the scientific work of Zhyvko *et al*., [5], who proposed a model of integrated assessment of the level of financial security of banks based on a value-based approach, which takes into account five groups of indicators — capital and resource, credit and investment, financial and productive, currency and monetary security of the bank. The authors propose to form a value-oriented bank strategy based on the level of its financial security. To this end, the authors used the GAP method to identify the causes of deviations in the level of financial security, which allowed them to identify the components that have the greatest impact on the level of security and the value of the bank. Romanovska and Parshyvliuk, [5], proposed an integral assessment of the financial security of banks based on the use of two groups of indicators — indicators that characterize the efficiency of the bank's activities; indicators that characterize the level of its security and ability to withstand crisis phenomena. Karcheva, [6], to assess the financial security potential of banks, developed a generalized indicator that is calculated on the basis of risk assessment and the existing strength potential of the bank. The author also proposed a mechanism for using early warning signals that take into account the dynamics and variability of liquidity and performance of banks. Baranovskyy *et al*., [7], based on the use of the taxonomy method, proposed a methodology for assessing the level of financial security of a bank based on the analysis of indicators-stimulators/destimulators of a solvent bank and comparison with the indicators of a "reference" bankrupt bank. The presented methodology makes it possible to clean up statistical data using the interquartile range.

Regarding the cyclicality of the economy itself, attention should be paid to the scientific work of Akaev and Sadovnichii, [8], who use the example of the US economy to show how the COVID-19 pandemic changed its short-term dynamics, causing a deep crisis recession in 2020, rather than the expected short-term

and shallow recession in 2022 caused by the inflating of a financial bubble during credit expansion. To predict the scenario of further economic development, the authors developed a model based on the Hyman Minsky theory of financial instability, which can serve to manage the processes of credit expansion and contraction in an unstable economy. Kakar Shayan Khan, [9], studied the relationship between the circular economy, sustainable infrastructure, and green financial technologies using the method of time-specific heterogeneous factor analysis for 39 European countries. Gallegati, [10], using data on global GDP growth rates for the period 1871–2016, developed a system for dating long wave phases based on a systematic temporal relationship between cyclical representations in growth rates and levels. The proposed methodology allows for an objective periodization of long waves, which is much more relevant than the one based on the phase-growth approach.

In general, the critical analysis of scientific developments on the issues raised suggests that they are characterized by a certain fragmentation in terms of assessing the level of financial security of banks and their response to the acceleration of economic cyclicality. Nevertheless, the authors of the article use some of the methodological approaches of the above-mentioned scientific works.

2. Materials and Methods

The variety of approaches to assessing the level of financial security of banks gives grounds to hypothesize that such an assessment should be based on the definition of a financial stress indicator. To assess the sensitivity of banks to the acceleration of economic cyclicality, the authors used the linear VAR method, Granger causality test, the Kilian boost method, and GIRF impulse response decomposition.

The sensitivity of bank performance indicators to the acceleration of economic cyclicality should be measured empirically, considering the dynamics of the financial cycle and the performance of the banking system as an interconnected system of endogenous factors. Considering the purpose of this study, the sample of variables should be selected taking into account the availability of relevant information and the specifics of the data used to generate time series. The selected indicators and their characteristics are presented in Table 1.

Table 1 shows that the sample is formed on the principle of representing the impact of cyclicality (FCI, CGDP), bank performance indicators (NIM, ROA, ROE), and indicators of financial security of banks (NPL, LTD). Since the sample period includes the time of the full-scale invasion of Ukraine, to account for the exogenous effects of this event, we introduce a dummy variable that takes the value “1.0” in the period 2022q1–2025q1.

To study the dynamics of these indicators, we used quarterly statistical data for the retrospective period 2009q1–2025q1. The values of the indicators during the retrospective period are shown in Table 2.

The main descriptive statistics of the variable series are presented in Table 3.

Table 3 suggests that ROA and ROE series have the least normal distribution, which are also characterized by high variability and a significant number of negative extremes. This is explained by the specifics of the formation of the indicators, since the net financial position involved in their calculation is determined at the end of the year and tends to pendulum dynamics in the intervening quarters. In addition, due to the specifics of taxation of the banking business (in particular, over the past two years), positive results that may appear within the year are significantly redistributed in the fourth quarters, which has a significant impact on descriptive statistics. At the same time, FCI and NPL are the most symmetrical and close to a normal distribution.

3. Results and Discussion

Given the relatively small sample size with a significant number of variables, for the primary estimation, a standard VAR (1 1) was built and the Granger Causality/Block Exogeneity Wald Test was implemented, the results of which allowed us to conceptualize the system of causal relationships between the variables (Fig. 1).

Table 1

Composition and characteristics of the sample for modeling

Indicator	Symbol	Frequency and sampling period	Series transformation	Order of integration of the transformed series
Financial cycle index	FCI	quarterly, 2009q1–2025q1	–	I(1)
Share of loans in GDP	CGDP		seasonal adjustment (TRAMO/SEATS)	I(1)
Net interest margin	NIM			I(1)
Return on assets	ROA			I(0)
Return on capital	ROE			I(0)
Share of non-performing assets	NPL		–	I(1)
Loan-to-deposit ratio	LTD		–	I(1)
Full-scale invasion period (fictitious variable)	WAR		–	–

Source: Combination of indicators proposed by the authors

Table 2

Dynamics of financial security indicators

Period	GDP	NIM	ROA	ROE	NPL	LTD	WAR
2009q1	0,9873	0,0161	-0,0081	-0,0600	0,0666	2,1952	0
2009q2	0,9071	0,0317	-0,0166	-0,1272	0,0902	2,1545	0
2009q3	0,9054	0,0470	-0,0235	-0,1775	0,0987	2,1348	0
2009q4	1,0647	0,0607	-0,0358	-0,2620	0,1410	2,2980	0
2010q1	1,1484	0,0138	-0,0051	-0,0349	0,1556	2,0310	0
2010q2	1,1936	0,0268	-0,0094	-0,0653	0,1650	1,8764	0
2010q3	1,2003	0,0422	-0,0109	-0,0753	0,1658	1,7857	0
2010q4	1,1784	0,0558	-0,0138	-0,0892	0,1704	1,8204	0
2011q1	1,1913	0,0142	-0,0002	-0,0015	0,1711	1,6229	0
2011q2	1,2142	0,0261	-0,0010	-0,0072	0,1705	1,5796	0
2011q3	1,2265	0,0392	-0,0055	-0,0371	0,1758	1,6085	0
2011q4	1,1840	0,0517	-0,0073	-0,0496	0,1765	1,6761	0
2012q1	1,1304	0,0116	0,0019	0,0129	0,1837	1,2528	0
2012q2	1,1151	0,0228	0,0014	0,0095	0,1752	1,2473	0
2012q3	1,0505	0,0350	0,0025	0,0167	0,1758	1,2200	0
2012q4	1,0458	0,0346	0,0043	0,0288	0,1941	1,4391	0
2013q1	1,0391	0,0103	0,0032	0,0212	0,1936	1,1341	0
2013q2	1,0255	0,0211	0,0010	0,0067	0,1930	1,1056	0
2013q3	1,0281	0,0311	0,0014	0,0097	0,1752	1,1025	0
2013q4	1,0775	0,0410	0,0011	0,0075	0,1639	1,3630	0
2014q1	1,0433	0,0119	-0,0015	-0,0109	0,1543	1,2321	0
2014q2	1,0777	0,0226	0,0010	0,0070	0,1607	1,2480	0
2014q3	1,1067	0,0334	-0,0081	-0,0583	0,1831	1,2251	0
2014q4	1,0942	0,0435	-0,0399	-0,3544	0,2207	1,4849	0
2015q1	1,1864	0,0101	-0,0562	-0,5928	0,2443	1,2167	0
2015q2	1,1944	0,0203	-0,0245	-0,2189	0,2501	1,1367	0
2015q3	1,2872	0,0341	-0,0433	-0,4058	0,2925	1,0656	0
2015q4	1,3169	0,0352	-0,0589	-0,7675	0,3177	0,9314	0
2016q1	1,2109	0,0093	-0,0066	-0,0639	0,3289	0,9043	0
2016q2	1,1729	0,0187	-0,0073	-0,0636	0,3385	0,8264	0
2016q3	1,1842	0,0371	-0,1275	-1,2813	0,3313	0,6457	0
2016q4	1,2277	0,0371	-0,1582	-1,6852	0,4951	0,6355	0
2017q1	1,2997	0,0095	0,0033	0,0274	0,5448	0,6060	0
2017q2	1,2401	0,0198	-0,0014	-0,0127	0,5616	0,5842	0
2017q3	1,2415	0,0300	0,0011	0,0083	0,5346	0,6039	0
2017q4	1,2332	0,0175	-0,0131	-0,1552	0,5223	0,6036	0
2018q1	1,1933	0,0089	0,0047	0,0545	0,5369	0,5860	0
2018q2	1,2192	0,0177	0,0045	0,0579	0,5234	0,5599	0
2018q3	1,1932	0,0266	0,0056	0,0758	0,5060	0,5928	0
2018q4	1,1772	0,0379	0,0117	0,1442	0,4894	0,6124	0
2019q1	1,1612	0,0103	0,0068	0,0753	0,4751	0,5949	0
2019q2	1,1513	0,0208	0,0164	0,1864	0,4689	0,5832	0
2019q3	1,1179	0,0316	0,0258	0,2599	0,4534	0,5670	0
2019q4	1,0603	0,0409	0,0294	0,2919	0,4576	0,5124	0
2020q1	1,0468	0,0102	0,0077	0,0783	0,4615	0,5043	0
2020q2	0,9437	0,0196	0,0114	0,1208	0,4558	0,7741	0
2020q3	1,0550	0,0291	0,0173	0,1807	0,4293	0,4479	0

Continuation of the table 2

2020q4	1,1778	0,0388	0,0180	0,1897	0,3783	0,4326	0
2021q1	1,1879	0,0115	0,0049	0,0505	0,3671	0,4351	0
2021q2	1,3437	0,0240	0,0134	0,1440	0,3400	0,4540	0
2021q3	1,2896	0,0372	0,0227	0,2230	0,3023	0,4948	0
2021q4	1,3246	0,0509	0,0328	0,3028	0,2726	0,4981	0
2022q1	1,0686	0,0142	-0,0001	-0,0007	0,2721	0,5291	1
2022q2	0,8686	0,0289	-0,0020	-0,0201	0,2979	0,4712	1
2022q3	0,9579	0,0432	0,0029	0,0348	0,3366	0,4278	1
2022q4	0,9362	0,0578	0,0081	0,1016	0,3814	0,3557	1
2023q1	1,2739	0,0168	0,0123	0,1376	0,3880	0,3241	1
2023q2	1,4443	0,0327	0,0231	0,2527	0,3895	0,2979	1
2023q3	1,2473	0,0494	0,0366	0,3534	0,3786	0,3028	1
2023q4	1,1992	0,0638	0,0251	0,2805	0,3734	0,2819	1
2024q1	1,1738	0,0167	0,0119	0,1176	0,3606	0,2861	1
2024q2	1,1749	0,0330	0,0226	0,2226	0,3455	0,2905	1
2024q3	1,1575	0,0490	0,0330	0,2991	0,3232	0,3077	1
2024q4	1,1259	0,0641	0,0241	0,2468	0,3027	0,2919	1
2025q1	1,1803	0,0168	0,0105	0,0974	0,2857	0,3095	1

Source: calculated by the authors using https://bank.gov.ua/

Table 3

Descriptive statistics of variable series

Indicator	FCI	CGDP	NIM	ROA	ROE	NPL	LTD
Arithmetic mean	0,022	1,370	0,030	-0,003	-0,030	0,308	0,934
Median	-0,100	0,758	0,028	0,002	0,019	0,303	0,635
Maximum	0,607	3,457	0,041	0,027	0,265	0,562	2,298
Minimum	-0,366	0,387	0,004	-0,156	-1,626	0,067	0,282
Standard deviation	0,246	0,963	0,007	0,030	0,294	0,135	0,576
Asymmetry coefficient	0,260	0,592	-0,377	-3,030	-3,085	0,212	0,771
Excess coefficient	1,906	1,896	3,994	14,712	15,953	1,887	2,462
Harkey-Bera test	3,970	7,103**	4,217	470,995***	557,495***	3,841	7,226**
Number of observations	65	65	65	65	65	65	65

Note: *, **, *** — significance at 10%, 5% and 1% respectively

Source: calculated by the authors

In Figure 1, the NIM variable is not labeled, as it is completely exogenous to the model. The two cyclicality indicators are interrelated and influence each other. The share of loans in GDP determines the ratio of loans to deposits in the system, and this is the only connection between the latter variable and the others, which also indicates its almost exogenous nature, which is explained by the regulatory nature of its formation due to consistent long-term supervision of the level of bank liquidity and tightening of requirements for it. The financial cycle index transmits its influence through three channels simultaneously: through the share of non-performing assets and further to profitability indicators, directly to ROA with the transition to NPL, and directly to ROE. This confirms the key, integral nature of this variable for the model.

In view of the above, the model was re-estimated by transferring the NIM variable to exogenous components. This allowed us to improve the determinacy of the model and reduce the risk of overfitting. A further study of the quality of the reestimated model showed its stationarity, but the previously identified non-normal distribution of some variables justifies the need to use bootstrap methods to build confidence intervals for impulse functions. Therefore, we used a neutral bootstrap according to Kilian with 999 single and 300 double replications. The problems with the distribution of residuals also dictate the need to use a generalized method of decomposition of impulses (instead of the ordered Cholesky decomposition). The impulse functions were estimated cumulatively over a horizon of 12 periods (3 years).

For the sake of clarity, it is advisable to consider the responses on the medium (1–6 periods) and long-term (7–12 periods) horizons separately for each variable (Fig. 2).

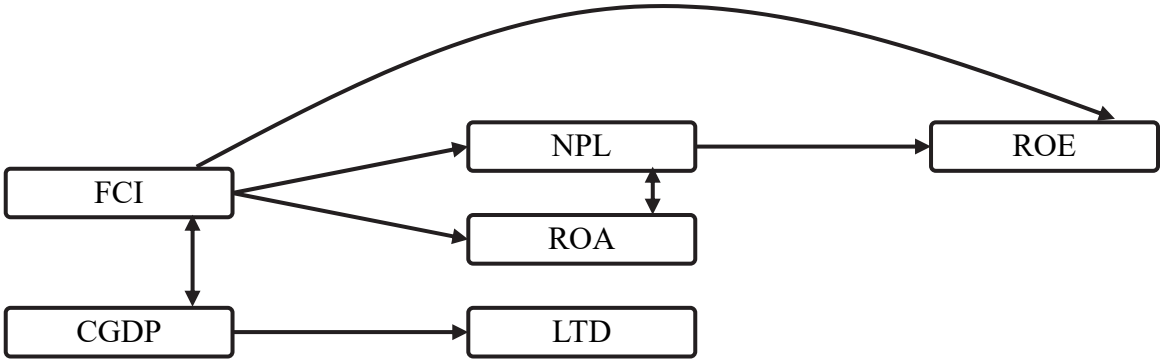

Figure 1. System of relationships between variables in the VAR model

Source: calculated by the authors

Decomposing the responses of the variables into impulses by duration, as shown in Figure 2, allows us to identify commonalities and differences in shocks over time. For example, an increase in the share of loans in GDP during the first half of the year causes a temporary deterioration in liquidity, but starting in Q3, due to the catch-up of savings, the ratio gradually levels off (albeit over time).

The acceleration of the financial cycle also has a negative impact on the level of non-performing assets, leading to an increase in their share during the first three quarters, but subsequently contributes to their steady decline. At the same time, the growth in return on assets has a positive impact on the quality of the loan portfolio only in the first six months, and then gradually rolls back the positive effect.

The acceleration of the financial cycle also has a rather contradictory effect on profitability indicators, immediately worsening them: in relation to assets — by six months, in relation to equity — by 3 quarters. Subsequently, profitability levels off and even starts to grow in Q6, a year and a half after the first shock. The

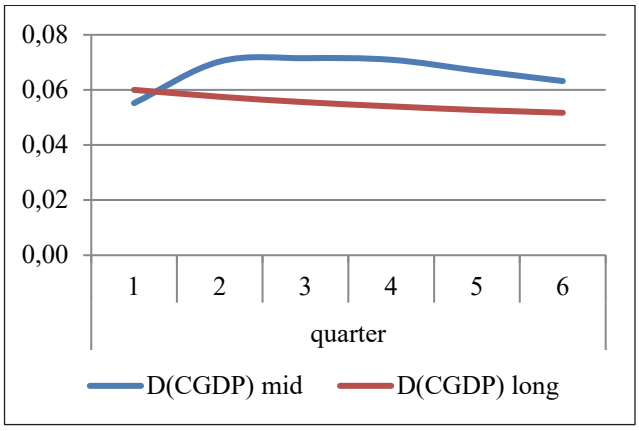

Figure 2.1. Loan-to-deposit ratio

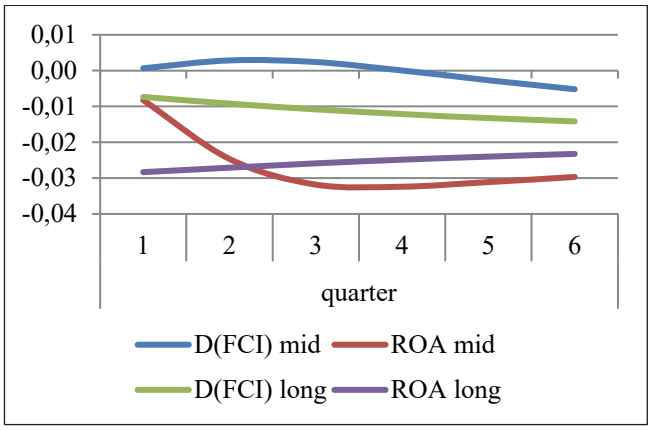

Figure 2.2. Share of non-performing assets

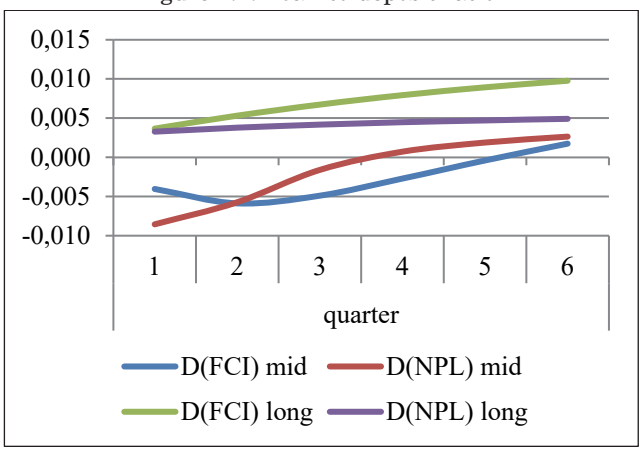

Figure 2.3. Return on assets

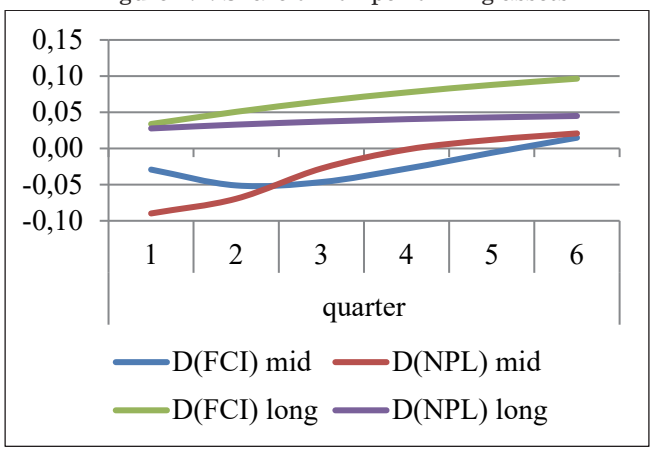

Figure 2.4. Return on capital

Figure 2. Impulse functions of the revalued model variables

Source: calculated by the authors

impact of the share of NPLs on profitability is non-linear, as the deterioration in banking performance is observed in a relatively short period of time — up to 1 year — and then the increase in NPLs statistically contributes to higher profitability. This can be explained by the immediate realization and short-term consequences of credit risk, which is fully offset by banks within a year and subsequently becomes a normal part of their financial model until the withdrawal of bad assets.

In general, the modeling showed a direct impact of the cyclical acceleration on the safety and efficiency of banking activities, which has a mixed nature and complex dynamics. In particular, in the short run, financial cycle shocks depress profitability, but in the long run they stimulate a recovery in capital productivity. The strengthening of lending in the national economy has a rather threatening effect on the banking system, as it stimulates active lending policy, but on the other hand, gradually leads financial institutions to credit expansion and liquidity loss.

Today, to overcome the negative impact of economic cyclicality on the banking business, there is a need to find new approaches to develop integrated stress testing models that consider the interaction of macroeconomic shocks, specific banking risks, and financial market reactions. Such models will allow forecasting the impact of different scenarios of the economic cycle (e.g., a sharp downturn, a prolonged recession, a rapid recovery) on key indicators of financial security of banks (capital adequacy, liquidity, loan portfolio quality, profitability). The model should take into account the interrelationships between the real sector, financial markets, and the banking sector. From this point of view, the macroeconomic model proposed by Djeundje and Crookthan, [11], is of interest, which is based on modeling both behavioral and macroeconomic variables in the future, while maintaining the correlation structure between them, to obtain a more comprehensive modeling methodology for loan portfolio stress testing. Cibák, *et al*., [12], substantiated the interaction of banking risks in crisis periods on the basis of empirical evaluation of data from post-Soviet countries. The proposed methodological approach is useful for regulators in justifying micro- and macroprudential policy instruments. When developing stress testing models, one should be guided by the fundamental document of the Basel Committee on Banking Supervision (BCBS) "Principles for sound stress testing practices and supervision", [13], although it is from 2009, the principles remain relevant, and further recommendations are based on it.

A controversial issue among the scientific community and practitioners is the impact of the latest financial technologies (FinTech, AI, Blockchain) on the cyclical stability and financial security of banks. Teslyuk, *et al*., [14], emphasize the need to create a separate structural unit in banking institutions that is able to manage network risks associated with the introduction of digital banking technologies. The authors of Sytnyk and Polovchak, [15], emphasize the importance of introducing measures based on advanced digital technologies that guarantee information security to banks to maintain stability and protect the banking system under martial law. Azarenkov, [16], identified the key areas for the formation of an effective cyber defense system — the use of a holistic approach to cyber defense, integrating risk management with technological innovations and the development of professional competencies of bank employees.

The modern cycle of national economies is linked by the latest concept of sustainable development. Therefore, there is a need to further analyze the integration of ESG factors into banks' business models and their impact on cyclical sustainability and financial security. Garrido-Merch, *et al*., [17], based on the use of Bayesian optimization, formed a model for building ESG portfolios based on a combination of risk-return analysis and ESG constraints. Lannone, *et al*., [18], investigated the sustainability of investments in environmental, social and governance aspects in times of financial instability. It was proved that ESG portfolios dominate traditional ones during market turmoil and are necessary in the formation of long-term investment strategies of financial institutions. Interesting from this point of view is the study conducted by Savluk, *et al*., [18], who empirically proved that investment lending by banks affects the reduction of greenhouse gas emissions. This was confirmed by the example of France and Poland in 2001–2014. Changes in trends in 2015–2018 are explained by an increase in CO2 emissions. The authors conclude that countries that have made the transition from administrative to market economies pay less attention to the environmental aspect of investment lending, as they focus on commercializing the economy.

In order to formulate strategic directions in Ukraine, it is advisable to conduct a comparative analysis of strategies for improving the financial security of banks in the context of cyclicality in countries with different levels of economic development (Table 3).

Ukraine, as an emerging market country, faces many challenges typical of EMDEs (capital volatility, dependence on commodities, geopolitical risks). Therefore, it needs to further implement Basel III; effectively use countercyclical instruments (calibration of CCyB, LTV/DTI instruments taking into account the specifics of the Ukrainian credit cycle); strengthen currency risk management; improve the mechanisms of rehabilitation and liquidation; and enable the NBU to make complex decisions independently.

4. Conclusions

Based on the study, the author substantiates the mechanisms for improving the financial security of banks in the context of accelerating economic cyclicality by assessing their sensitivity to macroeconomic fluctuations. The modeled system of interrelations between the financial cycle and banking performance indicators allows us to draw the following conclusions.

First, the study confirms that the acceleration of the financial cycle has a direct and mixed impact on

Table 3

Comparative analysis of strategies for improving the financial security of banks in cyclical conditions in countries with different levels of economic development

Comparison aspect	Developed economies (DEs)	Developing countries and emerging markets (EMDEs)
Economic and market characteristics	Mature, diversified financial markets; high institutional development; developed regulation; more stable capital flows.	Less developed but rapidly growing markets; lower institutional development; greater dependence on raw materials/external factors; volatile capital flows.
Key cyclical challenges	Systemic risks (too-big-to-fail); low interest rate risks (search for yield); digital/cyber risks; global interdependence.	Volatility of capital flows; dependence on raw materials; "twin deficits"; underdeveloped financial markets; dollarization; political and institutional instability.
Macroprudential policy		
Countercyclical capital buffer (CCyB)	Well-developed mechanisms, calibration based on credit cycle indicators.	More complex implementation due to data volatility, may be less flexible.
LTV/DTI restrictions	Widely used to cool real estate markets.	Very effective for countries with rapid growth in real estate lending.
Capital flow management (CFMs)	Not typically used (preference for free movement of capital).	Often used to mitigate sudden inflows/outflows (taxes, restrictions).
Currency position limits	Less critical, foreign currency liquidity markets are well developed.	An extremely important tool for combating currency risk and dollarization.
Microprudential regulation and supervision		
Basel III requirements (Capital, Liquidity)	Adequate CET1 level; strict compliance with LCR, NSFR.	Continuous capital strengthening; adaptation of LCR/NSFR requirements to local conditions and data.
Stress testing	Complex models, significant resources, and experience.	Limited resources and data, requiring adaptation of methodologies.
Credit risk management	Focus on complex models, ratings, securitization.	Greater focus on sectoral risks (raw materials), collateral adequacy, and credit concentration.
Institutional development and policy		
Central bank/regulator independence	A high level of independence allows for complex decisions to be made.	May be limited by political interference.
Effectiveness of bank resolution systems	Developed mechanisms (bail-in, Resolution Funds) for quick and effective resolution.	Implementation challenges due to weak legal system, limited resources.
International cooperation	Active participation in the development of global standards.	Growing participation, emphasis on adapting standards and addressing specific issues.

Source: systematized by authors, Öztekin [3]; Savluk, et al., [18]; IMF [20]; Suhail [21]; BIS [22]

the financial security and efficiency of the Ukrainian banking system. In particular, in the short term (up to a year), financial cycle shocks depress banks' profitability (ROA, ROE), which is manifested in a temporary deterioration in financial performance. However, in the long run (after a year and a half), these same shocks contribute to the recovery of capital productivity. This non-linear relationship emphasizes the difficulty of banks adapting to the dynamics of economic fluctuations.

Second, the study found that increased lending in the national economy is a source of both opportunities and risks for the banking system. Active lending policy stimulates economic growth, but at the same time it can lead financial institutions to credit expansion and, as a result, to a loss of liquidity and an increase in the share of non-performing assets (NPL). The modeling showed that an increase in the share of loans to GDP temporarily worsens liquidity, but that the loan-to-deposit (LTD) ratio gradually levels off, albeit over time.

Third, the empirical analysis showed that profitability and the share of non-performing assets are the most sensitive to cyclical fluctuations. The financial cycle index turned out to be a key integral variable that affects the financial security of banks through three channels: directly on ROA and ROE, as well as through NPL. This confirms that these indicators are the most vulnerable indicators in times of macroeconomic shocks and require special attention from banks and the regulator.

Based on the analysis and comparison of international practices, the following recommendations can be formulated to improve the financial security of Ukrainian banks:

Further implementation and adaptation of macroprudential policy instruments, such as the countercyclical capital buffer (CCyB) and LTV/DTI limits, taking into account the specifics of the Ukrainian credit cycle and the volatility of economic indicators.

Developing integrated stress testing models that consider the interaction of macroeconomic shocks, specific banking risks, and financial market reactions. This will allow for more effective forecasting of the impact of different economic development scenarios on key financial security indicators.

Strengthening currency risk management by tightly controlling the currency position of banks, which is especially important in the context of volatile capital flows and significant dependence on external factors typical for developing economies.

Establishing an effective system for resolving banks' problems and strengthening the institutional independence of the National Bank of Ukraine, which is the key to making timely and informed decisions in times of instability.

Thus, the results of the study indicate that in order to ensure the stability of the banking sector in the context of accelerated economic cyclicality, a comprehensive approach is needed that combines the improvement of internal risk management mechanisms in banks with adaptive macroprudential regulation.

5. References

[1] Arefiev, S., Serpukhov, M., Blahun, I., Varava, L., Baula, O., & Zhurbenko, N. (2025). Security-oriented business model of financial management of competitive strategy of innovative development of banking system entities. *Financial and Credit Activity Problems of Theory and Practice*, (3(62)), 26–43. https://doi.org/10.55643/fcaptp.3.62.2025.4793

[2] Guzman-Garzon, Rody, Galindo-Villardon, Purificación & Vicente-Galindo, Purificación (2025). Crisis Monitoring in Financial Sectors Using CAMEL Partial Triadic Analysis Model. *IEEE Access*, (13), 15650–15682. https://doi.org/10.1109/ACCESS.2025.3528412

[3] Gungoraydinoglu, Ali, Öztekin, Özde (2022). Financial crises, banking regulations, and corporate financing patterns around the world. *International Review of Finance*, (22 (3)), 506–539. https://doi.org/10.1111/irfi.12381

[4] Kovalenko V., Slatvinska, M., Sheludko, S., Makukha, S., & Valihur, V. (2023). The monetary component in ensuring the financial security of the state. *Financial and credit activity: problems of theory and practice*. 2023. (1 (48)), 8–22. https://doi.org/10.55643/fcaptp.1.48.2023.3972

[5] Romanovska, Yu, Parshyvliuk, D. (2023). Assessment of the financial security of bakiv institutions of Ukraine *Investments: practice and experience*, (4), 96–102. https://doi.org/10.32702/2306–6814.2023.4.96

[6] Karcheva, G., Karcheva I. (2022). Theoretical and practical aspects of managing the financial and economic security of banks. *Economic Analysis*, (32 (1)), 188–198. https://doi.org/10.35774/econa2022.01.188

[7] Baranovskyy O., Kopytko M., & Barylyuk M.-M. (2018). Use of taxonomy method for evaluation of financial security of commercial bank. *Financial and credit activity: problems of theory and practice*, (1 (24)), 4–14. https://fkd.net.ua/index.php/fkd/article/view/1602/1618

[8] Akaev, A.A., Sadovnichii, V.A. (2020). Forecasting a Cyclical Downturn (Recession) in the US Economy Using a Mathematical Model of Hyman Minsky's Theory of Financial Instability. *Doklady Mathematics*, (102 (2)), 422–426. https://doi.org/10.1134/S1064562420050245

[9] Kakar, Shayan Khan, Arshed, Noman, Le Hien, Tran Thi, Akhter, Sehrish, & Abdullahi, Nazir Muhammad (2025). The impact of circular economy, sustainable infrastructure, and green FinTech on biodiversity in Europe: A holistic approach *Technology in Society*, (81), 102841. https://doi.org/10.1016/j.techsoc.2025.102841

[10] Gallegati, Marco (2019). A system for dating long wave phases in economic development. A system for dating long wave phases in economic development. *Journal of Evolutionary Economics*, (29 (3)), 803–822. https://doi.org/10.1007/s00191-019-00622-1

[11] Djeundje, Viani Biatate & Crook, Jonathan (2025). Incorporating behavioural and macroeconomic correlations for the prediction of bank capital for credit risk. *Journal of the Operational Research Society*, https://doi.org/0.1080/01605682.2025.2467774

[12] Cibák, Ľuboš, Yermachenko, V., Kovalov, A., Zherdetska, L., & Kretov, D. (2024). The relationship between banking risks under the crisis: empirical assessment post-soviet countries data. *Financial and Credit Activity Problems of Theory and Practice*, (6(59)), 37–49. https://doi.org/10.55643/fcaptp.6.59.2024.4531

[13] Basel Committee on Banking Supervision (2009). Principles for sound stress testing practices and supervision. https://www.bis.org/publ/bcbs155.pdf.

[14] Teslyuk, S.A., Matviychuk, N.M., & Levchuk, A.O. (2024). Financial security of banking institutions in the context of digitalization, *Economy and Society*, (60). https://doi.org/10.32782/2524-0072/2024-60-117.

[15] Sytnyk, N., Polovchak, I. (2024). Digitization and cyber security in ensuring the banks security in wartime conditions. *Galician Economic Bulletin*, (4 (89)), 70–81. https://doi.org/10.33108/galicianvisnyk_tntu2024.04.070

[16] Azarenov, S. (2025). Cybersecurity and Security of the Banking Business Under Martial Law. *Fancial and credit systems: prospects for development*, (1 (16)), 9–19. https://doi.org/10.26565/2786-4995-2025-1-01.

[17] Eduardo, C. Garrido-Merch´an Bayesian, Gabriel Gonz´alez Piris, & Maria Coronado Vaca (2023). Optimization of ESG Financial Investments. Portfolio Management (q-fin.PM). [Submitted on 10 Feb 2023] https://arxiv.org/pdf/2303.01485

[18] Lannone, B. Duttilo, P., & Gattone, S.A. (2025). Evaluating the resilience of ESG investments in European markets during turmoil periods. Statistical Finance (q-fin.ST). Submitted on 4 Jan 2025. https://arxiv.org/pdf/2501.03269

[19] Savluk, S., Shulga, N., Zherdetska, L., & Serazhym, Y. (2025). Environmental determination of banks investment lending in the EU. *Financial and Credit Activity Problems of Theory and Practice*, (1(60), 11–19. https://doi.org/10.55643/fcaptp.1.60.2025.4549

[20] IMF (2025). Global Financial Stability Report. https://www.imf.org/en/publications/gfsr

[21] Rizwan, Muhammad Suhail (2021). Macroprudential regulations and systemic risk: Does the one-size-fits-all approach work? *Journal of International Financial Markets, Institutions and Money*, (74), 101409. https://doi.org/10.1016/j.intfin.2021.101409

[22] BIS (2025). Basel III Monitoring Report. https://www.bis.org/bcbs/publ/d592.pdf.

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ФІНАНСОВА БЕЗПЕКА БАНКІВ ТА ЇХ ЧУТЛИВІСТЬ ДО АКСЕЛЕРАЦІЇ ЦИКЛІЧНОСТІ ЕКОНОМІКИ

Анотація. *Сучасна економіка характеризується прискоренням циклічності, що посилює ризики для банківського сектору, який є запорукою макроекономічної стабільності. Для України, в умовах постійних економічних потрясінь та воєнного стану, питання фінансової безпеки банків та їх чутливості до циклічних коливань є особливо гострим. Дослідження, що пов'язують фінансову безпеку банків з динамікою економічного циклу, є фрагментарними, що обумовлює необхідність комплексного аналізу.*

У дослідженні використано методи лінійного VAR-моделювання, тест на причинність за Грейнджером, бутстреп-метод за Кіліаном та GIRF-декомпозицію імпульсного відгуку. Для моделювання використовувались щоквартальні статистичні дані за період 2009q1–2025q1, включаючи індикатор фінансового циклу, частку кредитів у ВВП, показники рентабельності, частку непрацюючих активів та співвідношення кредитів до депозитів.

Моделювання засвідчило прямий вплив акселерації циклічності на безпеку та ефективність банківської діяльності, який має змішаний характер. У короткостроковому періоді (до одного року) шоки фінансового циклу пригнічують прибутковість банків, тоді як у довгостроковій перспективі (після півтора року) сприяють її відновленню. Зростання частки кредитів у ВВП тимчасово погіршує ліквідність банківської системи. Найбільш чутливими до циклічних коливань виявилися показники рентабельності активів та капіталу, а також частка непрацюючих активів.

Наукова новизна полягає у побудові та емпіричному моделюванні системи взаємозв'язків між фінансовим циклом та індикаторами фінансової безпеки українських банків, що дозволило кількісно оцінити їхню чутливість до макроекономічних коливань та виявити нелінійний характер їхнього впливу.

Результати дослідження можуть бути використані НБУ для вдосконалення макропруденційної політики, зокрема для калібрування контрциклічного буфера капіталу. Банківські установи можуть застосовувати отримані висновки для розробки більш ефективних стратегій управління ризиками та підвищення стійкості до циклічних шоків. Перспективи подальших досліджень включають розробку інтегрованої моделі стрес-тестування з урахуванням макроекономічних циклів, аналіз впливу FinTech та ESG-факторів на циклічну стійкість банків, а також порівняльний аналіз стратегій підвищення фінансової безпеки в країнах з різним рівнем розвитку.

Ключові слова*: фінансова безпека, банківський сектор, циклічність економіки, VAR-моделювання, макропруденційна політика, стрес-тестування, чутливість банків, фінансовий цикл.*

JEL: G 20; G 39; O 22; O 32

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MODERN BANKING TECHNOLOGIES IN THE CONTEXT OF PROJECT MANAGEMENT

Abstract. *The role of digital innovations and financial technologies in modern project management is constantly growing. In the context of modern geopolitical challenges, ensuring the stability of financial systems is becoming increasingly important. This study examines the prospects for integrating modern banking technologies into project management as a means of improving financial decision-making, increasing operational efficiency and strengthening project security.*

The article reviews a number of approaches by scholars to the development of fintech technologies, such as artificial intelligence, blockchain, big data and digital customer identification, while highlighting the gap in practical, project-oriented financial tools. Methodologically, the study conducts a functional analysis of widely used project management tools and assesses their potential integration with financial technologies, including electronic digital signatures, API-based banking services and automated financial transactions. Special attention is paid to the adaptation of the GIT version control system to form a matrix of permissible project budgets, which allows generating and comparing several financial scenarios.

The results show that integrating digital banking solutions into project management systems increases security, speeds up financial processes, and supports more informed management decisions. Moreover, such integration complies with the principles of constraints, reducing costs and increasing efficiency without changing the time or scope of the project. The study concludes that combining existing digital financial tools with project management platforms is a promising direction for further research and practical application, offering significant potential for increasing the technological maturity and sustainability of modern projects.

Keywords: *project management, financial management, fintech, digital banking technologies, artificial intelligence, GIT version control, digital transformation.*

1. Introduction

The level of economic development of any system, ranging from the micro- to the macro-level, depends on innovation and the extent to which modern technologies are utilized, which, in turn, require adequate financial support. The implementation of such financial mechanisms is primarily the responsibility of banking institutions and alternative entities within the country's financial sector. Under current adverse geopolitical conditions — including military aggression and hybrid warfare — the issue of maintaining the stability of all financial mechanisms that support innovation and ensure the functioning of the economy as a whole becomes even more critical. The use of such technologies, in itself, is not an exclusive or defining characteristic of success; however, ignoring their advantages leads to a decline in competitiveness, efficiency, and the ability to function sustainably overall. As a result, the technological advancement of the banking sector determines the overall level of development of the financial system, to which all institutional components of the economic system must correspond. This issue

is particularly relevant for new market participants, enterprises, industries, and their subdivisions, which, by their nature, are project-based and at the stages of planning or implementation. The quality and efficiency of financial project management constitute fundamental prerequisites for the overall success of a project and for the attainment of its objectives through the most effective utilization of available and potential financial resources. One illustrative example is the growing popularity of project financing as a promising mechanism for mobilizing financial resources, especially in the implementation of large-scale investment projects. Accordingly, the application of technological innovations in contemporary financial management should be examined from two complementary perspectives: first, through the identification of prevailing trends and widely adopted technologies that demonstrate an innovative character; and second, through the determination of genuinely novel and prospective technologies, followed by the development of decision-making frameworks and practical solutions based upon them.

The purpose of this study is to identify the prospects for applying modern banking technologies in project management and to develop specific proposals for technological solutions of this kind.

The need for research in this area is further emphasized by the search for ways and methods of ensuring sustainable functioning and development across the entire sector of innovative enterprises [1]. The study of fintech innovations and the corresponding transformation of financial institutions (such as banks and insurance companies) has been addressed by Yurasova and Ivashko [2], particularly concerning the "use of artificial intelligence, blockchain, big data, and new customer service models," which represent vast areas for academic investigation. This list of technologies is typical for a wide range of scholars, including Naida and Zhekiu [3], who consider these technologies as innovative approaches to startup management, encompassing a broad spectrum of sectoral manifestations of digital transformation. A more specific and narrowly defined research focus was adopted by Zaika, Gridin, and Zaika [4], who examined the financial aspects of innovative development, sources of funding, and their adequacy for the implementation of innovative projects, while also developing mechanisms for the effective utilization of such funds as a means of enhancing the competitiveness of the economy. Similarly, Ivashkiv and Tymots [5] drew attention to the growing competition in the financial services market as a prerequisite for increasing its efficiency at the current stage of economic transformation. Nevertheless, within the extensive and multifaceted corpus of research conducted by economists, the issue of developing well-defined financial and innovation instruments for direct application in practical activities remains insufficiently addressed. While duly recognizing the scholarly contributions of the authors referenced in this article, it is important to note their shared characteristic of emphasizing the necessity of integrating advanced technologies without a specific focus on the concrete projects through which such technologies are implemented.

Among the most pertinent domains for the application of fintech solutions in management is project-based activity, where the demand for innovation and efficiency constitutes an indispensable prerequisite for achieving the anticipated results. Furthermore, it should be emphasized that one of the defining features of fintech instruments is their dynamic development and clear functional orientation. This is determined by the characteristics of potential industry development projects [6] and by the opportunities within the sphere of precise legislative regulation and unconditional compliance with confidentiality and security standards during the implementation of innovative projects.

2. Materials and Methods

A considerable number of studies by economists have examined the creation and use of modern banking service technologies without targeted specialization, or primarily focusing on the most dynamic segment — customer service. Examples include the works of Marich and Ratushnyak [7] — "Role and Place of Internet Technologies in the Development of the Banking Services System" as well as Borodenko and Haponiuk [8], who analyzed the impact of financial technologies on the activities of Ukrainian banks.

At the same time, the study of financial instruments for project implementation, specifically in light of their innovativeness and the advantages of using modern financial (mainly banking) technologies, remains extremely relevant yet underexplored. Therefore, there is a need to examine financial technologies from the perspective of different stages of project management, assessing their potential and limitations. The main criterion for the feasibility and efficiency of such innovative instruments is their viability, i.e., the possibility of practical application where the benefits outweigh the associated constraints. Another essential aspect is specialization and fine individual adaptation to specific projects or, conversely, the enhancement of their universality. However, the most important task of this research is to develop clear and concrete proposals, going beyond the general declarations of innovation, such as the often-cited advantages of applying artificial intelligence in finance. Despite numerous academic findings in this area, there remains a need for forming applied, practice-oriented recommendations that can be implemented effectively within modern financial and banking systems.

The practical toolkit for implementing project management decisions is a crucial aspect of any project's success. "Effective task organization, progress control, and communication are essential for achieving goals on time and with excellence. To facilitate this process, there is a wide range of project management tools, each offering unique advantages." [9]. Today, the use of online platforms such as Trello — a board that allows users to create lists and task cards — or its closest analogue, Monday.com, has become typical

and well-proven for project management. Other widely used services in project management include:

- Asana — for creating tasks, setting deadlines and priorities, and distributing them within a team;
- Microsoft Project — a tool for creating schedules, defining tasks and resources, managing budgets, and setting task dependencies;
- Jira — specialized in software development management, with functionality tailored to bugs, incidents, and their interrelations;
- Basecamp — designed for team communication, task allocation, and collaborative work on documents;
- TeamGantt — a specialized solution for working with Gantt charts, allowing users to create, edit, and track project timelines;
- TeamWork — a comprehensive project management tool that enables task creation, assignment of responsible persons, deadline setting, and exchange of comments and files;
- Podio — a collaborative platform combining social networking features with project management tools;
- Workzone — focused on task management and team communication, allowing discussions and plan adjustments.

The availability of such a broad range of tools enables the selection of those best suited to the specific requirements of a given project. Based on the reputation and widespread application of the aforementioned instruments, their functions can be analyzed from the perspective of their potential integration into project financial management or, conversely, the incorporation of financial functions within them — most commonly those related to interaction with banking institutions. In this way, it becomes possible to develop new, more functional instruments based on the combination of effective, proven, and secure solutions through their mutual integration.

Paradoxically, the capabilities of digital tools at the present stage extend far beyond simple duplication, offering enhanced functions, particularly in the areas of collaboration and security. A vivid example of such an innovation is the use of the electronic digital signature (EDS), which in Ukraine is currently offered as a free service for citizens who are clients of various banks (both state-owned and commercial) and users of the Diia system. To obtain an electronic signature, an individual applies to a qualified provider of trust services, fills out a registration form, and receives a set of a key file and password or the ability to sign documents online. As a result, electronically signed documents are more secure than handwritten ones, since each signature can be verified to identify the signatory. These documents also benefit from two levels of archival storage — long-term (10 years) and temporary (up to 10 years) — and possess legal validity for accounting purposes or even as admissible evidence in court proceedings. In contrast, screenshots, messaging transcripts, or printed email correspondence are not recognized by Ukrainian courts as valid evidence [10]. Therefore, in light of the above, it is reasonable to analyze the prospects for use electronic digital signatures as a financial instrument in project management. Such tool can be applied, for example, in negotiation procedures, document circulation, or when there is a need to verify financial data.

Traditional banks and government agencies are also following suit: for example, the National Bank of Ukraine and the Ministry of Digital Transformation are working together to digitize Ukraine's banking system. The result of this collaboration is accessible, world-class online services that open up new opportunities for both banks and their clients. "A digital state is when you don't need to stand in line, … to make copies of documents, waste time, and undergo stress. This is a state, where all official matters can be resolved anywhere using a phone or a computer. From now on, bank customers that have an electronic passport in Diia application no longer require paper documents to confirm their identification in a bank office" [11]. The adoption of best global practices, particularly the Estonian approaches to the functioning of a digital state, has served as a catalyst for the creation of a revolutionary yet logically coherent evolution in the relationship between the state and its citizens in the form of a digital application — the Ukrainian "Diia" system. The utilization of efficient and secure electronic client identification represents a foundational step toward the operation of a comprehensive system for providing electronic banking services. The integration of such an identification system has already been partially implemented within the Ukrainian Customs and Pension systems. Moreover, there are no significant barriers to extending this integration to include the identification of financially authorized managers within digital project management support systems.

The existence of such ready-made digital solutions provided by contemporary banking institutions facilitates the integration of traditional banking operations directly into project planning and management systems. This integration can be achieved without incurring additional costs, while substantially enhancing the overall digital security of the project. The list of such services traditionally includes account opening, attracting funds within established credit limits, opening deposits, issuing bank guarantees and sureties, facilitating money transfers, providing insurance services, and conducting stock exchange operations, among others. The practical application of such integrations is confirmed by the availability of ready-made products that provide integration of banking services into their clients' projects, which are "being powered significantly by Application Programming Interfaces (APIs) and sophisticated integration platforms… this strategy fosters a composable architecture, where financial institutions can assemble and reassemble services and capabilities with greater flexibility, much like building with digital Lego bricks… this collaboration can unlock new revenue streams and foster innovative customer solutions, including the rapidly expanding domain of embedded finance, where banking services

are seamlessly integrated into non-financial platforms" [12]. The timeliness of the implementation and proposal of such instruments is confirmed by the expectations of clients within the rapidly transforming financial sector, which is accompanied by the emergence of competitor solutions, especially those that use advanced digital technologies. In such a dynamic and competitive landscape, the capacity of financial institutions to innovate, adapt, and consistently deliver superior customer service has become a critical determinant of success. At the core of this capability lies the integration of digital banking technologies — an inherently complex process that has shifted from being a strategic consideration to an operational imperative [6]. So, modern financial institutions no longer merely provide a repository for funds; they provide comprehensive technological capabilities and tools to facilitate the management of clients' finances, including in the field of project management.

3. Results and Discussion

The era of modern FinTech instruments is shaping the development of innovative financial banking products and services. As a result of these innovations, a distinct subclass of banking institutions has emerged digital, or virtual banks — which combine a conservative approach to banking operations, including regulatory compliance, with progressive services offered to their clients. "Successful digital banks focus incessantly on what their current customers want. They provide a compelling value proposition and appealing product features, which they strengthen through continuous market testing. Successful digital banks employ many of the same customer-focused tactics that consumers have come to expect from leading consumer-oriented technology… Digital operators go beyond the simple event-based engagement that traditional banks rely on, to grow and scale at an accelerated pace. Digital banks also embrace an end-to-end approach that covers the full customer journey, including acquisition, engagement, deepening relationships, and customer referral" [13]. As the situation in recent years shows, such dynamics are not a temporary direction of industry development, but a sustainable global trend. However, there is still a range of areas where the implementation of banking technologies has significant potential — particularly in terms of financial support for project management. This is particularly relevant to project risk assessment (including financial risks, though not limited to them), the generation of ongoing managerial reporting, the monitoring of expenditures, and the evaluation of their effectiveness in the context of achieving set objectives. However, first and foremost, all these tasks require user identification, the presence of access rights, and the ability to manage this information, including for the purpose of complying with the project's security regulations.

As previously noted, one of the key advantages of electronic banking systems lies in the use of highly secure customer identification mechanisms. Regardless of their form (e.g., password-protected key files, access to cloud storage, or tokens), such systems can be employed to safeguard the financial aspects of project management. The application of ready-made banking technologies for client identification can be integrated into remote project management systems, thereby enhancing confidentiality, reducing the cost of developing customized solutions for each project, and ensuring access to financial resource management and reporting for relevant categories of managers.

The identification and differentiation of access rights — whether to financial resource management or to a specific share of those resources-enable greater efficiency in executing transactions. Where appropriate, these processes can also be automated to support timely notifications and approvals. In parallel with transaction access, project stakeholders may request updates to economic indicators to reflect shifts in income and expenditures caused, for instance, by changes in exchange rates, interest rates on bank lending, or cash inflows. Such updates help maintain the required level of liquidity and creditworthiness. Financial indicators play a critical role throughout all stages of project management, and understanding their dynamics enables more informed decision-making, particularly in evaluating compliance with forecasts and plans.

An alternative to authorization based on individual identification for transactions is the depersonalization of executors, replacing individual responsibility with pre-defined conditions. These conditions may include the achievement of target funding levels, absolute performance benchmarks, or the completion of specific processes — for example, submitting requests for bank guarantees, preparing currency purchase applications for international settlements, or automating payments for outsourced services subject to predefined criteria.

As proven by numerous scientists in research papers [7; 8], the latest banking technologies based on artificial intelligence solutions have the potential to automate a significant part of financial reporting, accounting for standard costs, budgeting and project profitability forecasting. This will significantly reduce the burden on management personnel. At the same time, the implementation of such technologies increases the overall technological maturity of projects and reflects the competencies of the human resources involved. The cybersecurity culture of the digital component of project management is aligned with the overall management framework, emphasizing its holistic nature; compliance with these norms demonstrates adherence to current standards. In turn, this fosters a culture of openness, transparency, mutual understanding, and trust among all project stakeholders, managers, and teams.

The use of artificial intelligence as a tool for forecasting and automation, despite its promising potential, also has several limitations. In particular, it cannot be recommended as the sole solution for especially sensitive financial aspects at the initial stages of project management, such as project budget preparation. The financial foundation of any project is its financial plan — the project budget — which requires exclusive

involvement of the project team during its formulation. It is also important to emphasize that, during project implementation, this plan undergoes rapid changes, adapting to the status of ongoing tasks, considering new influencing factors, responding to exchange rate fluctuations, or reflecting changes in the project team. At the same time, the project budget must account for each such change, consider its impact on the overall estimate, and provide options for implementing these changes. From this perspective, a software solution used in software development appears promising, namely the GIT version control system. Utilizing the approach proposed in this article, which leverages the advantages of digitalization and financial tools through functional integration of both components, we explore the potential for developing a technology based on the GIT version control system that can have practical application in project management.

GitHub is a well-known platform for "collaborative work on various projects, based on a system that enables tracking changes in files and coordinating the work of multiple contributors" [14]. A typical application of this platform occurs when "users constantly make edits, add new sections, revise text, and, naturally, want to preserve all versions of the document" — a principle that can be effectively applied to the process of project budget management during all of its stages.

The inherent flexibility required in a project's financial plan often leads to the creation of multiple versions of such a plan, forming a cascade of branches that reflect each decision made, the availability of alternatives, and their potential use in forecasting budgeting outcomes. An example of such a cascade of budget variants is presented in Figure 1, which includes only three conditional influencing factors — project duration, exchange rate fluctuations, and the need to hire additional personnel — and their corresponding effects on the total project budget. Consequently, the existence of three alternative impacts on the final result (reduction, stability, or increase) demonstrates the behavior of a power function, generating up to 27 possible initial budget configurations.

The potential use of a matrix of alternative budgets allows the addition of new project parameters and ensures the availability of pre-calculated financial plans in the event of potential risks. Preparing and computing such outcomes significantly reduces overall risk exposure and provides the foundation for reserve funds based on quantitative analysis. Although risk forecasting and its implications are not new in project management, applying this logical model can also serve to construct a comprehensive budget from individual components managed by different team leaders.

The technical component of such a system should automatically integrate probable development scenarios, generate a complete set of potential outcomes, and compile statistics on deviations from the original plan in a user-friendly format. However, the core purpose of this system is to ensure easy access, automated generation, and convenient use of the full range of potential project budgets.

This approach can serve as an effective tool for change management within projects and, when combined with relevant banking products (e.g., payment templates in client-bank systems), enables instant responses to managerial decisions or ensures project development according to pre-verified growth scenarios. Maintaining access to all versions facilitates returns to earlier configurations and provides enhanced collaboration, discussion, and co-management of projects — resulting in faster responsiveness, adaptability, and improved financial support for managerial decisions.

4. Conclusions

Today, technological advancement and process automation play a significant role in the financial

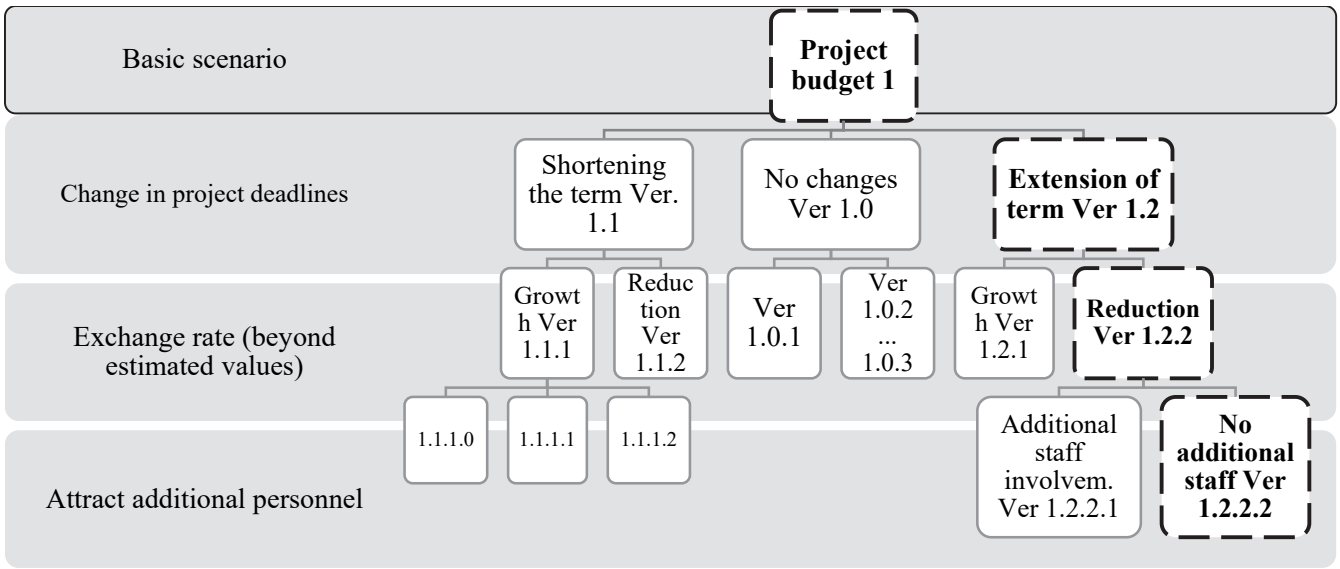

Figure 1. The structural and logical diagram of the matrix of potential versions of the project budget

Source: proposed by the author

sector and have become an integral part of the modern economy. This enables users interacting with digital systems to achieve time and resource savings, overall efficiency improvements, and reductions in errors across virtually all fields in which such technologies can be applied. Project management is no exception; moreover, for this domain, the general level of digitalization within the country where a project is implemented constitutes an additional essential factor. Another important factor influencing these requirements is the extent of digitalization and the adoption of software solutions in the financial sector. For example, the current level of digitalization and use of software technologies in Ukraine's financial industry corresponds to high international standards, ensuring effective interaction among relevant financial systems. It is worth noting that in certain parameters, the Ukrainian banking system, as a result of implemented decisions, ranks among the leading systems globally — for instance, in terms of transaction speed or accessibility of banking products.

Therefore, the use of such functional banking technologies is justified within project management — whether as standalone or integrated solutions, or as promising combinable services. Among these, the present article examines the potential for user identification and the use of banking technologies for verifying the authenticity of users of digital services. Depending on project scale, it is also possible to integrate banking services into project financial management systems at the API level, which opens broad prospects and constitutes a highly relevant subject for both theoretical research and the formulation of technical requirements for future banking software products.

The integration of existing project management software with selected financial instruments is proposed in this article as the most pragmatic and straightforward approach to identifying new solutions at the intersection of financial tools and technologies aimed at enhancing project management effectiveness. From the standpoint of managing the financial component of projects, promising areas for such integration include: budget creation and optimization (through the proposed incorporation of the GIT version control system), improved accessibility and responsiveness in team decision-making (cloud computing and data storage servers), financial support for executing project tasks (payment automation, creation of templates, etc.), and the generation of reports and analysis of efficiency indicators and overall project performance (use of artificial intelligence and big-data analytics). This list is not exhaustive, which highlights the relevance and potential of further research — specifically, the exploration of existing and emerging solutions and tools capable of increasing efficiency or creating new opportunities for project management.

In summarizing this study, it is appropriate to consider the need for integrating modern financial solutions into project management in accordance with the Triple Constraint concept, first introduced by Michael S. Dobson and applied by project managers for several decades [15]. According to this concept, the primary constraints in project management are cost (the overall project budget), scope (the volume of work required to achieve project objectives), and time (which fundamentally determines the project schedule) [16]. The implementation of modern banking solutions to optimize the financial dimension of project management enables organizations to achieve more efficient (reduced) expenditures and/or gain time advantages during project execution, while maintaining the same scope of work. This is accomplished by increasing the speed and efficiency of financial operations and the processes associated with them.

5. References

[1] Myroshnychenko, O. (2025). Assessment of the economic security of innovative enterprises. *Doctoral dissertation, University of Customs and Finance, Dnipro, Ukraine.* http://biblio.umsf.dp.ua/jspui/bitstream/123456789/8005/1/Dis_Myroshnychenko%20O.V.pdf

[2] Yurasova O., Ivashko L., Maksimova J., & Maksimov O. (2025). Innovation trends: impact on the development of the financial sector. *Smart Economy, Entrepreneurship and Security*, 3(1), 7–15. https://doi.org/10.60022/sis.3.(01).1

[3] Naida, I., & Zhekiu, A. (2025). Innovative approaches in startup management in the context of digital transformation. *Actual Problems of Sustainable Development*, 2, 14–22. https://doi.org/10.60022/2(7)-2S

[4] Zaika, S., Hrydin, O., & Zaika, O. (2023). Financial aspects of innovative development. *Economy and Society*, (55). https://doi.org/10.32782/2524-0072/2023-55-62

[5] Ivashkiv, T., & Tymots, M. (2024). The role of non-banking financial and credit institutions in the financial services market. *In Moderní aspekty vědy,* Vol. XLIV/ 93–102. http://repository.ukd.edu.ua/bitstream/handle/123456789/869/mono-44%20%283%29.pdf?sequence=1&isAllowed=y

[6] Schmiedeler, S. (2023). Project management in banking: Is it a thing? *Profit Resources.* https://profitresources.com/wp-content/uploads/2023/04/PRI-Project-Management-Whitepaper-1.pdf

[7] Marych, M., & Ratushniak, D. (2021). Role and place of Internet technologies in the development of the banking services system. *Business, Economics and Social Studies*, 71, 29–34. https://doi.org/10.32843/bses.71–27

[8] Borodenko, T., & Haponiuk, M. (2024). The impact of financial technologies on the activities of banks in Ukraine. *Sustainable Development of the Economy*, 12. https://doi.org/10.32702/2307-2105.2024.12.61

[9] Dallas, E. (2019). *Top 10 tools for effective project management. QATestLab Blog.* https://blog.qatestlab.com/2019/10/03/top-project-management-tools/

[10] Diia (2025). Electronic Document Signing Service. https://diia.gov.ua/services/pidpisannya-dokumentiv [Accessed 17 Oct. 2025].

[11] NBU and Ministry of Digital Transformation to Digitalize the Ukrainian Banking System. *Official website of the National Bank of Ukraine.* https://bank.gov.ua/en/news/all/nbu-ta-mintsifri-spilno-pratsyuyut-nad-tsifrovizatsiyeyu-bankivskoyi-sistemi-ukrayini [Accessed 17 Oct. 2025].

[12] Novozenovs, A. (2025). Core banking integration: Benefits, challenges & solutions. *Crassula*. https://crassula.io/blog/core-banking-integration/ [Accessed 11 Oct. 2025].

[13] Boston Consulting Group (2021). Winning the Digital Banking Battle in Asia Pacific. https://www.bcg.com/publications/2021/digital-banking-asia-pacific [Accessed 01 Oct. 2025].

[14] GIT (2025). Collaborative project management and version control. https://git.com [Accessed 12 Oct 2025]

[15] Dobson, M. (2004). The triple constraints in project management. *Berrett-Koehler Publishers.* https://books.google.com.ua/books?id=ihhFDwAAQBAJ&pg=PT10&hl=uk&source=gbs_toc_r&cad=2#v=onepage&q&f=false

[16] Baratta, A. (2007). The value triple constraint: measuring the effectiveness of the project management paradigm. *Paper presented at PMI Global Congress 2007 Project Management Institute*. https://www.pmi.org/learning/library/value-triple-constraint-measuring-effectiveness-7319

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СУЧАСНІ БАНКІВСЬКІ ТЕХНОЛОГІЇ В КОНТЕКСТІ ПРОЄКТНОГО МЕНЕДЖМЕНТУ

Анотація. *Роль цифрових інновацій та фінансових технологій в рамках сучасного проектного менеджменту постійно зростає. Під час існування сучасних геополітичних викликів забезпечення стабільності фінансових систем, стає все більш важливим. Це дослідження розглядає перспективи інтеграції сучасних банківських технологій в управління проектами як засобу покращення прийняття фінансових рішень, підвищення операційної ефективності та посилення безпеки проектів.*

В статті розглянуто ряд підходів вчених щодо розвитку фінтех-технологій, такі як штучний інтелект, блокчейн, big data та цифрова ідентифікація клієнтів, водночас висвітлюючи прогалину в практичних, проектно-орієнтованих фінансових інструментах. Методологічно дослідження проводить функціональний аналіз широко використовуваних інструментів управління проектами та оцінює їх потенційну інтеграцію з фінансовими технологіями, включаючи електронні цифрові підписи, банківські послуги на основі API та автоматизовані фінансові операції. Особлива увага приділяється адаптації системи контролю версій GIT для формування матриці допустимих бюджетів проекту, що дозволяє генерувати та порівнювати кілька фінансових сценаріїв.

Отримані результати показують, що інтеграція рішень цифрового банкінгу в системи управління проектами підвищує безпеку, прискорює фінансові процеси та підтримує прийняття більш обґрунтованих управлінських рішень. Більше того, така інтеграція відповідає принципам обмежень, знижуючи витрати та підвищуючи ефективність без зміни часу чи обсягу проекту. У дослідженні сформовано висновок, що поєднання існуючих цифрових фінансових інструментів з платформами управління проектами є перспективним напрямком для подальших досліджень та практичного застосування, що пропонує значний потенціал для підвищення технологічної зрілості та стійкості сучасних проектів.

Ключові слова: *управління проектами, фінансовий менеджмент, фінтех, технології цифрового банкінгу, штучний інтелект, контроль версій GIT, цифрова трансформація.*

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NETWORK GOVERNANCE IN THE SMART ECONOMY: A NOVEL FRAMEWORK FOR INTEGRATED PERFORMANCE ASSESSMENT

Abstract. *The rapid transformation of global economic systems under the influence of digitalization, platformization, and emerging Industry 6.0 technologies has intensified the need for advanced tools to evaluate the effectiveness of network governance. Traditional assessment approaches, which focus primarily on organizational performance at the firm level, are no longer sufficient for capturing the complexity, connectivity, and dynamic interactions inherent in modern networked enterprises. This study proposes a novel integrated framework for assessing the performance of network governance within the smart economy, combining structural, relational, institutional, strategic, and resilience-oriented perspectives.*

The research develops the S–Q–I–T–R model, which includes five key dimensions: network structure (S), interaction quality (Q), institutional maturity (I), strategic and innovation outcomes (T), and resilience capacity (R). The methodological foundation of the framework integrates Social Network Analysis, multi-criteria decision-making methods (AHP, entropy weighting, hybrid MCDM), Data Envelopment Analysis (including Network DEA), TOPSIS, and normalization procedures. This hybrid, multidimensional design enables both a comprehensive and analytically rigorous evaluation of network performance.

The proposed methodology offers a scalable and adaptable tool for studying business networks, service networks, entrepreneurial ecosystems, platform-based organizations, and cross-sectoral alliances. By addressing trust mechanisms, digital governance structures, innovation synergy, and resilience to disruptions, the framework is well aligned with the demands of smart and cyber-physical economic environments.

The findings contribute to the advancement of network governance theory and provide practitioners with a robust analytical instrument for diagnosing effectiveness, identifying weaknesses, and enhancing the strategic capacity of networked enterprises in the era of digital transformation and Industry 6.0.

Keywords: *network governance, smart economy, Industry 6.0, integrated performance assessment, resilience index.*

1. Introduction

The rapid transformation of the global economy, the digitalization of business processes, the active spread of platform models and the acceleration of innovation cycles are fundamentally changing the nature of entrepreneurial activity. In such conditions, flexibility, the ability to self-organize and the formation of horizontal connections that ensure rapid adaptation to external changes become key. It is these properties that are inherent in modern network business structures, which are increasingly considered as the basic form of organizing entrepreneurship in the conditions of the smart economy.

The smart economy, which is formed at the intersection of digital technologies, innovative mechanisms of cooperation and sustainable development, defines new requirements for the tools of enterprise management. In it, not only traditional factors of production play a key role, but also intellectual resources, interaction of participants in economic systems, the speed of information flows, the intensity of knowledge exchange and synergy between network entities. Entrepreneurship in such conditions takes on new forms, among which network structures — business ecosystems, platforms, franchise models, groups of enterprises — become the core of innovative and economic development.

Smart economy is an economic paradigm in which digital technologies, intelligent platforms, big data and horizontal interactions between enterprises create new value. According to Forrester forecasts, the global digital economy will grow to 16.5 trillion US dollars by 2028 to cover approximately 17% of global GDP [1]. This underlines the growing importance of digital networks and platforms in economic development. At the same time, mobile technologies and their impact on global connectivity generate additional value: according to estimates by GSMA Intelligence, digital transformation and expanded connectivity could add 11 trillion US dollars to global GDP by 2030, which will be about 8.4% of the economy [2]. At the same time, the global digital platforms market in 2024 was estimated at about 45.6 billion US dollars in the e-commerce platform segment alone, and by 2033 it is expected to grow at a CAGR of over 20% [3].

Another important component of the network economy is the creator economy: It's a $250 billion global force reshaping how brands build loyalty, drive engagement and grow their businesses. Once viewed as a playground for influencers, today's creator economy is at the center of serious business strategies — and it's only getting bigger. Goldman Sachs predicts it could nearly double to $480 billion by 2027, according to their 2023 Creator Economy report [4].

These data confirm the fundamental importance of network structures in modern economic development. In this context, entrepreneurship does not simply use digital tools, but is transformed: business networks, platforms, ecosystems become key actors in the economy. They create new value not only through products and services, but also through interaction, knowledge exchange, and synergy of participants.

At the same time, network business structures, which have a high potential for scalability, innovation, and flexible adaptation, face a number of challenges related to managing complex interdependencies between network participants. This necessitates the creation of new methodological approaches to assessing the effectiveness of management of such structures. Traditional tools applied to individual enterprises do not take into account the specifics of network interaction: multi-actor, lack of rigid hierarchy, information asymmetry, multi-level institutional maturity, distributed nature of resources, multi-channel communications, and dynamism of management circuits.

Existing methods in economic science for assessing the effectiveness of network systems are fragmentary and mainly focused on individual aspects of network functioning — structural characteristics, management relations, indicators of economic performance or the level of institutional interaction. A significant part of these methods was formed before the digital era and does not take into account modern factors — digital management platforms, the speed of information dissemination, the intensity of communications, the virtualization of part of interactions, the strategic flexibility of networks or their resilient nature. That's why, within the framework of the smart economy, the formation of a new, integrated methodology for assessing the effectiveness of network structure management, capable of taking into account the complexity and multidimensionality of modern business networks, is becoming particularly relevant. Such a methodology should provide a combination of structural, behavioral, institutional, strategic and sustainability parameters, which in the complex determine the network's ability to adapt to changes, ensure innovative growth and maintain competitiveness.

In the context of entrepreneurship, network structures are not just a form of business organization, but a mechanism for creating new value through cooperation, partnership and integration of complementary competencies. In the smart economy, network business models have become the foundation for the development of startups, service platforms, e-commerce, hotel and tourism networks, logistics clusters, digital marketplaces and innovation ecosystems. They form a new type of competitiveness — collective, based not only on products, but on connections, flows, integrated services and cross-functional competencies.

In this context, assessing the effectiveness of network structure management is a critically important condition for:

- strategic business development;
- identification of growth points and nodes of inefficiency;
- optimization of resource flows;
- increasing resilience to external shocks;
- strengthening innovation potential;
- forming competitive positions in the long term.

However, a comprehensive, methodologically coherent model for assessing network structure management

has not yet existed. This gap is filled by the proposed improved methodology, which is based on the synthesis of network analysis (SNA), Data Envelopment Analysis (DEA), multi-criteria decision-making (MCDM) methods, entropy weighting, trust indicators, interaction intensity and innovation synergy. Its uniqueness lies in the introduction of a new block — the resilience index (R) [5; 6; 7], which is key for the smart economy and entrepreneurship in conditions of instability, in particular military and post-war challenges.

From the point of view of the issues of modern scientific journals focused on entrepreneurship, innovation and the smart economy, the proposed methodology integrates several key thematic areas that are in the focus of international academic discussion:

– development of business networks and business ecosystems as drivers of economic growth;
– digital transformation of management systems;
– formation of adaptive business models in crisis conditions;
– increasing the resilience and innovativeness of business structures;
– use of quantitative and combined methods of assessing efficiency;
– combination of economic, behavioral and institutional theory in the study of network systems;
– construction of new analytical models for decision-making in the smart economy.

All this makes the improved methodology not just an assessment tool, but a conceptually new approach to understanding the effectiveness of business management in its modern network format. Unlike enterprises with a traditional structure, network systems are characterized by a multiplicity of interdependent elements, complex relationships, cross-functional roles and digital information flows. This requires a different management logic based on synergy, coordination, partnership, flexibility and adaptability, as well as modern methods of quantitative diagnostics of network interactions.

The proposed methodology allows for a comprehensive assessment of the network structure through five dimensions — structural, behavioral, institutional, strategic-innovative and resilience. It forms a holistic view of the network system, allows you to identify hidden nodes of inefficiency, determine the level of integration and coherence of interactions, assess the innovative ability of the network and its strategic position compared to other market players.

Thus, the improved methodology for assessing the effectiveness of network structure management is relevant not only in theoretical but also in practical terms. It can be applied to the analysis of enterprise groups, industry networks, hotel and tourism network associations, innovation clusters, franchising structures, and digital platforms.

2. Materials and Methods

This study is based on a combination of conceptual, analytical, and empirical methodological approaches designed to develop an integrated framework for assessing the effectiveness of network governance within the smart economy paradigm. The research relies on three groups of materials: (1) theoretical sources, (2) analytical tools for quantitative and qualitative evaluation of networks, and (3) conceptual models of networked enterprise systems.

1. Theoretical materials. The methodological foundation of the study draws on modern scientific literature related to network theory [8; 9], network governance [10; 11], smart economy concepts [12], entrepreneurial ecosystems [13; 14], digital platforms [15; 16; 17], and inter-organizational cooperation models [18]. Special attention is paid to theories addressing network coordination, trust-based interactions, and multi-actor decision-making in complex socio-economic systems. These materials serve as the conceptual basis for identifying the core dimensions of network effectiveness and forming the structure of the improved assessment methodology.

2. Methodological basis and analytical tools.

The methodological apparatus of the research is grounded in a multidisciplinary approach, which integrates:

Social Network Analysis (SNA) — to identify structural characteristics of networks, including density, centrality, connectivity patterns, and interaction intensity.

Multi-Criteria Decision-Making (MCDM) — to determine the relative importance of assessment dimensions. Methods such as AHP, entropy weighting, and hybrid approaches are used to obtain balanced and objective weights.

Data Envelopment Analysis (DEA) and Network DEA — to evaluate the efficiency of network nodes and multi-stage processes within networked enterprises.

TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) — for comparative assessment and ranking of network systems by their proximity to an ideal performance profile [19; 20].

Normalization techniques (min–max) — to ensure comparability of heterogeneous indicators.

Resilience assessment models — incorporating redundancy, recovery speed, and diversity metrics as key components for evaluating adaptive capacity within network structures.

These methods form the analytical foundation of the proposed framework and enable a structured, quantitative assessment of network governance effectiveness.

3. *Conceptual integration and model development.*

The methodological design also includes a conceptual synthesis approach. This involves integrating structural (S), interactional (Q), institutional (I), strategic/innovation (T), and resilience (R) dimensions into a unified assessment model. The S–Q–I–T–R framework is developed through systematic comparison of existing evaluation approaches, critical analysis of gaps in previous methodologies, and adaptation of network governance principles to the conditions of a smart economy.

4. *Algorithmic formulation*. The methodological section incorporates the development of a step-by-step assessment algorithm that includes indicator selection, data normalization, weight determination, aggregation of sub-indices, computation of the integrated performance index, and interpretation of results. This stepwise approach ensures replicability and transparency of the proposed assessment model.

In Figure 1 we demonstrate methodological framework for the author's integrated assessment of network governance in the smart economy.

Overall, the study uses a combination of theoretical systematization, comparative methodological analysis, and quantitative modeling approaches, which together create the foundation for the improved integrated methodology presented in the Results and Discussion section.

3. Results and Discussion

The improved methodology proposed below is based on the development of M. Bosovska's ideas [21] and supplements them with the tools of network analysis, multi-stage efficiency assessment, multi-criteria decision-making methods, entropy weighting, formalized trust indices and interaction intensity, as well as a new block — the resilience index, which is critically important for ensuring the stability of networks in conditions of turbulence and crisis phenomena.

The key task in improving the methodology was to expand M. Bosovska's aggregated index into a multilayer, dynamic methodology that integrates network topology (SNA metrics), multi-stage DEA (Network-DEA) for multi-component nodes, MCDM with objective (entropy/ML) weighting, stability/resilience metrics, and a real-time KPI dashboard for Industry 6.0 / services.

We propose to make certain conceptual changes to the methodology of M. Bosovska by adding the following components:

Index layers — it is necessary to divide each group (S, Q, I, T) into sublayers: structural, behavioral, operational, digital. This gives the most detailed dynamic assessment and preserves the aggregated index.

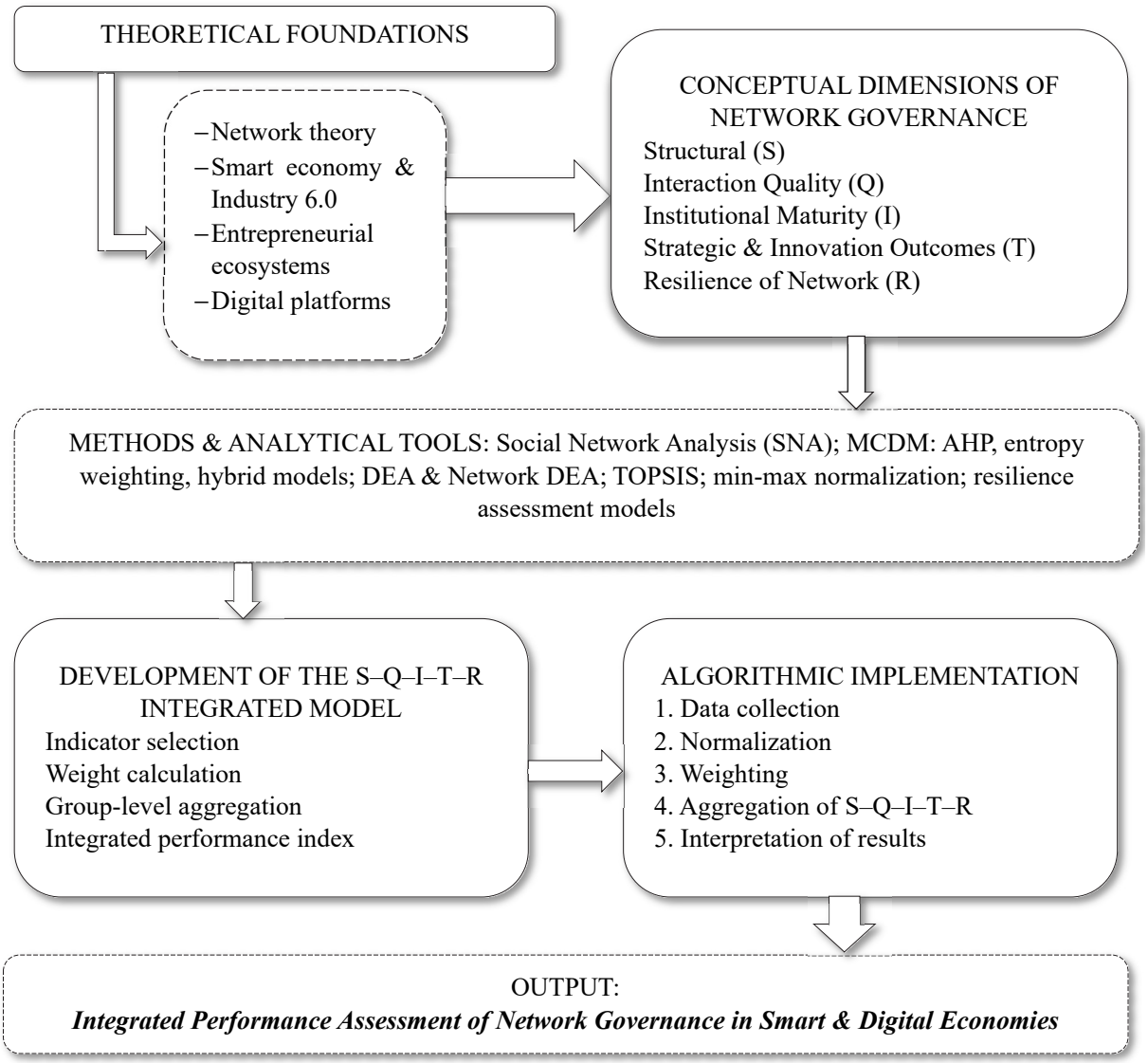

Figure 1. Methodological Framework for the Integrated Assessment of Network Governance in the Smart Economy

Source: created by authors

Integration of SNA metrics (centrality, betweenness, density, clustering coefficient) as a component of S, because the network structure determines the efficiency of coordination and diffusion of innovations. European cluster studies actively use SNA metrics.

Network-DEA (NDEA) instead of classic DEA: allows you to evaluate multi-stage DMUs (nodes with internal subprocesses) and measure the internal efficiency of the network. This is especially important for service platforms and industry 6.0, where DMUs are multifunctional nodes.

Dynamic / time component: the index should be calculated over time (quarterly/monthly) — add Δ-metrics (growth rates III, TI, ISI). In this context, it is advisable to use KPI frameworks with a time component.

Objective weighting: combine expert weights with the entropy method to reduce subjectivity (entropy and TOPSIS practices).

Resilience/stability (R) as a separate multicriteria in T or a separate layer (measures the speed of recovery from a shock, resource redundancy, supplier diversification). Industry 6.0 emphasizes the resilience and circularity of the economy.

Based on the above, we present the author's vision of a multilevel formula for the aggregate index.

$$I_{net}(t) = \sum_{g \in \{S,Q,I,T,R\}} W_g \cdot \tilde{M}_g(t), \quad (1)$$

g — group of indicators (S — scale/structure, Q — quality of interaction, I — institutions, T — strategic results, R — resilience);

W_g — global group weights (interact as $\sum W_g = 1$); these weights are defined as a combination of AHP (expert) and entropy method (objective information weight):

$$W_g = \alpha W_g^{AHP} + (1-\alpha) W_g^{entropy}, \alpha \in [0,1], \quad (2)$$

$\tilde{M}_g(t)$ — normalized aggregate group indicator g at time t, which itself consists of submetrics (S has *S_{topo}, S_{scale}, S_{III}* etc.).

Sub-measure normalization: Each indicator x is normalized to [0,1] (min–max or z-score->sigmoid) to avoid scale.

Let's consider the indicators in the middle of each group in more detail.

Group S (Structure / Network scale and structure):

$$\tilde{M}_S = \beta_1 S_{scale} + \beta_2 S_{density} + \beta_3 S_{central} + \beta_4 S_{III}, \quad (3)$$

S_{scale} — network scale (number of active nodes involved in the interaction);

$S_{density}$ — network density (degree of network connectivity: ratio of real connections to the maximum possible);

$S_{central}$ — average centrality (shows how much the network depends on key nodes);

S_{III} — interaction intensity index (average number of transactions/interactions per active participant);

β_i — sub-indicator weights (determine the importance of each indicator in group S).

Group Q (Quality / Quality of interaction):

$$\tilde{M}_Q = \sum \gamma_j Q_j, \quad (4)$$

Q_j — trust index, stability of cooperation or quality of information flow (calculation of a specific index depends on the context of the task);

γ_j — sub-indicator weights (determine the contribution of each Q-indicator).

Group I (Institutions / Institutional maturity):

$$\tilde{M}_I = \sum \delta_k I_k, \quad (5)$$

I_k — degree of formalization, digital maturity, contractual quality (calculation of a specific index depends on the context of the task);

δ_k — weights that determine the significance of each indicator.

Group T (Strategic results):

$$\tilde{M}_T = \sum \theta_m T_m, \quad (6)$$

T_m — innovation synergy index, economic result or market effect (calculation of a specific index depends on the context of the task);

θ_m — weighting factors that determine the importance of strategic outcomes.

Group R (Resilience / Resilience of network):

$$R = \varphi_1 \cdot Redundancy + \varphi_2 \cdot \frac{1}{T_{recovery}} + \varphi_3 \cdot Diversity. \quad (7)$$

Redundancy — redundancy, availability of reserve resources/suppliers;

$T_{recovery}$ — recovery time (speed of system return to normal after a crisis);

Diversity — diversity, diversification of partners, resources, markets;

φ_i — weighting factor of strategic importance of sustainability parameters.

Economic interpretation

- *Redundancy:* the more reserves, the more stable the network.
- $-\frac{1}{T_{recovery}}$: the sooner the network is restored, the better.
- *Diversity:* the more diverse the network, the less it depends on individual nodes.

Normalization is used to ensure comparability of values min–max:

$$x_{ij}^{norm} = \frac{x_{ij} - \min_i x_{ij}}{\max_i x_{ij} - \min_i x_{ij}} \quad (8)$$

This formula is used to bring different indicators to a single scale from 0 to 1.

All network parameters have different units of measurement:

- number of transactions — tens of thousands;
- level of trust — 0…10;

– innovations — pieces;
– institutional quality — points;
– density — from 0 to 1.

In order to correctly aggregate them, they need to be normalized.

x_{ij} — actual value of the j indicator for the i participant/network;

$min_i x_{ij}$ — the minimum value of the indicator j among all objects;

$max_i x_{ij}$ — the maximum value of the indicator j among all objects;

x_{ij}^{norm} — normalized value of the indicator in the interval [0;1]

This formula allows to: compare networks of different scales; integrate qualitative and quantitative indicators; create composite indices (S, Q, I, T, R).

The weights of the indicators are determined using the entropy model (the entropy approach avoids the subjectivity of expert assessments):

$$p_{ij} = \frac{x_{ij}^{norm}}{\sum_i x_{ij}^{norm}}$$

$$e_j = -\frac{1}{\ln n}\sum_{i=1}^{n} p_{ij} \ln p_{ij}, d_j = 1 - e_j \quad (9)$$

$$w_j^{entropy} = \frac{d_j}{\sum_j d_j}$$

x_{ij}^{norm} — normalized indicator value j;

p_{ij} — fraction of the value of indicator j for object i;

e_j — entropy of the index j — a measure of chaoticity;

d_j — coefficient of information utility of the indicator j;

$w_j^{entropy}$ — objective weight of the indicator j;

If $e_j \approx 1$ → all values are almost the same → indicator is not very informative → low weight.

If $e_j \approx 0$ → indicator varies greatly → significant → high weight.

In network structures, this has a very strong effect, for example: trust indicators (TI) can have low variation → small weight, and interaction intensity (III) and ISI usually have high variation → high weight.

The entropy method determines objective weights of indicators without the participation of experts. If the variation of the indicator is low, it is uninformative → lower weight. If the variation is high, the indicator "distinguishes" objects → higher weight.

To balance objective and subjective approaches, group weights are determined by the formula:

$$W_g = \alpha W_g^{AHP} + (1-\alpha) W_g^{entropy} \quad (10)$$

W_g^{AHP} — weight established by experts;

$W_g^{entropy}$ — weight established based on the entropy method;

α — method mixing ratio.

As noted above, for network structures, we propose to integrate the *Network DEA (NDEA) method* into the proposed methodology to assess the efficiency of nodes:

$$E_j = \frac{\sum_r u_r \sum_a y_{rj}^a}{\sum_i v_i \sum_a x_{ij}^a} \quad (11)$$

x_{ij}^a — inputs of node j at stage a;

y_{rj}^a — outputs of node j at stage a;

u_r, v_i — weight;

a — internal node subprocesses;

E_j — node efficiency.

Finally, the *TOPSIS method* is used to compare alternatives:

Distance to the ideal (positive ideal):

$$S_i^+ = \sqrt{\sum_{j=1}^{k} (v_{ij} - v_j^+)^2} . \quad (12)$$

Distance to the anti-ideal (negative ideal):

$$S_i^- = \sqrt{\sum_{j=1}^{k} (v_{ij} - v_j^-)^2} . \quad (13)$$

Comprehensive rating:

$$C_i = \frac{S_i^-}{S_i^- + S_i^+}, \quad (14)$$

v_{ij} — normalized value of criterion j for the object i;

v_j^+ — ideal value (maximum);

v_j^- — anti-ideal value (minimum);

C_i — network/participant performance rating;

S_i^+ — distance to the ideal;

S_i^- — distance to the anti-ideal.

The final linear algorithm of our improved methodology for assessing the effectiveness of network structure management is shown in Fig. 2.

The improved methodology allows for a comprehensive assessment of the effectiveness of network structure management, taking into account their multicomponent nature, dynamism, and high sensitivity to external influences. The methodology integrates structural, behavioral, institutional, strategic, and resilience factors, as well as modern mathematical tools — SNA, Network DEA, MCDM, entropy weighting. Compared to others, the proposed approach provides a multi-layered, more accurate, and objective diagnosis of network systems, which forms its scientific novelty. Among the main limitations

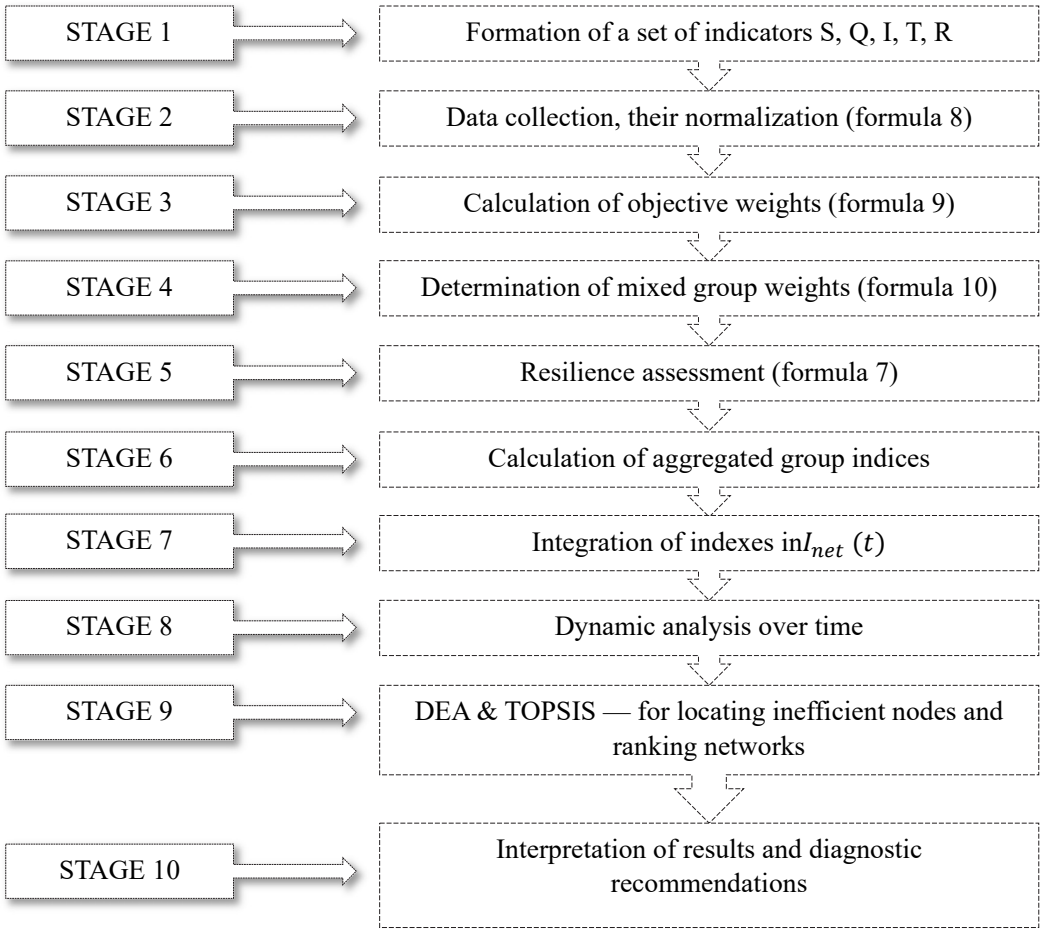

Figure 2. Linear algorithm of methodology for assessing the effectiveness of network structure management
Source: created by authors

and risks of the proposed approach, it is worth highlighting: the need for high-quality data; potential dependence on expert assessments; difficulty of implementation in networks with limited digitalization; the need for periodic updating of weights according to changes.

The use of modern mathematical tools, in particular entropy weighting, multi-criteria models (MCDM), network Data Envelopment Analysis (Network DEA) and TOPSIS tools, which ensure objectivity, accuracy and the ability to rank network systems, is an important advantage of the improved methodology. The introduction of trust indices, innovation synergy, interaction intensity and resilience allows us to take into account the latest trends in the development of network structures, including digitalization, cognitive aspects and adaptability mechanisms. Thus, the improved methodology provides a full, deep and dynamic assessment of the network system, allowing us to identify the strengths and weaknesses of the network, determine its strategic positions, innovation capacity, internal coordination efficiency and level of resilience to crisis impacts. This creates a methodological basis for the formation of sound management decisions on optimizing the configuration, developing interactions and increasing the resilience of network structures.

4. Conclusions

The present study provides a comprehensive and conceptually grounded methodological advancement aimed at improving the assessment of network governance effectiveness within the rapidly transforming landscape of the smart economy. As economic systems become increasingly shaped by digitalization, platformization, and the emergence of cyber-physical production and management architectures associated with Industry 6.0, traditional approaches to evaluating enterprise performance demonstrate clear methodological limitations. In this context, the research introduces an integrated, multidimensional framework — the *S–Q–I–T–R* model — that addresses the complexity, dynamism, and interconnectedness inherent in modern networked enterprise structures.

A central contribution of this work lies in recognizing that network governance can no longer be interpreted through the lens of isolated organizational units, linear managerial processes, or static resource flows. Instead, networked enterprises represent adaptive socio-technical ecosystems characterized by distributed decision-making, real-time digital interactions, high relational density, and constant recombination of competencies embedded within nodes and linkages. These characteristics necessitate a methodological shift toward models that capture systems-level

behavior while maintaining analytical rigor and quantitative measurability. The proposed framework effectively responds to this requirement by combining conceptual, structural, behavioral, institutional, strategic, and resilience dimensions into a unifying assessment architecture.

The structural dimension (S) serves as the foundational layer of the framework, capturing the network's configuration, scale, connectivity, and intensity of interactions. Unlike traditional hierarchical or firm-centric models, the smart economy relies on fluid, scalable, and digitally mediated architectures that allow enterprises to expand or reconfigure in response to environmental dynamics. By incorporating Social Network Analysis tools, the methodology enables the evaluation of structural efficiency, centrality distribution, and communication pathways — factors that determine the agility and coordination capacity of network systems.

The interaction quality dimension (Q) expands the analytical lens toward relational mechanisms, including trust, communication quality, knowledge exchange, and cooperation intensity. In smart and digitally augmented environments, relational capital operates as a strategic asset, directly influencing innovation performance, resilience, and the sustainability of inter-organizational partnerships. The introduction of measurable trust and interaction indices contributes to bridging the gap between qualitative assessments and quantitative measurement.

The institutional dimension (I) reflects the growing importance of governance structures, standards, and digital management infrastructures. Industry 6.0 presupposes the coexistence of AI-driven decision systems, autonomous coordination mechanisms, transparent digital contract systems, and real-time monitoring technologies. The proposed framework therefore emphasizes institutional maturity as a critical driver of governance efficiency and systemic coherence, allowing researchers and practitioners to analyze the reliability, transparency, and regulatory alignment of network governance models.

The strategic and innovation dimension (T) captures the capacity of networked enterprises to generate, co-create, transfer, and commercialize innovations — activities that increasingly define competitive positioning in the smart economy. The introduction of the Innovation Synergy Index (ISI) provides a structured means to measure the degree of complementarity and shared value creation across the network. This focus aligns with contemporary research establishing that innovation is no longer the outcome of individual entities, but a product of collective actions embedded in ecosystems and entrepreneurial networks. Therefore, by measuring innovation intensity and market outcomes, the methodology offers a sound basis for strategic performance evaluation.

Perhaps the most forward-looking component of the framework is the resilience dimension (R), which positions adaptive capacity at the core of network effectiveness. In a world characterized by geopolitical shocks, digital disruptions, supply chain volatility, and market uncertainty, resilience determines whether networks sustain performance, adapt, or collapse. The introduction of a formalized Resilience Index — integrating redundancy, diversity, and recovery speed — represents an essential conceptual and methodological addition. It aligns the assessment framework with global trends emphasizing sustainable business models, adaptive governance, crisis-readiness, and long-term survivability.

From a methodological standpoint, the framework's strength lies in its hybrid analytical apparatus. By integrating MCDM methods (AHP, entropy weighting, and hybrid models), the methodology balances subjective expert knowledge with objective statistical variation. Network DEA expands the assessment beyond simple input-output efficiency, providing a nuanced view of multi-stage, interconnected processes characteristic of network enterprises. TOPSIS, as a comparative ranking tool, enhances decision-making by enabling the evaluation of each network's proximity to an ideal governance profile. Together, these methods ensure a rigorous, transparent, and replicable approach.

Furthermore, the methodological algorithm developed within the framework enhances its practical applicability. It outlines a step-by-step process — from indicator selection and normalization to aggregation, interpretation, and comparative evaluation — making the model accessible not only for academic analysis but also for managerial implementation. This increases its relevance for practitioners operating in service networks, hotel chains, franchising systems, digital platforms, entrepreneurial ecosystems, and industrial clusters.

From a broader perspective, the study contributes to the theoretical understanding of network governance by offering a holistic conceptualization aligned with the requirements of smart and cyber-physical economies. It shifts the focus from narrow operational metrics to a multidimensional perspective that captures the real complexity and potential of networked enterprises. By doing so, the research advances academic discourse in several areas: network theory, entrepreneurial ecosystems, digital transformation, innovation management, and organizational resilience.

The practical implications of the developed methodology are equally significant. It provides managers, policymakers, and analysts with a comprehensive instrument for diagnosing network performance, identifying structural vulnerabilities, assessing innovation potential, and formulating strategic interventions. In environments shaped by rapid technological change, the widespread deployment of AI, and growing interdependence among enterprises, the proposed framework offers an evidence-based foundation for strengthening governance mechanisms and enhancing competitiveness.

In conclusion, the S–Q–I–T–R integrated framework represents a substantial methodological advancement, tailored to the realities of networked enterprise

systems in the smart economy and Industry 6.0. It offers a robust analytical tool capable of capturing structural complexity, relational dynamics, institutional maturity, strategic outcomes, and resilience — components that collectively define the success and sustainability of modern network governance. The proposed model not only enriches academic theory but also provides practical value for enterprises navigating the challenges and opportunities of a digitally enabled, innovation-driven economic landscape.

5. References

[1] O'Grady, M. (2024, July 23). The Global Digital Economy Will Reach $16.5 Trillion And Capture 17% Of Global GDP By 2028. https://www.forrester.com/blogs/the-global-digital-economy-will-reach-16-5-trillion-and-capture-17-of-global-gdp-by-2028

[2] O'Grady, M. (n 1)

[3] Statista (2025). eCommerce — Worldwide. https://www.statista.com/outlook/emo/ecommerce/worldwide

[4] Forbes (2025, Jube 16). How The Creator Economy Is Reshaping Modern Marketing — And Why Brands Are Paying Attention? https://www.forbes.com/sites/lowes-creator/2025/06/16/how-the-creator-economy-is-reshaping-modern-marketing — and-why-brands-are-paying-attention/

[5] Tang, K.T. (2006). Mathematical Methods for Engineers and Scientists 1 — Complex Analysis, Determinants and Matrices. Springer Berlin Heidelberg.

[6] Velten, K., Schmidt, D.M., & Kahlen, K. (2024). Mathematical Modeling and Simulation: Introduction for Scientists and Engineers. Wiley-VC H.

[7] Stokey, N.L., & Lucas, R.E. (1989). Recursive Methods in Economic Dynamics. Harvard University Press.

[8] Chakrabarti, A., Pichl, L., & Kaizoji, T. (2020). Network Theory and Agent-Based Modeling in Economics and Finance. Springer Singapore.

[9] Van der Leji, M.J. (2006). The Economics of Networks: Theory and Empirics. Rotterdam.

[10] Gaurav, A.K. (2024). Network governance: Concepts, theories, and applications: Naim Kapucu and Qian Hu. (1st ed.). New York, NY: Routledge, 2020. *Administrative Theory & Praxis,* 47(3), 269–272.

[11] Klijn, E.H., & Koppenjan, J.F.M. (2012), Governance network theory: past, present and future. *Policy and Politics*, 40 (4), 187–206.

[12] Apostol. D., Bălăceanu, C., & Constantinescu, E.M. (2015). Smart-Economy Concept — Facts And Perspectives. International Conference "European Perspective of Labor Market — Inovation, Expertness, Performance"), Institute for Economic Forecasting Conference Proceedings 141113, Institute for Economic Forecasting.

[13] Bejjani, M., Gocke, L., & Menter, M. (2023). Digital entrepreneurial ecosystems: A systematic literature review. *Technological Forecasting and Social Change*, 189, 122372.

[14] Fernández, M.T., Blanco Jiménez, F.J., & Cuadrado Roura, J.R. (2015). Business incubation: innovative services in an entrepreneurship ecosystem. *The Service Industries Journal*, 35(14), 783–800.

[15] Jin, G.Z., Leccese, M., & Wagman, L. (2025). The Role of Digital Platforms in Shaping Tech Venture Innovation. *NBER Working Paper,* 33370. https://doi.org/10.3386/w33370.

[16] De Reuver, M., Sørensen, C., & Basole, R. C. (2018). The Digital Platform: A Research Agenda. *Journal of Information Technology*, 33(2), 124–135. https://doi.org/10.1057/s41265-016-0033-3

[17] Nerbel, J.F., & Kreutzer, M. (2023). Digital platform ecosystems in flux: From proprietary digital platforms to wide-spanning ecosystems. *Electron Markets,* 33(6). https://doi.org/10.1007/s12525-023-00625-8

[18] Holm, C.G., & Kringelum, L.B. (2022). Intra-Organizational Business Model Implications of Inter-Organizational Collaboration. *Journal of Business Models*, 10(1), 1–10. https://doi.org/10.54337/jbm.v10i1.6827

[19] Tang, K.T. (n 5)

[20] Stokey, N.L., & Lucas, R.E. (n 7)

[21] Bosovska, M. (2015). Methodological approaches to assessing the performance of the networks based on multi approaches. *Investments: practice and experience*, 3, 23–26.

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МЕРЕЖЕВЕ УПРАВЛІННЯ В РОЗУМНІЙ ЕКОНОМІЦІ: НОВА ОСНОВА ДЛЯ ІНТЕГРОВАНОЇ ОЦІНКИ ЕФЕКТИВНОСТІ

Анотація. *Швидка трансформація глобальних економічних систем під впливом цифровізації, платформізації та нових технологій Індустрії 6.0 посилила потребу в передових інструментах для оцінки ефективності мережевого управління. Традиційні підходи до оцінки, які зосереджені переважно на організаційній ефективності на рівні фірми, більше не є достатніми для врахування складності, зв'язності та динамічної взаємодії, властивої сучасним мережевим підприємствам. Це дослідження пропонує нову інтегровану основу для оцінки ефективності мережевого управління в рамках розумної економіки, що поєднує структурні, реляційні, інституційні, стратегічні та орієнтовані на стійкість перспективи.*

У дослідженні розроблено модель S–Q–I–T–R, яка включає п'ять ключових вимірів: мережева структура (S), якість взаємодії (Q), інституційна зрілість (I), стратегічні та інноваційні результати (T) та здатність до стійкості (R). Методологічна основа фреймворку об'єднує аналіз соціальних мереж, багатокритеріальні методи прийняття рішень (AHP, ентропійне зважування, гібридний MCDM), аналіз охоплення даних (включаючи мережевий DEA), TOPSIS та процедури нормалізації. Цей гібридний, багатовимірний дизайн дозволяє проводити як комплексну, так і аналітично ретельну оцінку ефективності мережі.

Запропонована методологія пропонує масштабований та адаптивний інструмент для вивчення бізнес-мереж, мереж послуг, підприємницьких екосистем, організацій на основі платформ та міжгалузевих альянсів. Розглядаючи механізми довіри, структури цифрового управління, синергію інновацій та стійкість до збоїв, фреймворк добре узгоджується з вимогами розумних та кіберфізичних економічних середовищ.

Результати дослідження сприяють розвитку теорії управління мережами та надають практикам надійний аналітичний інструмент для діагностики ефективності, виявлення слабких місць та підвищення стратегічного потенціалу мережевих підприємств в епоху цифрової трансформації та Індустрії 6.0.

Ключові слова*: управління мережами, смарт-економіка, Індустрія 6.0, інтегрована оцінка ефективності, індекс стійкості.*

JEL: O33; L86; M15

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APPLICATION OF NATURAL LANGUAGE PROCESSING TO AUTOMATE THE ANALYSIS OF USER FEEDBACK

Abstract. *The purpose of the research is to develop a system for automated analysis of user feedback based on natural language processing methods to identify sentiments, key aspects and themes. The relevance of the research topic is due to the growing need for businesses in effective tools for analyzing large volumes of text data, which would allow extracting valuable insights from user feedback and transforming them into specific recommendations for improving products and services. This topic is of particular importance in the context of e-commerce, services and software development, where the quality and speed of response to user feedback directly affect the competitiveness of companies. Research methods include machine learning, deep neural networks, statistical text analysis methods and methods for assessing the quality of models. Classical algorithms, neural network models, transformer architectures are used. The statistical significance of the results obtained was experimentally confirmed and recommendations for selecting models for various scenarios were developed. The relevance of the research topic is due to the growing business need for effective tools for analyzing large volumes of text data, which would allow extracting valuable insights from user reviews and transforming them into specific recommendations for improving products and services. The research results can be used in e-commerce, service companies, software development, marketing, and analytics to automate review analysis and identify trends in large volumes of text data.*

Keywords*: natural language processing, analysis of responses, aspect-oriented analysis, machine learning.*

1. Introduction

In the digital age, user interactions with products and services have created an unprecedented flow of feedback and comments. Companies, from small startups to large corporations, receive hundreds and thousands of text-based reviews every day through a variety of channels — email, social media, specialized platforms and internal feedback systems. It is in this unstructured data that the most valuable information about customer satisfaction, their needs and expectations is contained.

According to research, more than 90% of company leaders recognize the importance of analyzing user feedback for making strategic decisions, but only about 30% of organizations have systems that allow them to effectively process and analyze this data. Traditional manual analysis of reviews has long ceased to meet modern business requirements. Reviewing tens of thousands of comments requires huge human resources, which makes the process extremely costly. In addition, the subjectivity of human assessment often leads to inconsistency in interpreting user opinions.

Even the best analysts are unable to process such volumes of data quickly enough for companies to quickly respond to changing consumer sentiment.

Natural language processing (NLP) offers a solution to this problem through the use of algorithms that can automatically analyze the semantics of text, determine the tone of utterances, and isolate key themes from large data sets. Thanks to the rapid development of machine learning technologies and deep neural networks, modern NLP systems demonstrate impressive accuracy in understanding the context and nuances of human speech. Recent advances in NLP, including the development of transformer models such as BERT, GPT, and RoBERTa, have significantly expanded the capabilities of natural language processing. These models are able to understand the context of words in a sentence, take polysemy and idiomatic expressions into account, and successfully process texts in different languages. Their application to user feedback analysis opens up new horizons for understanding customer needs and improving products and services [7, 14, 21].

Implementing automated user feedback analysis using NLP not only significantly reduces time and resources, but also provides deeper analytical results. NLP systems are able to detect hidden trends and patterns that are inaccessible during manual analysis, and also ensure the scalability of the solution in accordance with the growth of data volumes. In addition, such systems can operate 24/7, ensuring constant monitoring of feedback and instant detection of critical problems.

The relevance of the research topic is due to the growing business need for effective tools for analyzing large volumes of text data, which would allow extracting valuable insights from user feedback and transforming them into specific recommendations for improving products and services. This topic is of particular importance in the context of e-commerce, the service sector, and software development, where the quality and speed of response to user feedback directly affect the competitiveness of companies.

The main tasks include studying modern approaches to natural language processing, analyzing text classification algorithms and sentiment analysis, as well as developing and evaluating the effectiveness of a system for automated analysis of user feedback. The paper examines the theoretical aspects of natural language processing, investigates various models and algorithms for analyzing responses, and experimentally evaluates their effectiveness on real data. The methodological basis of the research is machine learning methods, deep neural networks, statistical methods of text analysis, and methods for assessing the quality of machine learning models. The experimental part of the paper uses the Python programming language and natural language processing libraries such as NLTK, spaCy, Transformers, and TensorFlow.

The results of the study can be used to develop software solutions that will allow companies to better understand the needs of their customers, respond quickly to problems, and improve the quality of their products and services. The practical significance of the work lies in the possibility of implementing the developed methods and models into the business processes of organizations of various scales to improve interaction with customers and increase their loyalty. In today's digital world, user review analysis has become a critical element for any business seeking to prove the quality of its products and services. However, the scale and unstructured nature of this data pose significant challenges for traditional analysis. The main problem addressed in this study is the inefficiency and limitations of manual analysis of large volumes of text-based user reviews. This problem has several important aspects:

1. Exponential growth in data volumes. Modern companies receive thousands of new reviews every day through various channels. According to the Customer Experience Trends Report 2024, the number of online reviews is increasing by about 18% every year, which is almost twice as much as in 2020 (10%). For the largest e-commerce platforms, this figure is even higher — Amazon records about 22% annual growth in the number of reviews, and marketplaces in the service sector about 25%. By 2025, it is predicted that leading companies will receive an average of 30–50 thousand reviews every day (Fig. 1), which makes manual processing of such volumes of information practically impossible;

2. Subjectivity and inconsistent analysis. Human interpretation of text is subjective, which can lead to different conclusions about the same review. Independent studies conducted in 2023–2024 in the cloud and financial services sectors show that the level of agreement between different analysts when assessing the tone of reviews is only 60–75%, and when identifying specific issues mentioned in the reviews, this figure drops to 55%.

3. Critical time costs. Manual analysis requires significant time resources. According to McKinsey experts (2024), an analyst spends an average of 2–3 minutes on in-depth analysis of one review of average duration, which for a company with 1000 reviews daily means 30–50 hours of work per day, or 5–8 analysts working full-time exclusively on review processing. This approach makes it impossible to respond promptly to critical issues.

4. Limited ability to detect hidden patterns. Analysts are often unable to detect hidden trends and relationships in large data sets, especially when these patterns occur over a long period of time or across different user segments. Forrester Research (2024) found that about 68% of valuable insights from user feedback remain undiscovered through manual analysis, especially when it comes to correlations between different aspects of a product and user reactions.

5. The increasing complexity of multilingual analysis. The globalization of business has led to the need to analyze reviews in many languages. By 2025, this figure is predicted to be 55–60%.

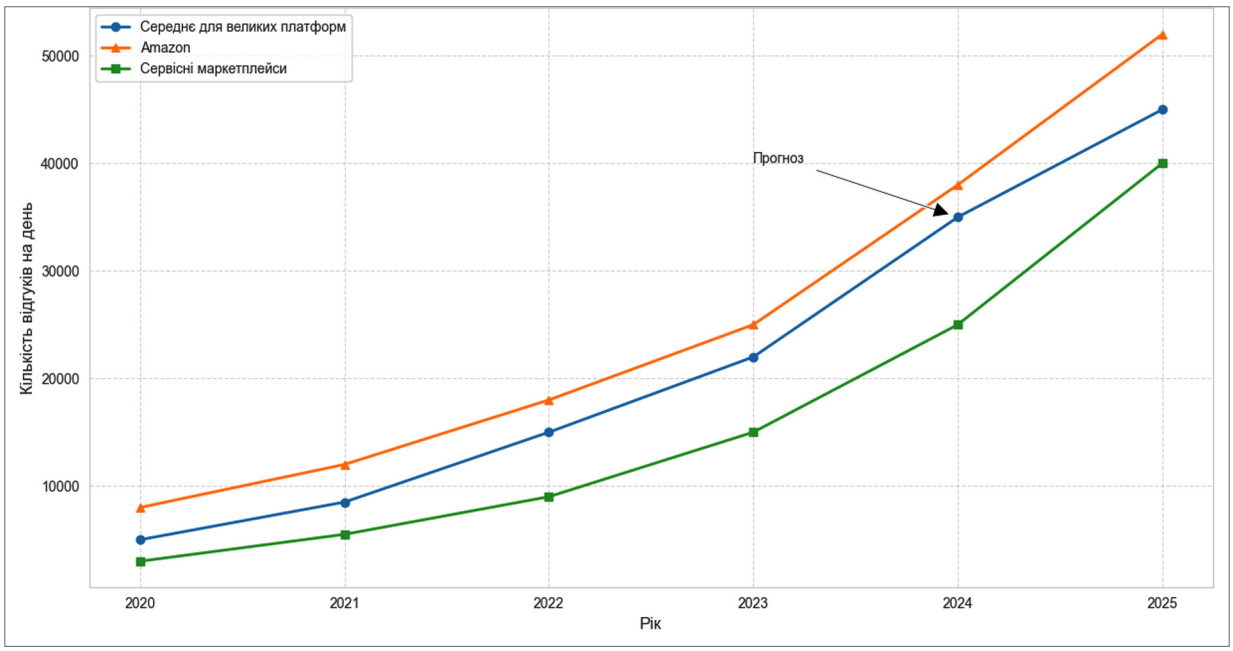

Figure 1. Dynamics of growth in the number of daily reviews on leading platforms

6. Lack of standardization and subjectivity of assessments. Different analysts may use different methodologies and assessment criteria, which makes it difficult to compare results and develop a unified strategy for responding to feedback. Such variability makes it impossible to compare data over time and makes it difficult to track progress in improving products and services.

7. Rising costs for review analytics. Economic research shows that the cost of manual review analysis is skyrocketing. According to the Customer Experience Association, the average annual cost of review analytics for the average company has increased to $280,000 in 2024, and is projected to reach $350,000–400,000 by the end of 2025.

Setting research objectives. Based on the analysis of the issues and existing approaches to automating user feedback analysis, key challenges and promising research directions have been identified. A clear statement of research objectives will allow structuring further work and focusing on the most relevant aspects of the problem.

The main goal of this study is to develop and evaluate the effectiveness of a comprehensive system for automated user feedback analysis based on modern natural language processing methods, which will ensure high accuracy in detecting tone, key aspects and topics, the ability to work with feedback in different languages, and effectively integrate into the business processes of organizations of various scales.

To achieve the goal, it is necessary to solve the following specific tasks:

1. Development of effective methods for pre-processing user feedback.

This task includes research and development of methods for cleaning and normalizing text data, processing informal vocabulary, abbreviations, emoticons, spelling errors and other features of user reviews. The developed methods should ensure the preservation of the informativeness of the text when removing noise, take into account the multilingual nature of reviews and the specifics of different domains. The relevance of this task is confirmed by the fact that the quality of pre-processing of the text directly affects the effectiveness of subsequent analysis. According to a study by the Data Science Center (2024), improving the quality of pre-processing can increase the accuracy of review classification by 8–12%.

2. Research and comparative analysis of modern models for classifying the tone of responses. The task involves adapting and evaluating the effectiveness of various NLP models for analyzing the tone

Table 1

Average time spent on manual analysis of reviews of varying complexity

Feedback type	Average length (words)	Analysis time (min)	Number of reviews per working day (8 hours)	Number of analysts for 1000 reviews/day
Short	10–30	1–2	240–480	2–4
Average	31–100	2–4	120–240	4–8
Long	101–300	4–8	60–120	8–16
Detailed	>300	8–15	30–60	16–33

of responses — from classical machine learning approaches to modern transformer architectures and large language models. Particular attention will be paid to the balance between accuracy, computational requirements and processing speed, as well as the ability to adapt to specific domains. The relevance of the task is due to significant differences in the effectiveness of different models depending on the context of application.

3. Development of a method for aspect-oriented tonality analysis for different domains.

This task focuses on developing an approach that will allow not only to determine the overall tone of the response, but also to identify specific aspects of products or services and the corresponding tone for each of them. The method should be adaptable to different domains (electronics, hospitality, software, etc.) and work effectively with limited training data. The relevance of the task is confirmed by studies that show that aspect-oriented tone analysis provides businesses with 35–40% more valuable insights compared to simple tone classification.

4. Creating effective methods for identifying themes and key aspects in response corpora.

The task involves developing and evaluating methods to automatically identify the main topics discussed in large sets of reviews and isolate key aspects of products or services. This will allow companies to obtain a structured view of which aspects of their products are most often mentioned in reviews and which topics cause the most resonance. The relevance of this task lies in the need to effectively categorize and structure large volumes of unstructured text data for further analysis and decision-making.

5. Developing an approach to multilingual review analysis. This task focuses on creating methods that will allow for the effective analysis of reviews in different languages without significant loss of accuracy and while preserving linguistic and cultural features. Both translation-based approaches and methods using multilingual models and cross-lingual knowledge transfer will be explored. The relevance of the task is due to the increasing globalization of business and the need to analyze reviews in different languages.

6. Creating methods for interpreting and visualizing the results of feedback analysis.

The task involves developing approaches to ensure the explainability of analysis results and their effective visualization for end users. This involves researching explainable AI methods, creating intuitive visual representations of analysis results, and developing recommendations for interpreting these results. The relevance of this task is confirmed by the fact that even the most accurate analysis results have limited value if end users cannot correctly interpret them and use them for decision-making.

7. Development and evaluation of a comprehensive automated feedback analysis system. This integrative task involves combining the developed methods and models into a single system that will provide a full cycle of feedback analysis — from collection and pre-processing to the generation of insights and recommendations. The system should be adaptive to different domains and types of feedback, scalable and efficient in terms of computing resources. The relevance of the task lies in the need to create a practically oriented solution that can be directly implemented in the business processes of organizations of various scales.

8. Experimental evaluation of the effectiveness of the developed methods on real data. The task includes conducting comprehensive experiments to evaluate the effectiveness of the developed methods and the system as a whole on real sets of responses from different domains and in different languages. Aspects such as classification accuracy, quality of aspect detection, processing speed, scalability, and adaptability to new domains will be evaluated. The relevance of this task is due to the need for empirical confirmation of the effectiveness and practical value of the developed methods and system.

To solve the tasks, a comprehensive methodological approach will be used, combining machine learning, deep learning, natural language processing, and data analysis. The research will be conducted in several stages:

1. Analytical stage. At this stage, a detailed analysis of existing methods and models, their advantages and limitations will be conducted. Modern research in the field of NLP and feedback analysis will be studied, the most promising approaches and technologies will be identified;

2. Design and development stage. At this stage, specific methods and models will be developed to solve the tasks set. The development will include both the adaptation of existing approaches and the creation of new methods and architectures optimized for feedback analysis;

3. Experimental stage. This stage includes conducting experiments to evaluate the effectiveness of the developed methods and models. Experiments will be conducted on real sets of reviews from different domains (e-commerce, hotel business, software, services, etc.) and in different languages. Standard metrics such as accuracy, completeness, F1-measure, as well as specialized metrics to assess the quality of aspect and topic detection will be used for evaluation;

4. Analytical and generalization stage. At this stage, the results of the experiments will be analyzed, patterns will be identified, and conclusions will be formulated regarding the effectiveness of the developed methods and models. The main advantages and limitations of the proposed approaches, as well as directions for further research, will be identified.

To implement the methods and conduct experiments, modern tools and libraries for natural language processing will be used, in particular: Python programming language as the main language for implementing algorithms and conducting experiments; libraries for NLP: NLTK, spaCy, Transformers (Hugging Face), Stanza; frameworks for machine learning: TensorFlow,

PyTorch, Scikit-learn; tools for data analysis and visualization: Pandas, NumPy, Matplotlib, Seaborn, Plotly [11, 16, 22].

Both publicly available datasets (e.g. SemEval, Amazon Reviews, Yelp Dataset, IMDB) and data specifically collected and labeled for this study will be used to evaluate the models.

As a result of the tasks set, it is expected to obtain: a set of methods and models for automated analysis of user feedback, ensuring high accuracy of tonality classification, identification of aspects and topics, as well as effective work with feedback in different languages; recommendations for choosing optimal methods and models for analyzing feedback in different domains and with different requirements for accuracy, speed and scalability; empirical data on the effectiveness of different approaches to analyzing feedback on real data sets, which can be used for further research in this area. Thus, this study is aimed at solving the current scientific problem of automating user feedback analysis and has significant practical value for business. The tasks set cover key aspects of this problem and are aimed at creating an effective and practically oriented solution.

2. Materials and Methods

Methodological support for organizing research. Effective research in the field of automation of user review analysis requires careful planning, a structured approach and the use of appropriate methodologies. This section discusses the methodological aspects of organizing research, starting from data collection and preparation and ending with the evaluation of results and their interpretation. Data quality is crucial for the success of research in the field of review analysis. A methodological approach to data collection and preparation involves the implementation of a number of sequential stages, each of which has its own characteristics and requirements. Collection of representative sets of user reviews can be carried out from various sources, including commercial platforms (Amazon, Yelp, Google Play), social networks (Twitter, Facebook), specialized industry sites and internal feedback systems of companies. For research purposes, it is advisable to use existing publicly available datasets, such as: IMDB Large Movie Review Dataset — 50,000 reviews of movies with tone labels; Amazon Product Reviews — millions of user reviews of different product categories; Yelp Dataset — reviews of businesses with ratings from 1 to 5; SemEval ABSA Datasets — tagged datasets for aspect-oriented sentiment analysis. When collecting data yourself, it is important to adhere to ethical and legal norms, obtaining the necessary permissions and ensuring the anonymization of personal data. For automated data collection from web sources, web scraping tools are used, taking into account the access policies of the relevant platforms.

Preparing the collected data includes several key steps:

1. Text cleaning and normalization. This stage involves removing noise (HTML tags, special characters), correcting spelling errors, and normalizing text (lowercase conversion, standardizing the writing of numbers, dates, and addresses). Particular attention should be paid to specific elements of user feedback, such as emoticons, acronyms, and slang, which often carry important semantic load.

2. Data labeling. To train models with a teacher, high-quality data labeling is required, which may include: sentiment labels (positive, negative, neutral); highlighting aspects and the corresponding tone for them; thematic labels. Labeling can be done manually by qualified experts or using crowdsourcing platforms such as Amazon Mechanical Turk or Toloka. To ensure the quality of the labeling, it is recommended to use several independent experts for each review with subsequent coordination of the results.

3. Stratification and balancing of data sets. To ensure the representativeness of data sets, it is necessary to take into account the distribution of classes, response lengths, data sources and other factors. Imbalanced data sets can lead to model bias and deterioration of their generalization ability. To solve the problem of imbalance, techniques can be used: increasing the representation of rare classes through duplication or generation of synthetic data; reducing the representation of dominant classes; using weighted loss functions when training models.

4. Data quality validation. This stage involves checking the consistency of the markup, identifying and resolving ambiguities, and assessing inter-expert agreement using metrics such as Cohen's kappa or Fleiss' kappa.

5. Developing and training models for feedback analysis requires a systematic approach that takes into account the specifics of the tasks and available resources.

The methodical approach involves the sequential implementation of the following stages.

The first stage involves selecting the basic model architecture for a specific task. Several factors should be considered when selecting a model: the nature of the task (tonality classification, aspect detection, thematic modeling); the volume and quality of available data; computational resources; processing time requirements; the required level of interpretability of results. In the case of limited computational resources or strict performance requirements, it is advisable to use compact models or classic machine learning algorithms. With high accuracy requirements and the ability to use powerful computing equipment, preference should be given to modern transformer architectures.

The next step involves splitting the data into training, validation, and test sets. Standard practice is to split the data in a 70%/15%/15% or 80%/10%/10% ratio. It is important to ensure that all samples are representative by stratifying them by key characteristics (class, domain, data source). For small data sets, it is recommended to use cross-validation with multiple folds to obtain more reliable estimates of model performance.

The process of training and optimizing models includes: choosing a loss function according to the task

(cross-entropy for classification, MSE for regression tasks, specific loss functions for multi-task models); choosing an optimizer and determining training parameters (batch size, learning rate, number of epochs); regularization to prevent overtraining (L1/L2 regularization, dropout, data augmentation); monitoring the training process and early stopping when a plateau is reached on the validation sample; searching for optimal hyperparameters using grid search, random search or Bayesian optimization.

To improve the quality of models, it is advisable to use transfer learning techniques: the use of pretrained models (e.g., BERT, RoBERTa) with subsequent additional training on specific data; adapter learning, which allows you to effectively adapt large models to new domains with minimal computational resources; multi-task learning to improve the generalization ability of models.

Qualitative assessment and correct interpretation of results are important components of the research process. A methodological approach to assessing the effectiveness of feedback analysis models involves the use of a set of metrics adapted to specific tasks.

For tonality classification tasks, the main metrics are: accuracy — the proportion of correctly classified samples; precision — the proportion of correctly positively classified samples among all positively classified samples; recall — the proportion of correctly positively classified samples among all actually positive samples; F1-score — the harmonic mean of precision and recall. In the case of unbalanced datasets, it is especially important to use F1-score and macro-averaged metrics that take into account the performance of the model on all classes.

For aspect-oriented sentiment analysis, the evaluation is carried out in two stages: assessment of the quality of aspect detection (F1-score for the sequential labeling or named entity detection task); assessment of the accuracy of sentiment classification with respect to correctly detected aspects. Additionally, a combined metric can be used that takes into account both the correctness of aspect detection and the correctness of sentiment determination.

Specific metrics are used for topic modeling tasks, such as: topic coherence — a measure of the semantic coherence of words in a topic; perplexity — a statistical measure that reflects how well the model predicts new data; topic diversity — a measure of the differences between the detected topics.

When evaluating multilingual models, it is important to test across languages and verify the stability of the model's performance. It is advisable to use cross-lingual test datasets that allow us to assess the model's ability to transfer knowledge between languages.

Interpretation of results should be done taking into account the context of the study and the characteristics of the data. It is important to analyze not only quantitative metrics, but also qualitative analysis: studying model errors, classifying them and identifying patterns; visualizing model activations to understand which parts of the text it pays attention to; analyzing the level of confidence of the model in its predictions; comparative analysis of the results of different models on the same data sets.

To ensure the reliability of the results, it is recommended to conduct statistical analysis: determining the statistical significance of differences between models using the t-test, Wilcoxon test or bootstrapping; analyzing the sensitivity of models to changes in data and hyperparameters; checking the stability of results on different data subsamples.

Effective research in the field of feedback analysis requires the use of appropriate software and tools. The main components of the technology stack are programming languages, machine learning and natural language processing libraries, and tools for data visualization and analysis.

The recommended programming language for NLP research is Python due to its simplicity, flexibility, and rich ecosystem of libraries for data processing and machine learning. Alternative options include R (especially for statistical analysis) and Java (for industrial systems development).

For processing and analyzing text data, it is recommended to use the following libraries and tools: NLTK, spaCy, and Stanza for basic text processing, tokenization, lemmatization, and syntactic analysis; scikit-learn for classic machine learning algorithms and preprocessing tools; gensim for thematic modeling and creating vector representations of words; PyTorch, TensorFlow, or Keras for developing and training neural network models; Transformers (Hugging Face) for working with transformer models.

For data analysis and visualization, the following are recommended: pandas for manipulating structured data; matplotlib, seaborn, plotly for creating visualizations; numpy for numerical calculations; scipy for statistical analysis.

To ensure reproducibility of results and efficient organization of experiments, it is recommended to use: Weights & Biases, MLflow or TensorBoard for tracking experiments and visualizing training metrics; Docker or conda for creating isolated environments with all necessary dependencies; Git for version control and code storage; Jupyter Notebooks for interactive development and documentation of experiments.

When developing industrial feedback analysis systems, the following can be additionally used:

Apache Kafka or RabbitMQ — for organizing streaming data processing; Elasticsearch — for efficient storage and search in text data; Redis — for caching results and speeding up the system; Flask, FastAPI or Django — for creating APIs and web interfaces.

Systematic organization and careful documentation of experiments are necessary conditions for ensuring the reliability and reproducibility of research results. A methodical approach to organizing experiments involves following a structured protocol.

Each experiment should have a clearly defined goal and hypotheses to be tested. The documentation of

the experiment should include: a description of the input data (source, volume, characteristics, preprocessing method); detailed information about the model architecture and its hyperparameters; a description of the learning process (loss function, optimizer, learning rate, number of epochs); evaluation results on the validation and test sets for all relevant metrics; error analysis and interpretation of the results; comparison with baseline models and previous experiments.

To ensure reproducibility of results, the following should be recorded: versions of all libraries and dependencies used; configuration of the computing environment; parameters of random number generators; fixed-state data sets or their generation protocols.

It is recommended to conduct ablation studies to determine the contribution of each component of the model or method to the overall effectiveness. This helps to better understand which aspects of the proposed solution are most important.

For long-term studies, it is advisable to create a model repository that stores trained models along with all necessary meta-information. This allows you to reuse models in new experiments, compare their performance, and track research progress.

The developed methods and models of feedback analysis have practical value only if they are successfully implemented into real business processes. The methodology for implementing the research results includes a number of sequential steps.

The first stage involves preparing the model for deployment: optimizing the model to improve inference efficiency (quantization, distillation, pruning); testing the stability and reliability of the model on different datasets; integrating the model with APIs and other system components; developing mechanisms for monitoring and updating the model.

At the stage of system deployment, it is necessary to ensure: scalability — the system's ability to process variable amounts of data; resilience — the system's ability to function in the event of errors and failures; performance monitoring — tracking key system performance metrics in real time; user feedback — collecting information about the quality of the system's operation and identifying problems.

An important aspect of implementation is ensuring that results are interpretable for end users: visualizing key insights in a clear form; providing explanations for the decisions made by the model; enabling detailed analysis of results for business analysts; creating intuitive dashboards to monitor trends and identify anomalies.

To keep the system up to date, it is necessary to: regularly update models using new data; track data drift — changing characteristics of input data over time; adapt models to new domains and languages; and improve the system based on user feedback.

Methodological support for research in the field of automation of user feedback analysis is a complex process that covers all stages from data collection to the implementation of results. The effectiveness of the study largely depends on the quality and representativeness of the data, the correct choice of models and methods, the systematic organization of experiments, and careful evaluation of the results.

The developed methodological recommendations provide a structured approach to conducting research, which allows obtaining reliable and reproducible results. Particular attention is paid to ensuring data quality, choosing adequate assessment metrics, and interpreting results in the context of specific business tasks.

The application of the proposed methodological support allows for effective organization of research in the field of automation of user feedback analysis and ensuring the successful implementation of the developed models and methods into practice.

Automating user feedback analysis requires the use of a wide range of natural language processing methods and models. Over the past decades, this area has undergone rapid development, moving from simple statistical methods to complex neural network architectures. Let's consider the evolution of these approaches, their features and effectiveness in the context of automating user feedback analysis.

Summarizing the analysis of approaches, methods, and models for automating user feedback analysis, several key conclusions can be drawn.

The current landscape of feedback analysis technologies is represented by a wide range of methods, from simple dictionary approaches to complex neural network architectures and large language models. The choice of a particular method depends on many factors: the volume and quality of available data, domain specificity, processing speed requirements, the required level of accuracy and interpretability of the results.

Transformer models, especially the domain-specific versions of BERT and RoBERTa, demonstrate the best balance of accuracy, speed, and resource intensity for most practical review analysis tasks. They provide high accuracy in understanding context and language nuances, which is critical for correctly interpreting user reviews.

Large language models with few-shot training open up new possibilities for rapidly deploying feedback analysis systems in new domains and for new products. They are especially valuable in situations with limited training data or when rapid adaptation to new feedback types is required.

Aspect-based sentiment analysis is the most informative approach for businesses, as it allows you to gain a detailed understanding of the strengths and weaknesses of products or services. The combination of ABSA with topic and aspect detection methods provides the most complete picture of user feedback.

Multilingual models provide better results for multilingual analysis compared to the "translation + analysis" approach, especially when understanding cultural and linguistic nuances is important. These models are becoming increasingly important in a globalized business environment.

The optimal solution for most business problems is a combination of different methods, which allows to ensure high accuracy, efficiency and adaptability of the feedback analysis system. This approach allows to use the advantages of each method and minimize their limitations.

Table 2 presents a comparison of the effectiveness of different approaches for key feedback analysis tasks based on recent research and benchmarks from 2023–2025 (Table 2).

Successfully integrating feedback analytics into business processes requires not only choosing the right technology, but also understanding the business context and needs of a particular organization. According to McKinsey, companies that effectively use user feedback analytics demonstrate 15–20% higher customer retention rates and 10–15% higher average revenue per customer [8].

The most successful implementations of feedback analytics are characterized by several key features.

First, they provide integration with existing systems such as CRM, customer support systems, and analytics platforms. This allows you to combine data from different sources and gain a comprehensive understanding of customer needs and problems.

Second, effective feedback analytics systems provide results in a clear and actionable format. They don't just generate statistical reports, they also highlight specific issues that need attention and provide recommendations for resolving them. This is especially important for users who are not technically trained but who make strategic decisions based on the analysis results.

Third, successful feedback analytics systems automate the full cycle — from collecting and analyzing feedback to generating insights and recommendations. This significantly reduces the time from receiving feedback to responding to it, which is critically important in today's fast-paced business environment.

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The modern landscape of review analysis technologies is represented by a wide range of methods, from simple dictionary approaches to complex neural network architectures and large language models. The choice of a specific method depends on many factors: the volume and quality of available data, domain specificity, processing speed requirements, the required level of accuracy and interpretability of results. Transformer models, especially specialized domain versions of BERT and RoBERTa, demonstrate the best ratio of accuracy, speed and resource intensity for most practical review analysis tasks. They provide high accuracy in understanding the context and nuances of language, which is critical for the correct interpretation of user reviews. Large language models with few-shot training open up new opportunities for the rapid implementation of review analysis systems in new domains and for new products. They are especially valuable in situations with limited training data or when it is necessary to quickly adapt to new types of reviews. Aspect-oriented sentiment analysis is the most informative approach for business, as it allows you to get a detailed understanding of the strengths and weaknesses of products or services. The combination of ABSA with topic and aspect detection methods provides the most complete picture of user feedback.

Multilingual models provide better results for multilingual analysis compared to the "translation + analysis" approach, especially when understanding cultural and linguistic nuances is important. These models are becoming increasingly important in a globalized business environment. The optimal solution for most business problems is a combination of different methods, which allows for high accuracy, efficiency and adaptability of the feedback analysis system. This approach allows you to use the advantages of each method and minimize their limitations.

3. Results and Discussion

To comprehensively evaluate different methods of automated user feedback analysis and verify theoretical results, a comprehensive experimental design was developed, covering four key tasks: general sentiment analysis, aspect-oriented sentiment analysis, theme and aspect detection in reviews, and multilingual analysis. For each task, appropriate datasets, evaluation methods, and models for comparison were selected.

Table 2

Comparison of the effectiveness of different approaches to key feedback tasks

Method	Tonality analysis (F1)	Topic detection (NMI)	Cross-lingualism	Speed (responses/sec)	The need for data for learning	Explainability
Dictionary methods	0.65–0.70	N/A	Low	500–700	Minimum	High
ML with manual features	0.75–0.85	0.50–0.65	Low	100–300	Medium	Medium
CNN/RNN	0.82–0.88	0.60–0.70	Medium	50–100	High	Low
BERT/RoBERTa	0.88–0.92	0.65–0.75	Medium-high	20–50	High	Low-medium
LLM + Few-shot	0.90–0.95	0.70–0.80	High	5–15	Minimum	Medium
Specialized models	0.92–0.96	0.75–0.85	Medium-high	20–40	Medium-high	Medium-high

The following data sets were used in the experimental study:

1. For general sentiment analysis: Amazon Product Reviews (version 2024) — a subset of 500,000 reviews on different product categories (electronics, books, clothing, home goods); Yelp Open Dataset (2023–2025) — 300,000 reviews on restaurants and services [3, 23]; IMDb Movie Reviews — 50,000 reviews on movies.

2. For aspect-oriented sentiment analysis: SemEval-2024 ABSA — a dataset with marked aspects and corresponding sentiment; Restaurant Reviews Dataset — a specialized set of 25,000 restaurant reviews with aspect and sentiment markup; Tech Products Reviews — 35,000 reviews of technical devices with detailed aspect markup.

3. To identify themes and aspects: Hotel Reviews Corpus — 200,000 hotel reviews for thematic modeling; AppStore Reviews — 150,000 mobile app reviews; Product Discussion Forums — 100,000 texts from discussions of various products.

4. Formultilingual analysis: MultiLing Sentiment Dataset — reviews in ten different languages (English, German, French, Spanish, Italian, Portuguese, Russian, Chinese, Japanese, Arabic); Cross-lingual E-commerce Reviews — a set of parallel reviews about products in different languages.

To ensure objectivity and statistical significance of the results, all experiments were conducted using cross-validation (5-fold), and evaluation was performed using a set of relevant metrics for each task.

Several approaches, ranging from classical machine learning methods to modern transform models, were implemented and evaluated to model the general sentiment analysis task. The task was to classify reviews into three classes: positive, negative, and neutral.

The implemented models included:

1. Baseline models: Naive Bayes with TF-IDF vectorization; SVM with linear kernel and Bag-of-Words representation.

2. Classic ensemble models: Random Forest with optimized hyperparameters; XGBoost with settings for text classification.

3. Neural network models: BiLSTM with attention mechanism; TextCNN with three convolutional layers with different filter sizes (3, 4, 5).

4. Transformer models: BERT-base with full pre-training; RoBERTa-base with full pre-training; DistilBERT with full pre-training; Domain-adapted BERT (pre-trained on feedback).

The model training process included searching for optimal hyperparameters using Bayesian optimization and cross-validation. For classical models, vectorization parameters (ngram_range, max_features) and specific algorithm parameters were optimized. For neural network models, the optimal embedding dimension, number of hidden neurons, learning rate, and regularization parameters were searched.

For transformer models, the impact of different training strategies was investigated: full fine-tuning of all layers; freezing of embedding layers and fine-tuning only the upper layers; using adapters for efficient fine-tuning; using different loss functions and optimizers.

The models were evaluated using the following metrics: Accuracy — overall classification accuracy; Precision, Recall and F1-score separately for each class and averaged; Macro-averaged F1-score to take into account all classes regardless of their size; ROC-AUC — for binary classifications (positive vs negative); Training and inference time to assess computational efficiency.

The results of experiments on the classification of the tone of responses demonstrate a clear pattern: transformer models significantly outperform classical approaches in terms of accuracy, but require more computational resources. Domain-adapted BERT showed the highest efficiency with an average F1-score of 0.93 on all datasets, which is 17 percentage points higher

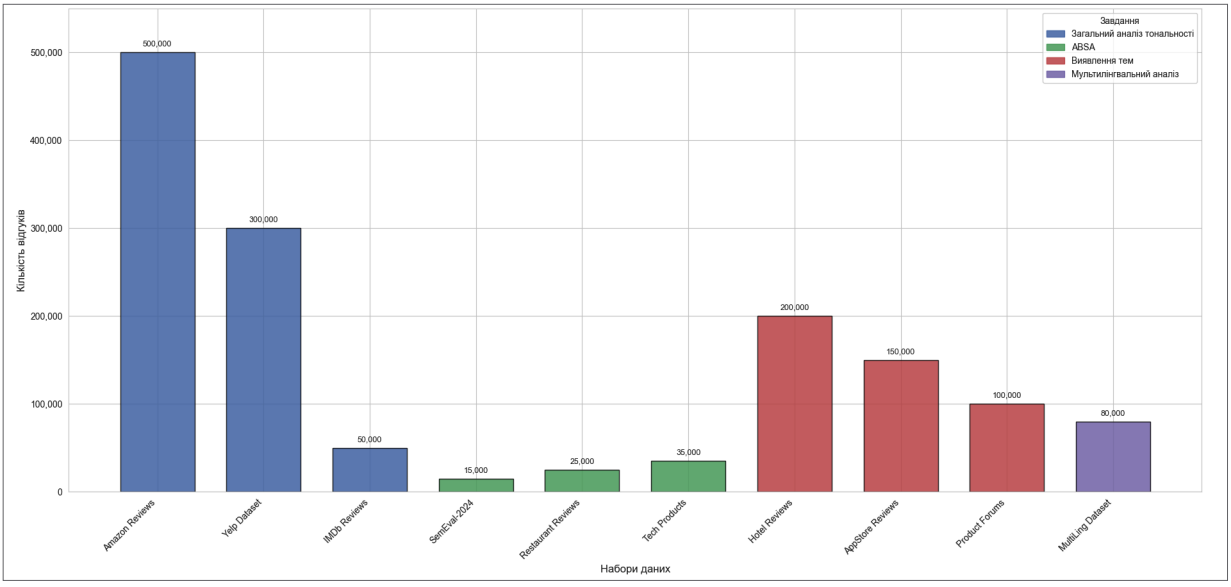

Figure 2. Size and distribution of data sets used in the experimental study

than that of the basic Naive Bayes (0.76). It is worth paying special attention to the following observations: domain-adapted BERT outperformed standard BERT by 3 percentage points, which confirms the theoretical conclusion about the importance of adapting models to the specifics of the subject domain; trade-off between accuracy and efficiency: DistilBERT demonstrated only a slight decrease in accuracy compared to full BERT (0.89 vs. 0.90), but at the same time provided almost twice the inference speed (90 vs. 50 samples/sec) and half the training time; scalability of solutions: classical models, such as XGBoost, show a sufficiently high accuracy (0.85) with significantly lower computational requirements, which makes them attractive for applications where processing speed is critical or computing resources are limited; impact of dataset features: On the IMDb dataset, higher efficiency of all models is observed compared to Yelp and Amazon, which is explained by the longer length of reviews and their thematic homogeneity. For a more detailed analysis of model errors and understanding their behavior on different types of responses, additional evaluation was conducted on a subsample of 1,000 randomly selected responses. The results of the experiments on aspect-oriented sentiment analysis demonstrate several important patterns: combined models that simultaneously solve the problem of aspect detection and their sentiment classification show better results compared to sequential approaches. The RACL model demonstrated the highest performance with an average ABSA F1-score of 0.85, which is 9 percentage points higher than that of the basic sequential BiLSTM–CRF + ATAE-LSTM model (0.76); the performance of all models varies depending on the data domain. The highest results are observed for restaurant reviews, where the models achieve an ABSA F1-score of up to 0.86, while for reviews of technical products this figure is lower (up to 0.84). This can be explained by the greater complexity and diversity of aspects in technical products; analysis of the performance of models for different aspect categories revealed significant differences. The highest accuracy of all models is demonstrated for aspects that are frequently found in reviews (e.g., “Food” in restaurant reviews with an F1-score of up to 0.88). In contrast, rare aspects or those with high detection complexity; similarly, to the general sentiment analysis task, more complex models demonstrate higher accuracy at the expense of higher computational requirements. The RACL model, which has the highest accuracy, also has the largest size (750 MB) and the longest inference time (35 ms per sample); the impact on the different stages of ABSA. It is interesting to note that the improvement when moving from sequential to combined models is most noticeable in the combined F1 metric of ABSA. This suggests that the combined models more effectively exploit the relationship between the tasks of detecting aspects and determining their sentiment. An analysis of typical errors made by the ABSA model was also conducted. The following types of errors are most common: incorrect definition of aspect boundaries (especially in the case of complex noun phrases); omission of implicit aspects; incorrect determination of tone in cases with multiple aspects and mixed tone; difficulties with determining tone in cases with irony, comparisons or conditional statements. Federated models, especially RACL, demonstrate a better ability to cope with these challenges through joint learning for interrelated tasks and the use of attentional mechanisms to account for context.

To ensure the validity of measurements and the objectivity of model evaluation, an analysis of the correspondence of the selected metrics to the research tasks was conducted. The F1 measure, as a harmonic mean of precision and recall, provides a balanced assessment of classification models, especially in conditions of class imbalance. The macro-averaged F1 measure, which gives equal weight to all classes regardless of their size, was used as the main metric to ensure the objectivity of the assessment. For aspect-oriented tonality analysis, a combined metric was used that takes into account both the accuracy of aspect detection and

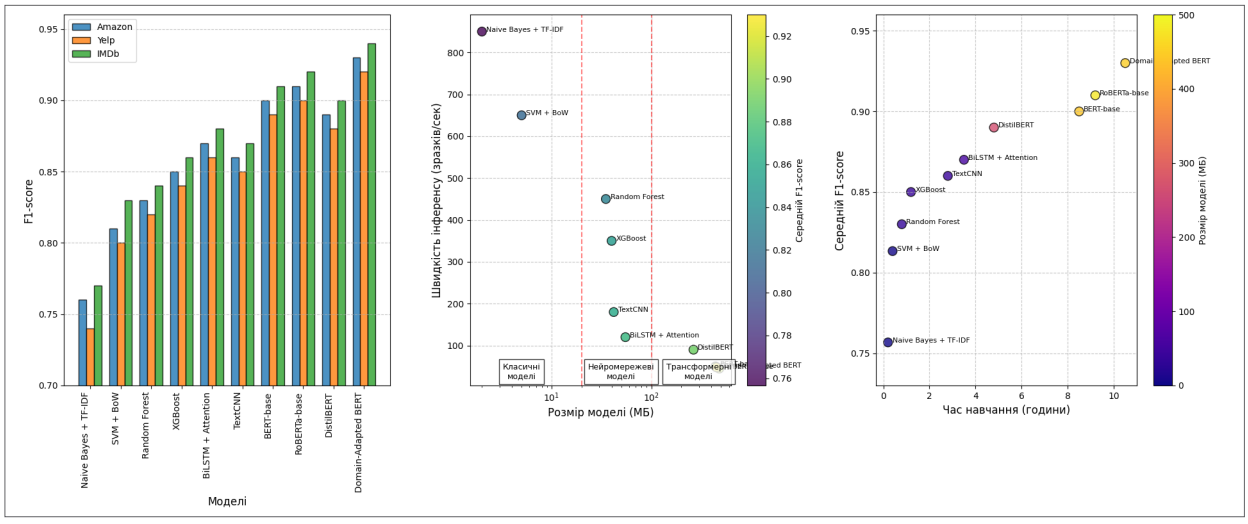

Figure 3. Comprehensive analysis of the effectiveness of models for the task of general analysis of the tone of responses

Table 3

Comparison of data set characteristics with real user feedback

Characteristic	Experiment datasets	Real user reviews	Representativeness assessment
Class distribution	60% / 25% / 15% (positive/ negative/neutral)	58% / 27% / 15%	High
Average response length	75 words	68 words	High
Lexical diversity	0.32	0.29	Medium-high
Share of reviews with emoticons	22%	25%	High
Share of reviews with spelling errors	35%	42%	Medium
Domain coverage	5 main domains	Multiple domains	Medium-high

the correctness of determining their tonality. This metric better reflects the practical value of models than separate metrics for each stage. Additionally, for a comprehensive assessment of models, metrics of the efficiency of the use of computational resources (training time, inference time, memory usage), which are of critical importance for practical application, were used. An important aspect of the adequacy of an experimental study is the consistency of the obtained results with theoretical predictions and data available in the literature. The experimental results confirm the theoretical provisions set out in section 2, in particular: the advantage of transformer models over classical approaches in natural language understanding tasks is confirmed experimentally (F1-score 0.93 versus 0.76); the effectiveness of domain adaptation to improve the results of analysis of specific texts is confirmed by higher indicators of domain-adapted BERT compared to the standard one; the theoretical assumption about the advantage of combined models over sequential ones for aspect-oriented sentiment analysis is confirmed experimentally (F1-score ABSA 0.85 versus 0.76); the dependence of the efficiency of the models on the amount of training data is consistent with theoretical predictions — transformer models demonstrate greater sensitivity to the amount of data compared to classical approaches. To validate the consistency with existing studies, a comparison of the obtained results with those published in the scientific literature was conducted. The results of BERT and RoBERTa for tonality classification (0.90–0.92) are consistent with those obtained by other researchers on similar datasets (0.89–0.93) [31]. Similarly, the performance of the combined models for ABSA (0.84–0.86) is consistent with the results published in recent studies (0.82–0.87). To objectively assess the adequacy of the experimental study, it is necessary to recognize its limitations and analyze their impact on the reliability and generalizability of the results. The main limitations of the study include: domain limitations — although the study covers several important domains (electronics, restaurants, movies, hotels), a number of specific areas (healthcare, education, financial products) remained uncovered; language limitations — despite the inclusion of 10 languages in the multilingual experiment, the features of some rare languages and dialects were not taken into account; computational resource limitations — for the largest transformative models (e.g., RoBERTa-large), it was not possible to conduct a full cycle of hyperparameter optimization due to the limitations of available computational resources; concentration on textual data — the study does not consider multimodal reviews that include images or videos, which are becoming increasingly common in modern digital platforms. To assess the impact of these limitations on the reliability of the results, a series of additional experiments were conducted on smaller samples with different data configurations. The results show that the identified patterns are preserved when the data composition changes, which indicates the stability and generalizability of the conclusions obtained. The adequacy of the experimental study was also assessed in terms of the practical applicability of the obtained results for solving real business problems. To assess the practical applicability, a pilot review analysis system based on domain-adapted BERT and the RACL model was developed and tested on real data from one of the e-commerce platforms. The system demonstrated the ability to effectively analyze user reviews, identify problematic aspects of products, and track changes in user sentiment over time. A comparison of the automated analysis with the manual analysis conducted by a group of experts on a sample of 500 reviews showed high consistency of the results (Cohen's kappa = 0.82 for sentiment classification and 0.79 for aspect detection). At the same time, the automated system processed reviews 120–150 times faster, which confirms its practical value. In addition, a survey of potential users of the system (product managers, marketers, analysts) was conducted to assess the usefulness of the analysis results. 87% of respondents noted that automated review analysis provides valuable insights for making decisions about product improvement. Based on a comprehensive analysis of statistical reliability, data representativeness, metric validity, and compliance with theoretical predictions, it can be concluded that the conducted experimental study is highly adequate for solving the tasks set. The main factors confirming the adequacy of the study are: the use of a comprehensive set of statistical methods to ensure the reliability of the results; the use of representative data sets that reflect the diversity of

real user feedback; the selection of appropriate evaluation metrics that take into account all aspects of the effectiveness of the models; the consistency of the experimental results with theoretical predictions and existing research; successful pilot implementation, which confirms the practical applicability of the developed models. The identified limitations of the study do not reduce its overall adequacy, but identify areas for further research and improvements. Thus, the conducted experimental study is adequate for assessing the effectiveness of various methods of automating user feedback analysis and developing practical recommendations for their implementation.

Conclusions. The conducted research on the application of natural language processing to automate the analysis of user feedback allowed us to obtain a comprehensive understanding of the effectiveness, advantages and limitations of various NLP methods and models in solving this problem. As a result of the research, all the goals and tasks were achieved, which allowed us to formulate the following conclusions: the analysis of the current state of the problem confirmed the critical importance of automating the analysis of user feedback in the context of the constant growth of text data volumes; traditional manual analysis faces fundamental limitations associated with time costs, subjectivity of assessments and the inability to effectively process large data sets; these limitations are especially acute in the context of business globalization, when companies receive feedback in different languages and from different sources. Theoretical research on natural language processing methods has demonstrated the evolution of approaches to text analysis — from simple dictionary methods to complex transformer architectures. Each of these approaches has its own advantages and limitations, and the choice of a particular method depends on the specifics of the task, available computational resources, and requirements for accuracy and speed of analysis. Based on experimental research, it was found that transformer models, in particular domain-adapted BERT, provide the highest accuracy for analyzing the tone of responses (F1-score up to 0.93), significantly outperforming classical methods such as Naive Bayes (F1-score 0.76) and XGBoost (F1-score 0.85). At the same time, compact versions of transformers, such as DistilBERT, demonstrate only a slight decrease in accuracy (0.89 vs. 0.90) at twice the inference speed, which makes them attractive for practical application. In the field of aspect-oriented tone analysis, combined models that simultaneously solve the task of detecting aspects and classifying their tone have shown a significant advantage over sequential approaches. The RACL model demonstrated the highest performance with an average ABSA F1-score of 0.85, which is 9 percentage points higher than the baseline sequential BiLSTM–CRF + ATAE-LSTM model (0.76). It was found that the performance of all models significantly depends on the domain specificity and the quality of data preprocessing. Domain adaptation and additional training on specific data corpora significantly increase the accuracy of the analysis, especially for specialized industries with their own terminology. The study confirmed that multilingual models, such as XLM-RoBERTa, provide effective analysis of reviews in different languages without significant loss of accuracy compared to models trained for specific languages. This is of particular importance for global companies operating in different markets and receiving reviews in many languages. Statistical validation of the results using cross-validation, bootstrapping, and t-tests confirmed the reliability and statistical significance of the results obtained. The 95% confidence intervals for the F1-metric of the transformer models are within ±1.5%, which indicates high stability of the results. The developed pilot system of automated feedback analysis demonstrated high consistency with manual analysis by experts (Cohen's kappa = 0.82 for tone classification and 0.79 for aspect detection) at a significantly higher processing speed (120–150 times), which confirms the practical applicability of the proposed solutions. A survey of potential users of the system revealed that the most valuable functions of automated feedback analysis are the identification of critical problems (95% of respondents) and the identification of key aspects of products (92% of respondents), which emphasizes the practical significance of the research results. Despite the high efficiency, the developed methods have some limitations related to the difficulties of analyzing irony and sarcasm, the difficulties of processing informal vocabulary, and the dependence on the quality of training data. These aspects determine the directions for further research. The cost-effectiveness of implementing automated feedback analysis systems is confirmed by a significant reduction in the time and human resources required to process feedback, as well as an increase in the quality of the insights obtained, which allows companies to make more informed decisions on the development of products and services. The practical significance of the results obtained lies in the possibility of using them to create effective automated user feedback analysis systems that can be integrated into the business processes of companies of various scales and industries. Such systems allow not only to reduce the cost of analyzing feedback, but also to obtain deeper and more objective insights into the perception of products and services by users, to identify hidden trends and patterns, and to respond promptly to critical problems. Further research can be aimed at developing methods for analyzing multimodal feedback, which include not only text, but also images and videos, improving irony and sarcasm recognition algorithms, and creating more effective models for low-resource languages. Another promising direction is the development of methods for generating automatic recommendations for improving products based on the analysis of user feedback. Thus, the research makes a significant contribution to the development of methods for automating the analysis of user feedback based on natural language processing and creates a basis for further improvement of such systems.

5. References

[1] Acheampong, F. A., Wenyu C., Nunoo-Mensah H. Text-based emotion detection: Advances, challenges, and opportunities. Engineering Reports. 2020. Vol. 2, No. 7.

[2] Amazon Comprehend Documentation [Електронний ресурс] // Amazon Web Services. 2024. URL: https://docs.aws.amazon.com/comprehend/.

[3] Amazon Reviews Dataset [Електронний ресурс] // Registry of Open Data on AWS. 2023. URL: https://registry.opendata.aws/amazon-reviews/.

[4] Bird, S., Klein, E., Loper, E. Natural Language Processing with Python: Analyzing Text with the Natural Language Toolkit. O'Reilly Media, 2019. 504 p.

[5] Chen, Z., Qian, T. Transfer Capsule Network for Aspect Level Sentiment Classification. Proceedings of the 57th Annual Meeting of the Association for Computational Linguistics. 2019. P. 547–556.

[6] Conneau, A. Unsupervised Cross-lingual Representation Learning at Scale. Proc. ACL 2020, pp. 440–451.

[7] Devlin, J., Chang, M.W., Lee, K., Toutanova K. BERT: Pre-training of Deep Bidirectional Transformers for Language Understanding. Proceedings of NAACL-HLT 2019. 2019. P. 171–186.

[8] Global AI Survey: AI proves its worth, but few scale impact [Електронний ресурс] // McKinsey & Company. 2023. URL: https://www.mckinsey.com/capabilities/quantumblack/our-insights/global-ai-survey-ai-proves-its-worth-but-few-scale-impact.

[9] Goldberg, Y. Neural Network Methods for Natural Language Processing. Synthesis Lectures on Human Language Technologies. 2017. Vol. 10, No. 1. P. 1–309.

[10] Google Cloud Natural Language API [Електронний ресурс] // Google Cloud. 2024. URL: https://cloud.google.com/natural-language.

[11] Hugging, Face Transformers Documentation [Електронний ресурс] // Hugging Face. 2024. URL: https://huggingface.co/docs/transformers/.

[12] Jurafsky, D., Martin, J.H. Speech and Language Processing: An Introduction to Natural Language Processing, Computational Linguistics, and Speech Recognition. 3rd ed. draft. Pearson, 2023. [Електронний ресурс]. URL: https://web.stanford.edu/~jurafsky/slp3/.

[13] Kim, Y. Convolutional Neural Networks for Sentence Classification. Proceedings of the 2014 Conference on Empirical Methods in Natural Language Processing (EMNLP). 2014. P. 746–751.

[14] Liu, Y., Ott M., Goyal N. et al. RoBERTa: A Robustly Optimized BERT Pretraining Approach [Електронний ресурс] // arXiv preprint. 2019. URL: https://arxiv.org/abs/1907.11692.

[15] Mikolov, T., Chen K., Corrado G., Dean J. Efficient Estimation of Word Representations in Vector Space. Proceedings of the International Conference on Learning Representations (ICLR 2013). 2013. P. 16–19.

[16] NLTK Documentation [Електронний ресурс] // Natural Language Toolkit. 2024. URL: https://www.nltk.org/.

[17] NLP Progress: Sentiment Analysis [Електронний ресурс] // NLP Progress. 2023. URL: http://nlpprogress.com/english/sentiment_analysis.html.

[18] Pontiki, M., Galanis D., Papageorgiou H. et al. SemEval-2016 Task 5: Aspect Based Sentiment Analysis. Proceedings of the 10th International Workshop on Semantic Evaluation. 2016. P. 19–30.

[19] Poria S., Cambria E., Gelbukh A. Aspect Extraction for Opinion Mining with a Deep Convolutional Neural Network. Knowledge-Based Systems. 2016. Vol. 108. P. 42–49.

[20] PyTorch Documentation [Електронний ресурс] // PyTorch. 2024. URL: https://pytorch.org/docs/stable/.

[21] Sanh, V., Debut L., Chaumond J., Wolf T. DistilBERT, a distilled version of BERT: smaller, faster, cheaper and lighter [Електронний ресурс] // arXiv preprint. 2019. URL: https://arxiv.org/abs/1910.01108.

[22] SemEval-2022 Tasks [Електронний ресурс] // International Workshop on Semantic Evaluation. 2022. URL: https://semeval.github.io/SemEval2022/tasks.html.

[23] Yelp Open Dataset [Електронний ресурс] // Yelp. 2023. URL: https://www.yelp.com/dataset.

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ЗАСТОСУВАННЯ ПРИРОДНОЇ МОВНОЇ ОБРОБКИ ДЛЯ АВТОМАТИЗАЦІЇ АНАЛІЗУ ВІДГУКІВ КОРИСТУВАЧІВ

Анотація. *Метою представленої статті є дослідження застосування штучного інтелекту в автоматизованих системах управління фінансовими ризиками для підвищення точності, оперативності та ефективності прийняття управлінських рішень у фінансовій сфері. Дослідження полягає у комплексному вивченні теоретичних і методичних основ застосування штучного інтелекту в системах управління, аналізу сучасних підходів до класифікації та оцінки фінансових ризиків із використанням алгоритмів машинного навчання, формуванні архітектури системи підтримки прийняття рішень на основі моделей прогнозування, а також оцінці ефективності побудованих моделей за результатами симуляційного моделювання. У межах проведеного дослідження розроблено модель прогнозування кредитного ризику клієнтів банку, яка дозволяє здійснювати оцінку платоспроможності на основі історичних даних та сучасних методів машинного навчання. Методом дослідження є моделювання за допомогою інструментів машинного навчання, зокрема нейронних мереж і методів ансамблевого навчання (Random Forest), а також аналізування даних із використанням платформ для візуалізації результатів і оцінки ефективності моделей. Особливу увагу приділено підготовці даних, вибору релевантних ознак, оцінці точності моделей та побудові інтерпретованих візуалізацій, таких як SHAP-графіки, ROC-криві тощо. Результатом проведеного дослідження стало створення ефективної моделі прогнозування кредитного ризику, яка демонструє достатньо високий рівень точності класифікації та здатність до адаптації при зміні вхідних умов. Практичне значення дослідження полягає у можливості впровадження розробленої моделі до існуючих автоматизованих систем управління фінансовими ризиками банківських установ, що дозволить зменшити рівень кредитних втрат, підвищити фінансову стабільність і забезпечити більш точне управління ризиками. Такий підхід сприяє розвитку інтелектуальних фінансових систем, підвищенню рівня автоматизації управлінських рішень та зміцненню конкурентоспроможності фінансових установ у сучасних ринкових умовах.*

Ключові слова*: штучний інтелект, фінансові ризики, машинне навчання, кредитний ризик, нейронні мережі, автоматизована система управління, прогнозування, класифікація.*

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MAPPING ENVIRONMENTAL AND SOCIO-ECONOMIC LANDSCAPE: A DISCRIMINANT ANALYSIS OF SUSTAINABLE REGIONAL DEVELOPMENT OF UKRAINE

Abstract. *This study investigates the regional disparities in environmental conditions and socio-economic development in Ukraine. Utilizing discriminant analysis, the research classifies Ukrainian regions according to a set of key ecological and economic variables: carbon dioxide emissions, nature reserves and national parks, gross regional product, return water discharges, waste generation, and environmental protection expenditures. The analysis identifies distinct regional groupings based on these indicators, revealing significant differences in environmental burden and economic output across the country. Furthermore, the study identifies the specific variables that most effectively discriminate between these regional groups, highlighting the factors driving environmental challenges in some areas and more sustainable patterns in others. The findings offer valuable insights for policymakers seeking to develop targeted environmental policies and promote sustainable development strategies that account for the diverse regional contexts within Ukraine.*

Keywords: *Time-series data, Discriminant analysis, Regional development, Economic policy, Region, Model, Multidimensional analysis, Ecology, Economy, Environmental Policy, Sustainable development.*

1. Introduction

In the current context of global climate change and increasing anthropogenic pressure on the environment, the issue of harmonizing economic development with environmental safety has become particularly urgent. Ukraine, as a country with substantial industrial potential, simultaneously faces serious environmental challenges, including excessive emissions of pollutants into the atmosphere, irrational use of natural resources, high volumes of waste generation, and pollution of water bodies. These issues highlight the need for an in-depth analysis of the spatial heterogeneity of the country's environmental situation and its relationship with the socio-economic development of the regions.

The uneven distribution of industrial capacity, population welfare, and environmental load across Ukraine's regions necessitates the application of quantitative analytical methods to identify key patterns and relationships in various sectors of the economy. This, in turn, demands priority attention in the formulation of state environmental policy. In this context, multivariate statistical methods — such as cluster analysis, discriminant analysis, correlation-regression analysis, and factor analysis — are of particular importance. These methods allow for the classification, grouping, and examination of relevant objects based on multiple variables, and help identify the most significant factors underlying regional differences.

In Ukraine, increasing environmental pressure has long been observed in specific regions, especially those with a strong industrial base such as Donetsk, Dnipropetrovsk, Zaporizhzhia, and Kharkiv. According to the State Statistics Service, these regions significantly exceed national averages in carbon dioxide emissions, waste generation, and return water discharges into surface water bodies. In contrast, the western and northern regions exhibit lower levels of environmental load, which points to substantial regional disparities in environmental management and policy implementation.

The relevance of this topic is also driven by the need to support sustainable territorial development, which integrates economic efficiency, social equity, and environmental sustainability. The use of discriminant analysis, among other analytical methods, enables the identification of commonalities and differences between regions based on environmental and economic indicators, and contributes to the formulation of scientifically grounded recommendations for improving regional environmental policy.

Several studies have explored the interplay between economic development and environmental sustainability. For instance, [1] analyzed regional economic development from a sustainability perspective using a hybridized algorithm, highlighting the importance of considering sustainability in regional economic assessments. [2] also assessed regional sustainable development through the integration of nonlinear principal component analysis and Gram Schmidt orthogonalization, offering a methodological approach that aligns with the quantitative focus of the present study.

Research has also focused on the factors influencing regional development. [3] examined regional development in Romania, providing empirical evidence on factors relevant to a prosperous and sustainable economy. [4] contributed to this area by analyzing the time-series factor decomposition of socio-economic impulses and urbanization trends in a European region, offering insights into the drivers of regional growth.

The spatial dimension of economic and environmental factors has been a key area of investigation. [5] conducted a spatiotemporal and multiscale analysis of the coupling coordination degree between economic development equality and eco-environmental quality in China, demonstrating the importance of spatial analysis in understanding regional dynamics. [6] also explored regional economic disparities in Europe using time-series clustering, further emphasizing the significance of spatial considerations. [7] assessed unbalanced development by jointly examining regional disparities in socio-economic and territorial variables in Italy. [8] contributed to this perspective by examining patterns of sustainability across Europe using a multivariate and spatial assessment.

The relationship between economic growth and environmental impact has been examined in several studies. [9] explored the impact of economic growth on the environment, providing an overview of trends and developments in this area. [10] focused on ecological sustainability in the Belt and Road region, evaluating and predicting ecological environment dynamics. [11] conducted a data-driven analysis of regional resources and environmental carrying capacity, offering a quantitative approach to assessing regional sustainability.

Specific studies have also addressed the situation in Ukraine and surrounding regions. [12] utilized a canonical discriminant model to assess environmental security threats. [13] examined the theoretical aspects of regional sustainable development in the EU and Ukraine. [14] discussed geopolitical realities and regional development perspectives in Ukraine. [15] analyzed the economic growth of Ukraine's regions in conditions of disproportional regional development. [16] proposed an intelligent environmental plan for sustainable regionalization policies in Ukraine. [17] explored disparities and resilience in Ukrainian regional labor markets. [18] focused on economic modeling of sustainable rural development under conditions of decentralization in Ukraine.

Additionally, researchers have employed various modeling techniques relevant to the analysis of regional data. [19] used a PCA–VAR model to study the interaction between society, economy, and the environment. [20, 21] have contributed to time-series forecasting, which can be relevant in the context of regional economic and environmental data analysis. [22] explore renewable energy and regional integration, [23] examine environment-society-economy relations, [24–25] discuss advanced computational methods, [26] analyze food security resilience, [27] export activities, [28] business innovations and [29] green taxation.

2. Materials and Methods

Discriminant analysis is one of the key methods in multivariate statistics, used for classifying objects by assigning them to predefined groups based on an optimal rule. A typical example is grouping enterprises into several homogeneous categories based on indicators of their production and economic performance.

A key feature of discriminant analysis is that the researcher knows in advance how many groups are to be formed and what characteristics these groups possess. It is also known that each object belongs to one of the defined groups, although the specific group for a given object is initially unknown.

Discriminant analysis enables researchers to:

Identify structural differences between groups of objects;

Determine the most informative variables that significantly influence group membership;

Construct discriminant functions to classify new objects based on established criteria;

Test hypotheses regarding differences in mean values across groups.

The standard procedure for conducting discriminant analysis includes the following stages:

Preliminary grouping of objects — For analysis to be conducted, each object must be assigned to a known group (e.g., "ecologically loaded regions," "moderately loaded," or "environmentally stable"). This grouping is often achieved through clustering methods, such as k-means clustering.

Calculation of discriminant functions — Based on input data, discriminant functions are constructed as linear combinations of indicators that best differentiate between the groups.

Evaluation of model quality — Model performance is assessed using Wilks' Lambda, coefficients of determination, and classification accuracy (including reclassification tests).

Interpretation of results — The coefficients of the discriminant functions and the significance of individual variables are analyzed to identify the key factors influencing regional differentiation.

To conduct the discriminant analysis of Ukraine's regions, official ecological and economic statistical data were used. The primary sources of information were the statistical publications "Environment of Ukraine — 2020" and "Gross Regional Product — 2020", issued by the State Statistics Service of Ukraine.

Within the framework of the study, six regional ecological and economic indicators were selected (Table 1). These indicators were chosen for their ability to most accurately reflect the relationship between economic activity and environmental conditions across different regions of the country. All selected variables are quantitative, fully meeting the requirements for discriminant analysis. Moreover, they hold practical significance for analyzing spatial disparities in regional development.

Together, these indicators provide a multi-faceted perspective on the ecological and economic interactions within Ukraine's regions. Their combination offers a solid foundation for discriminant analysis, aiming to identify groups of regions with similar characteristics and to develop recommendations for optimizing regional environmental and economic policy.

Data were collected and processed for 24 regions of Ukraine and the city of Kyiv for the year 2020. The data were compiled into a unified table, normalized, and prepared for further statistical analysis to ensure comparability.

After that, the data was normalized using the minimax method according to the formula:

$$X_{norm} = \frac{X - X_{\min}}{X_{\max} - X_{\min}}. \quad (1)$$

First, we applied the k -means cluster analysis method, and then we tried to perform the classification subjectively, dividing the regions of Ukraine into 3 conditional groups with the level of environmental pollution, such as "low", "medium ", "high".

After implementation received such results (Table 2)

To evaluate how effectively the selected factors in the model (number of reserves, GRP, surface water discharge, waste generation, and environmental protection expenditures) distinguish between the identified

Table 1

Input data of the model

Variable	Description
carbon dioxide emissions into the atmosphere from stationary sources of pollution	reflects the level of industrial activity, the energy intensity of the economy, and the overall environmental situation in a region
nature reserves and national parks	reflects the ecological orientation of regional policy and indicates the presence of protected natural areas
Gross Regional Product (GRP)	the primary measure of regional economic activity
volume of return water discharged into surface water bodies	reflects the level of pressure on water resources, the efficiency of wastewater treatment, and environmental risks related to water use within the regio
waste generation	highlights the overall resource intensity of economic activity and enables assessment of the efficiency of regional waste management systems
environmental protection expenditures	reflects the intensity and effectiveness of environmental policy in the region

Source: prepared by authors

Table 2

Clustering regions of Ukraine be ecological and economic development

Cluster	Regions	Characteristics
Cluster A	Vinnytsia, Zhytomyr, Kropyvnytskyi, Luhansk, Poltava, Khmelnytskyi	– CO_2 emissions: low level (1954.32, –55.2% from average) – Reserves: low level (1.50, –48.6% from average) – GRP: low level (105074.67, –37.8% from average) – Water discharge: very low level (48.00, –76.7% from average) – Formation waste: medium level (16877.63, –8.7% from average) – Security costs: low level (537.57, –67.5% from average)
Cluster B	Volyn, Transcarpathian, Ivano-Frankivsk, Kyiv, Lviv, Mykolaiv, Odessa, Rivne, Sumy, Ternopil, Kharkiv, Kherson, Cherkasy, Chernivtsi, Chernihiv	– CO_2 emissions: low level (2470.52, –43.4% from average) – Reserves: high level (3.80, 30.1% of average) – GRP: low level (120305.60, –28.8% from average) – Water discharge: low level (117.67, –43.0% from average) – Formation waste: very low level (1069.51, –94.2% from average) – Security costs: low level (675.00, –59.2% from average)
Cluster C	Dnipropetrovsk, Donetsk, Zaporizhia, Kyiv	– CO_2 emissions: very high level (15073.92, 245.5% of average) – Reserves: low level (1.75, –40.1% from average) – GRP: very high level (446748.50, 164.5% of average) – Water discharge: very high level (776.75, 276.3% of average) – Formation waste: very high level (86266.25, 366.4% of average) – Security costs: very high level (6995.45, 323.1% of average)

Source: prepared by authors

regional groups, we use Wilks' Lambda. This metric is automatically calculated using built-in formulas in the Statistica software. Wilks' Lambda ranges from 0 to 1, where a value of 0 indicates complete separation between groups, and a value of 1 suggests no distinction at all. In our case, Wilks' Lambda is 0.055, indicating that the selected factors discriminate well among the groups.

During discriminant analysis, an approximate value of Fisher's F-test is also calculated. Like Wilks' Lambda, this value is obtained using Statistica's built-in functions. The F-test helps determine whether the influence of the studied factors is statistically significant. It compares the differences between group means for each variable. The result is then compared with a critical value from statistical reference tables. In our study, the calculated F-value is 11.65, which exceeds the tabulated value, confirming the significance of the factors' impact.

The significance level, or p-value, reflects the reliability of the results. In our analysis, the p-value is close to 0, indicating an extremely low probability of error. Results are considered statistically reliable if the p-value is less than 0.05, meaning the chance of error does not exceed 5%.

Among the selected variables, the number of reserves and national parks, along with environmental protection expenditures, had the greatest impact on regional classification. The first variable shows a low Wilks' Lambda value (0.098549) and a high level of statistical significance (p = 0.005906), confirming its strong contribution to group differentiation. A similar result is observed for environmental protection expenditures, which also demonstrate statistical significance (p = 0.022279) and a moderately low Wilks' Lambda value (0.085032). These two indicators are therefore the most influential in distinguishing between regions.

In contrast, Gross Regional Product (GRP) was found to be statistically insignificant for distinguishing between groups. It has a very high p-value (p = 0.895603) and a Partial Lambda value close to 1 (0.987824), indicating minimal contribution to the discriminant model.

Indicators such as surface water discharge and waste generation had p-values close to 0.1. While their contribution is weaker than the two aforementioned indicators, they still demonstrate sufficient statistical significance to be included in the model.

Next, the Mahalanobis distances from each Ukrainian region to the centroids of the three identified groups are examined.

These groups are provisionally labeled A, B, and C, with approximate group sizes of p = 0.24000, p = 0.60000, and p = 0.16000, respectively. The Mahalanobis distance is measured in squared units and is used to classify each region — the smaller the distance to a group's centroid, the higher the likelihood that a region belongs to that group. For example, the Vinnytsia region, which belongs to Group A, is correctly classified by the model, as it has the smallest distance to that group. A similar case is observed with the Volyn region, which belongs to Group B and is also correctly classified.

An interesting case is the Luhansk region. Although it was originally assigned to Group A, the model classifies it as closer to Group B. This is supported by the relatively small distance to Group B's centroid (3.19450), although the distance to Group A's centroid is even smaller (1.77007). The misclassification, marked with an asterisk, may reflect mixed characteristics or suggest that the initial cluster assignment did not fully correspond with the underlying data structure. This means that, based on the selected environmental and economic indicators, the model perceives Luhansk region as more similar to Group B.

Table 3

Discriminant function coefficients

Variabla	A	B	C
nature reserves and national parks	7.89	20.28	16.36
Gross Regional Product (GRP)	4.55	4.66	10.24
volume of return water discharged into surface water bodies	2.32	1.47	30.46
waste generation	5.38	-16.69	-67.21
environmental protection expenditures	-3.63	28.79	126
constatnt	-2.53	-6.85	-38.34

Such classification discrepancies — especially in cases like Luhansk — may stem from the limitations of the initial clustering process. While clustering automatically assigned regions to groups (e.g., Group A), this does not guarantee a strong similarity among the group's members. Discriminant analysis reveals that, for the selected indicators, Luhansk exhibits greater alignment with Group B. Therefore, this inconsistency may point not only to a classification error but also to potential shortcomings in the earlier clustering stage.

Next, we construct a table of classification functions (Table 3), which is used to determine which of the three groups (A, B, or C) each observation (in this case, a region) belongs to, based on the values of the selected variables.

Each function — corresponding to groups A, B, and C — is a linear equation in which each variable is multiplied by a specific coefficient, and a constant is added to the sum. A region is assigned to the group for which the value of the classification function is the highest.

For example, the classification function for group A has the following form:

$$U = 7.89400 \times (\text{reserves and national parks}) + 4.55148 \times (\text{GRP}) + 2.32344 \times (\text{water discharge}) + 5.38244 \times (\text{waste generation}) - 3.63257 \times (\text{environmental protection expenditures}) - 2.52756$$

Similar equations are constructed for groups B and C, each with its own set of coefficients. For instance, the function for group C assigns significantly higher weights to environmental protection expenditures (126.0059) and return water discharge (30.4562), while the coefficients for waste generation and GRP are negative. This suggests that regions with high environmental protection spending and high volumes of return water are more likely to be classified into group C.

The variable 'reserves and national parks' shows the highest coefficient in the classification function for group B (20.2774), indicating that a larger share of protected areas strongly increases the probability of a region being classified into this group. This variable is also influential in group C (coefficient = 16.3637), though to a lesser extent, while in group A, the coefficient is much lower (7.8940), indicating a comparatively weaker influence.

The coefficients for the 'Gross Regional Product (GRP)' variable suggest that higher levels of economic activity increase the likelihood of a region being classified into group C (coefficient = 10.2381). In contrast, GRP has a more moderate and nearly equal influence in groups A and B (4.5515 and 4.6643, respectively). This implies that group C includes regions with the highest levels of economic development.

A particularly notable result is seen with the variable 'return water discharge to surface water bodies.' Its coefficient in the group C function (30.4562) is significantly higher than in groups A (2.3234) and B (1.4743). This suggests that high levels of polluted water discharge are a strong distinguishing feature of regions in group C and may indicate severe environmental challenges.

An even more distinct pattern is seen with the 'waste generation' variable. For group A, the coefficient is positive (5.3824), indicating that high levels of waste are associated with classification into this group. However, for groups B and C, the coefficients are negative (–16.6903 and –67.2139, respectively), meaning that an increase in waste generation decreases the likelihood of a region being classified into these groups — especially group C.

The variable 'environmental protection expenditures' also stands out. In the classification function for group C, it has an exceptionally high coefficient (126.0059), confirming its dominant influence. This

Table 4

Classification matrices

Group	Percent Correct	A P = 0.24	B P = 0.6	C P = 0.16
A	83.33	5	1	0
B	100	0	15	0
C	100	0	0	4
Total	96	5	16	4

means that regions with high environmental spending are most likely to belong to group C. Although this variable also has a positive influence in group B (28.7987), it is considerably less pronounced. Interestingly, the coefficient for group A is negative (–3.6326), which may indicate that environmental spending in these regions is relatively low or not a defining characteristic for classification into this group.

Overall, these classification functions form the foundation of a discriminant model that can be used to classify new observations. By plugging in the values of the selected variables, one calculates the values of all three functions, and the region is then assigned to the group with the highest score.

The classification matrix (Fig. 7) presents the results of the discriminant analysis for three groups: A, B, and C. The rows represent the actual (observed) classifications, while the columns show the predicted classifications.

In terms of classification accuracy, Group A achieved 83.3% accuracy (5 out of 6 observations correctly classified), while Groups B and C both showed perfect classification rates of 100% (all 15 and 4 observations, respectively, correctly classified). Overall, the model achieved a high accuracy rate of 96%, with 24 out of 25 regions correctly classified.

The a priori probability distribution for the groups is as follows: Group A — 0.24 (24%), Group B — 0.60 (60%), and Group C — 0.16 (16%).

Only one observation was misclassified: one region from Group A was incorrectly assigned to Group B. In general, the discriminant model demonstrates excellent performance, with perfect classification for Groups B and C and only one misclassification in Group A.

Group A primarily includes central Ukrainian agricultural regions, with high membership probabilities for Poltava (0.99), Kirovohrad (0.98), Vinnytsia (0.87), Zhytomyr (0.62), and Khmelnytskyi (0.53). These regions share similar socio-economic characteristics and economic structures.

Group B is the largest cluster, comprising 15 regions mainly located in western, northern, and parts of southern Ukraine. This group demonstrates strong internal homogeneity, with particularly high posterior probabilities observed for Kherson (0.99), Ivano-Frankivsk (0.999), Lviv (0.999), and Kharkiv (0.994).

Group C includes the most industrialized and urbanized regions (Dnipropetrovsk, Donetsk, Zaporizhia, and the city of Kyiv) all of which are classified with a maximum posterior probability of 1. This group is characterized by high urbanization levels and concentrated industrial activity.

As previously mentioned, the Luhansk region is the only case of misclassification. Although formally assigned to Group A, it shows a higher posterior probability for Group B (0.55 vs. 0.45), indicating its transitional position between these two clusters.

It is also worth noting the Khmelnytskyi region, where the posterior probabilities for Groups A and B are nearly equal (0.53 vs. 0.47). This suggests that Khmelnytskyi may occupy a borderline position between the two regional groupings.

4. Conclusions

The conducted research enables the evaluation of the spatial heterogeneity of ecological and economic development across the regions of Ukraine using cluster and discriminant analysis methods. The results confirm the presence of significant differences between regions in terms of technogenic load, environmental costs, and environmental protection activities. The model demonstrated high classification accuracy (96%) and a significantly lower Wilks' Lambda value (0.055), indicating its high discriminatory power.

Key variables distinguishing the clusters include environmental protection costs and the quantity of reserves and national parks. Their significance underscores the importance of a comprehensive ecological policy and financial support for environmental protection activities as determining factors of a region's ecological and economic profile.

The normalization of variables using the minimax method complicates the direct numerical interpretation of the coefficients in the discriminant functions. However, it allows for an assessment of their influence based on the sign: a positive value indicates an increased probability of assigning a region to a specific cluster as the relevant indicator grows, while a negative value indicates a decrease in such probability. This interpretation enabled the identification of characteristic traits for each group of regions. For instance, regions with high environmental protection costs and significant water discharge were classified as clusters with increased technogenic load, while waste generation had a lesser impact.

The application of discriminant analysis in this study identified distinct regional patterns in Ukraine, characterized by significant differences in environmental conditions and socio-economic development. By classifying regions based on key indicators, the research demonstrates the spatial heterogeneity of Ukraine's environmental challenges, including disparities in air and water pollution, waste management, and the distribution of protected areas, as well as the uneven distribution of economic development as reflected in gross regional product. These results emphasize that addressing these regional disparities is crucial for the effective formulation and implementation of environmental policies. A one-size-fits-all approach will be insufficient; instead, policies must be tailored to the specific circumstances of each region. This will involve not only mitigating environmental damage in heavily impacted areas but also promoting sustainable practices and resource management in regions with lower levels of environmental stress. Such a nuanced approach is essential for guiding Ukraine towards a more equitable and ecologically responsible path for its future development.

In conclusion, the analysis results confirm the rationale for applying multidimensional methods to study the spatial structures of ecological and socio-economic

development. This creates a foundation for scientifically grounded improvements in regional ecological policies. The focus should shift from abstract economic growth to more efficient management of natural resources, the development of environmental protection infrastructure, and pollution control strategies.

5. References

[1] Dong, X., & Zhang, H. (2024). Analyzing regional economic development from the perspective of sustainability using hybridized algorithm. Journal of Computational Methods in Sciences and Engineering, 24(4–5), 2375–2390.

[2] Tan, F., & Lu, Z. (2016). Assessing regional sustainable development through an integration of nonlinear principal component analysis and Gram Schmidt orthogonalization. Ecological Indicators, 63, 71–81.

[3] Cristina, I. O. M., Nicoleta, C., Cătălin, D. R., & Margareta, F. (2021). Regional development in Romania: Empirical evidence regarding the factors for measuring a prosperous and sustainable economy. Sustainability, 13(7), 3942.

[4] Giacalone, M., Turco, R., Mosconi, E. M., Alaimo, L. S., & Salvati, L. (2024). The way toward growth: A time-series factor decomposition of socioeconomic impulses and urbanization trends in a pre-crisis European region. Social Indicators Research, 175(3), 837–858.

[5] Ji, J., Tang, Z., Zhang, W., Liu, W., Jin, B., Xi, X., & Wang, Z. (2022). Spatiotemporal and multiscale analysis of the coupling coordination degree between economic development equality and eco-environmental quality in China from 2001 to 2020. Remote Sensing, 14(3), 737.

[6] López-Villuendas, A. M., & del Campo, C. (2023). Regional economic disparities in Europe: Time-series clustering of NUTS 3 regions. International Regional Science Review, 46(3), 265–298.

[7] Salvati, L., Venanzoni, G., & Carlucci, M. (2016). Towards (spatially) unbalanced development? A joint assessment of regional disparities in socioeconomic and territorial variables in Italy. Land Use Policy, 51, 229–235.

[8] Shaker, R. R., & Zubalsky, S. L. (2015). Examining patterns of sustainability across Europe: A multivariate and spatial assessment of 25 composite indices. International Journal of Sustainable Development & World Ecology, 22(1), 1–13.

[9] Ekonomou, G., & Halkos, G. (2023). Exploring the impact of economic growth on the environment: An overview of trends and developments. Energies, 16(11), 4497.

[10] Zhang, D., Wu, L., Niu, X., Guo, Z., Zhang, Z., Li, S., & Xu, H. (2022). Looking for ecological sustainability: A dynamic evaluation and prediction on the ecological environment of the belt and road region. Sustainable Production and Consumption, 32, 851–862.

[11] Lin, A., Liu, Y., Zhou, S., Zhang, Y., Wang, C., & Ding, H. (2023). Data-driven analysis and evaluation of regional resources and the environmental carrying capacity. Sustainability, 15(10), 8372.

[12] Kovalchuk, O., Karpinski, M., Babala, L., Kasianchuk, M., & Shevchuk, R. (2023). The canonical discriminant model of the environmental security threats. Complexity, 2023(1), Article 5584750.

[13] Buzko, I., Vartanova, O., Trunina, I., & Khovrak, I. (2019). Theoretical aspects of regional sustainable development in the EU and Ukraine. In SHS Web of Conferences (Vol. 61, p. 01001). EDP Sciences, Les Ulis.

[14] Pascariu, G. C., Holovko-Havrysheva, O., & Krayevska, O. (2023). Ukraine: Geopolitical realities and regional development perspectives. Regional Science Policy & Practice, 15(1), 3–7.

[15] Shults, S., Simkiv, L., Andrusiv, U., Bilyk, I., & Klym, N. (2022). Economic growth of regions of Ukraine in conditions of disproportional regional development. Journal of Optimization in Industrial Engineering, 15(1), 269–279.

[16] Papagiannis, F., Gazzola, P., Burak, O., & Pokutsa, I. (2020). An intelligent environmental plan for sustainable regionalisation policies: The case of Ukraine. Environmental Science & Policy, 108, 77–84.

[17] Zomchak, L., & Hakava, S. (2025). Unveiling disparities and resilience in Ukrainian regional labor markets: Multidimensional ranking approach. In Developments in information and knowledge management systems for business applications (Vol. 8, pp. 495–516). Springer, Cham.

[18] Khomiuk, N., Bochko, O., Pavlikha, N., Demchuk, A., Stashchuk, O., Shmatkovska, T., & Naumenko, N. (2020). Economic modeling of sustainable rural development under the conditions of decentralization: a case study of Ukraine. (Unpublished manuscript).

[19] Tan, F., & Lu, Z. (2015). Study on the interaction and relation of society, economy and environment based on PCA–VAR model: As a case study of the Bohai Rim region, China. Ecological Indicators, 48, 31–40.

[20] Yemets, K., Izonin, I., & Dronyuk, I. (2025). Enhancing the FFT-LSTM time-series forecasting model via a novel FFT-based feature extraction–extension scheme. Big Data and Cognitive Computing, 9(2), 35. https://doi.org/10.3390/bdcc9020035

[21] Yemets, K., Izonin, I., & Dronyuk, I. (2025). Time series forecasting model based on the adapted transformer neural network and FFT-based features extraction. Sensors, 25, 652. https://doi.org/10.3390/s25030652

[22] Ullah, A., Nobanee, H., Ullah, S., & Iftikhar, H. (2024). Renewable energy transition and regional integration: energizing the pathway to sustainable development. Energy Policy, 193, Article 114270.

[23] Sporchia, F., Paneni, A., Pulselli, F. M., Caro, D., Bartolini, S., & Coscieme, L. (2021). Investigating environment-society-economy relations in time series in Europe using a synthetic input-state-output framework. Environmental Science & Policy, 125, 54–65.

[24] Izonin, I., Tkachenko, R., Holoven, R., Yemets, K., Havryliuk, M., & Shandilya, S. K. (2022). SGD-based cascade scheme for higher degrees Wiener polynomial approximation of large biomedical datasets. Machine Learning and Knowledge Extraction, 4, 1088–1106. https://doi.org/10.3390/make4040055

[25] Oleksiv, V., Izonin, I., Kharchuk, V., Tkachenko, R., & Doroshenko, A. (2018). Identification of IT sector stakeholder's requirements to master's program in information system in Lviv region. In CEUR Workshop Proceedings (Vol. 2105, pp. 429–437).

[26] Zomchak, L., & Kukhotska, T. (2025). Building Food Security Resilience in Ukraine: The Autoregressive Approach to Food Price Forecasting. *In Developments in Information and Knowledge Management Systems for Business Applications: Volume 8* (pp. 403–424). Cham: Springer Nature Switzerland.

[27] Vdovyn, M., & Zomchak, L. (2022). Export in services of Ukraine: pre-pandemic period, Covid-19 and war. *Věda a perspektivy*, *8*(15), 48–57.

[28] Zolkover, A., Iatseniuk, R., & Aiyedogbon, J. (2025). Strategic priorities for business innovation and investment in post-war Ukraine. *Smart Economy, Enterpreneurship and Security, 3*(1), 55–63.

[29] Zolkover, A., Lagovska, O., Valihura, V., Zhelef, G., & Shynkar, T. (2024). Assessing the Impact of Green Taxation Policies on Sustainable Growth. *Grassroots Journal of Natural Resources*, *7*(3), 331–348.

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КАРТУВАННЯ ЕКОЛОГІЧНОГО ТА СОЦІАЛЬНО-ЕКОНОМІЧНОГО ЛАНДШАФТУ: ДИСКРИМІНАНТНИЙ АНАЛІЗ СТАЛОГО РЕГІОНАЛЬНОГО РОЗВИТКУ УКРАЇНИ

Анотація. *Це дослідження вивчає регіональні диспропорції в екологічних умовах та соціально-економічному розвитку України. Використовуючи дискримінантний аналіз, дослідження класифікує українські регіони відповідно до набору ключових екологічних та економічних змінних: викиди діоксиду вуглецю, природні заповідники та національні парки, валовий регіональний продукт, скиди зворотних вод, утворення відходів та витрати на охорону навколишнього середовища. Аналіз виявляє чіткі регіональні угруповання на основі цих індикаторів, демонструючи значні відмінності в екологічному навантаженні та економічному виробництві по всій країні. Крім того, дослідження ідентифікує конкретні змінні, які найбільш ефективно дискримінують між цими регіональними групами, висвітлюючи чинники, що спричиняють екологічні проблеми в одних областях та більш стійкі моделі в інших. Отримані результати пропонують цінні відомості для політиків, які прагнуть розробити цільову екологічну політику та сприяти впровадженню стратегій сталого розвитку, що враховують різноманітні регіональні контексти в Україні.*

Ключові слова: *часові ряди, дискримінантний аналіз, регіональний розвиток, економічна політика, регіон, модель, багатовимірний аналіз, екологія, економіка, екологічна політика, сталий розвиток, еколого-економічний.*

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THE POTENTIAL OF DIGITAL TECHNOLOGIES FOR ORGANIZING ENVIRONMENTALLY RESPONSIBLE TOURISM IN SMART CITIES

Abstract. *The role of digital technologies in the development of environmentally responsi-ble tourism within the context of smart cities is explored in the article. The re-search objective of identifying the main areas of application of digital solutions in this area and analyzing their impact on the sustainable development of smart city tourism is achieved in the article. A review of modern scientific literature was conducted to identify key trends and directions for further research regarding the implementation of digital solutions in this field. The main negative impacts of tra-ditional tourism on the urban environment are summarized. A comprehensive analysis of digital technologies in the context of environmental sustainability of tourism, in particular in identifying four key areas of their application: infor-mation and communication technologies for tourists; transport systems and logis-tics; urban environment monitoring and management systems; analytics, artificial intelligence, and decision support determined the scientific novelty of the article. It is demonstrated that these technologies not only enhance the quality of the tour-ist experience but also enable travel planning with environmental criteria in mind, significantly reducing negative environmental impacts and promoting the rational use of urban resources. The practical value of the article is the formation of theo-retical and methodological foundations for the development of digital tools that contribute to the formation of a culture of conscious consumption of tourist ser-vices, support for the strategy of sustainable development of cities and improve-ment of their ecological condition.*

Keywords: *Urban tourism, Environmentally responsible tourism, Smart cities, Digital tech-nologies.*

1. Introduction

Tourism is one of the leading sectors of the global economy. For Ukraine, especially in the context of war, it is an important factor in the economic resilience of certain regions. However, tourism places increased pressure on the environment, including pollution of air and water resources, deterioration of ecosystems, increased resource consumption, and overload of transport and municipal infrastructure. Excessive tourist loads cause damage not only to natural areas but also to cities that receive a large numbers of tourists. In response to these challenges, the development of environmentally responsible tourism, aimed at minimizing negative impacts on natural resources and protecting the environment, is becoming increasingly relevant.

For Ukraine, which is currently developing post-war recovery plans, the priority is not only the restoration of infrastructure destroyed but also the development of cities based on the Smart City concept. This concept relies on the widespread implementation of digital technologies to improve citizens' quality of life. The introduction of smart technologies in the tourism sector contributes not only to infrastructure development but also to fostering responsible tourist behavior, which is an important factor in preserving the urban environment.

Despite the growing interest in digital solutions in tourism, the issue of integrating smart technologies within the context of urban environmental sustainability remains insufficiently studied. The aim of this article is to investigate the role of digital technologies in the development of environmentally responsible tourism in smart cities, as well as to analyze case studies of their implementation.

Recent scientific studies indicate a growing interest within the academic communi-ty regarding the role of digital services in transforming tourism under the frameworks of smart city and sustainable development concepts. Most authors [1, 2, 5, 8, 9] em-phasize that digital technologies — particularly artificial intelligence, big data, and virtual reality — open new opportunities to enhance the efficiency of tourism services, optimize resource use, and reduce negative environmental impact. Researchers pay special attention to the application of artificial intelligence in the tourism sector. Spe-cifically, Bingöl and Yang [1] and Tuo Y. [15] consider artificial intelligence a key tool for ecological management in smart destinations, highlighting its potential in optimizing resource consumption and forecasting tourist flows. Chan, C.-S. and colleagues [2] explored how pre-trip virtual reality (VR) experiences and the use of smart devices during on-site visits can enhance the tourism experience for individuals with hearing impairments on Yim Tin Tsai Island (Hong Kong). The study also provides practical recommendations for the design of VR applications and the effective use of smart devices to improve the accessibility of tourist routes.

Many authors, including Samancioglu et al. [11] and Zhang et al. [18], emphasize the important role of big data analytics in resource coordination and the digital sustainability of cities. At the same time, they note potential challenges related to data management and privacy that may hinder the adoption of such technologies in tourism. Stroumpoulis et al. [13] and Ionescu and Sârbu [6] have studied the impact of digital solutions on improving the quality of tourism services, particularly in mobility, navigation, and informational support for travelers. Grincheva [4] and Madeira et al. [7] highlight the significance of smart analytics and creative approaches in shaping sustainable urban environments in the context of tourism. A comprehensive analysis of successful examples of smart technology implementation in the tourism sector across different countries is also important, especially concerning the development of mobile applications, sensor networks, and environmental monitoring [4, 5, 8, 12, 17]. Hashim, H. [5] conducted an in-depth analysis of the role of e-government in advancing smart city initiatives in Saudi Arabia, with particular emphasis on the integration of ICT, the Internet of Things, big data, and cloud computing technologies. The study identifies critical challenges — such as cybersecurity concerns, infrastructure interoperability, citizen trust, and regulatory frameworks — and offers strategic recommendations and best practice guidelines aimed at overcoming these obstacles and enhancing the efficiency, transparency, and sustainability of urban governance.

Overall, scholars adopt a comprehensive approach to studying digital technologies in tourism, considering technological, social, economic, and environmental aspects of the process. At the same time, they emphasize that technological innovations alone do not guarantee responsible tourist behavior or an increased level of ecological awareness.

The literature identifies several promising directions for future research. These in-clude modeling the impact of technologies on tourist ecosystems under climate change conditions and integrating digital tools into sustainable development strate-gies. However, these directions are still in an active stage of development and require analysis of practical case studies and objective assessment of their effectiveness.

2. Materials and Methods

To achieve the stated aim, the study employed a set of general scientific research methods. The methods of analysis and synthesis were applied to systematize con-temporary scientific literature on environmentally responsible tourism, the smart city concept, and digital technologies. The abstract-logical method was used to identify the main negative impacts of traditional tourism on the urban environment. The dialectical method served to formulate theoretical generalizations regarding the po-tential for implementing digital technologies in environmentally responsible tourism, to identify the related challenges, and to outline possible solutions. Comparative analysis enabled a case study of smart city practices in introducing digital services aimed

at reducing the environmental impacts of tourism. Graphical and tabular methods were used to present the research findings in a visual form. No software or code implementations were applied in this study.

3. Results and Discussion

To substantiate the objectives of using digital technologies in the tourism sector, it is first necessary to analyze the main environmental problems caused by traditional tourism activities in cities. The negative impact of tourism on a destination due to an excessive number of visitors — experienced both by local residents (through a decline in quality of life) and by the tourists themselves — is known as over-tourism. This phenomenon is characterized by exceeding the permissible tourism load on the urban environment, leading to environmental degradation and increased social tension. At the same time, even a relatively small number of tourists can pose challenges for a city, particularly by overloading infrastructure and creating other issues, examples of which are presented in Figure 1.

Thus, traditional tourism activities in cities can cause a wide range of negative environmental and infrastructural impacts. The impact of tourism is felt at all stages of providing tourist services — both primary (transportation, accommodation, catering, excursion services) and auxiliary (souvenir trade, medical services, animation, vehicle rental, etc.).

One approach to minimizing the negative impact of tourism on the urban ecosystem is the implementation of environmentally responsible tourism (also known as eco-friendly tourism), which is viewed as a transformation of traditional tourism that incorporates principles of environmental sustainability. The concept of this approach is to minimize the ecological footprint of tourism activities through the application of resource-saving, energy-efficient, and nature-oriented practices. Unlike ecotourism, which focuses on visiting natural sites and preserving the natural environment, environmentally responsible tourism integrates ecological principles into the operation of the existing tourism system without fully transforming the organization of tourism or the destination, including the city. This form of tourism aims to meet tourists' needs with minimal negative impact on the natural and socio-cultural environment, rational use of resources, and support for biodiversity conservation.

Key practices of this approach include optimizing transportation routes; using low-carbon-footprint transportation; employing environmentally safe materials in the construction and maintenance of tourist facilities; implementing energy-saving technologies at all stages of tourist services; reducing water and electricity consumption; managing waste responsibly; developing a circular economy; and maintaining biodiversity, among others.

Thus, environmentally responsible tourism is a practical response to the challenges of sustainable development in urbanized environments, particularly within the Smart City concept. A Smart City actively

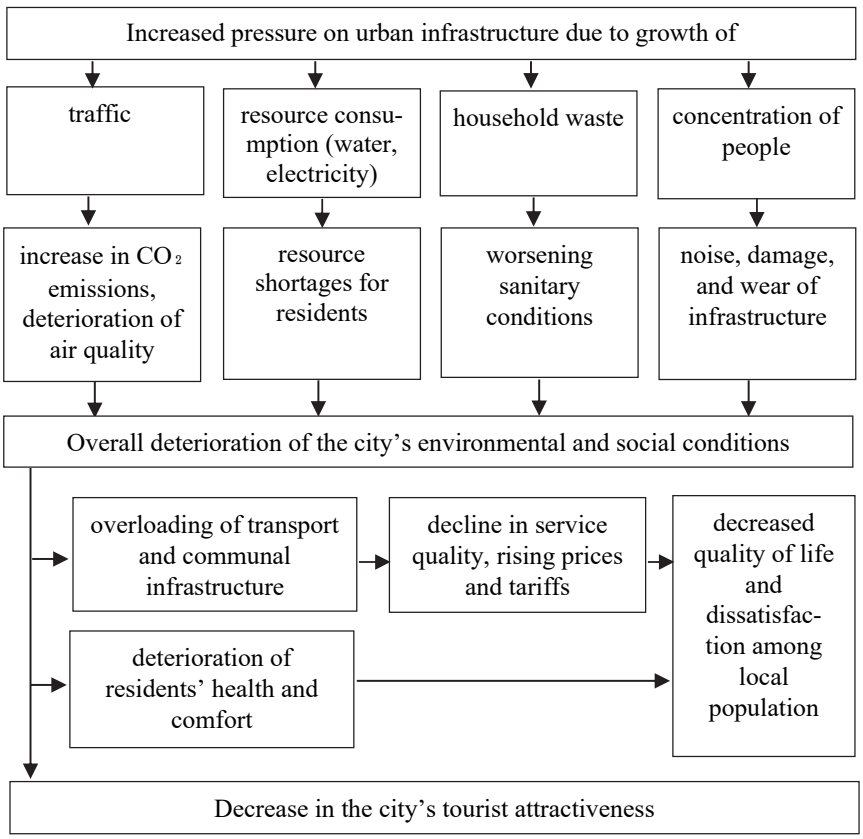

Figure 1. Main Negative Impacts of Traditional Tourism on Modern Cities

Source: developed by the authors

Table 1

Key Directions for the Use of Digital Technologies in the Development of Environmentally Responsible Tourism within Smart Cities

Digital Technologies	Examples of Programs / Tools	Application in Tourism	Effect on Environmentally Responsible Tourism
Information and Communication Technologies for Tourists			
Mobile applications for tourists — eco-guides, maps, etc.	AllTrails, iNaturalist, Green Travel App	Providing tourists with ecological information, optimizing movement	Increasing tourists' environmental awareness, reducing negative environmental impact
Interactive (digital) maps and information displays	Touch Screen Kiosks, Visit Seattle App, MazeMap, IndoorAtlas	Real-time tourist information, interactive navigation and engagement	Increasing ecological awareness, promoting responsible tourist behavior
Virtual and Augmented Reality (VR/AR)	Google Arts & Culture VR, Timelooper, Sketchfab	Virtual tours, educational and awareness-raising programs	Contributing to the preservation of tourist sites and reducing infrastructure load
Geoanalytics, GPS Navigation	QGIS, Kili Technology, Mapbox, HERE Technologies	Routing and monitoring of tourist flows	Prevention of overcrowding, improvement of environmental conditions in tourist areas
Transport Systems and Logistics			
Intelligent Transport Systems (ITS) — Smart Parking Systems, Public Transport Monitoring Systems, Bike/Scooter Sharing Systems, etc.	Parkopedia, Moovit, Transit, Citymapper, Bolt	Optimization of urban mobility	Reduction of emissions and carbon footprint, improvement of traffic flow
Intelligent booking systems	Booking.com, Airbnb, Amadeus, Galileo, Sabre	Personalization of offers, demand and availability management, resource optimization (hotels, transport, excursions)	Rational use of resources, reduction of waste, lowering carbon footprint through load optimization
Urban Environment Monitoring and Management Systems			
Sensors, GIS, Monitoring	EnviroSensor, AirVisual (IQAir), Civic Data Lab, PurpleAir, ArcGIS, QGIS	Monitoring of environmental conditions: collection, analysis, and visualization of real-time data; tracking air quality, noise levels, water pollution, and landscape changes	Timely detection of environmental issues, supporting decision-making in environmental management
Real-time IoT sensors	Libelium, ThingsBoard, OpenSensors.io, Blynk, PurpleAir	Continuous collection and transmission of environmental data via IoT networks for monitoring urban environments and infrastructure	Operational management of environmental load, rapid response to changes, and reduction of environmental impact
Smart lighting, energy-efficient systems	Philips Hue, LIFX, Cree Lighting, Schneider Electric EcoStruxure	Energy saving in tourist areas through automated lighting control and optimization of energy consumption	Reduction of energy use, decrease in greenhouse gas emissions
Smart management systems for renewable energy sources	Siemens EnergyIP, Schneider Electric EcoStruxure Grid, General Electric (GE) Grid Solutions, IBM Intelligent Operations Center for Smarter Cities, Enel X	Optimization of energy consumption in tourist infrastructure, integration and management of clean energy sources (solar, wind, etc.)	Reduction of carbon footprint, increased energy efficiency, and stability of energy supply
Smart Eco-Tourism Infrastructure	Smart Forest City (Cancún), Green View City Dashboard, EcoCounter, Urban GreenUP, Smart Parks	Integration of digital technologies into the creation and management of green tourism infrastructure: eco-routes, automated irrigation, visitor sensors, vegetation condition monitoring	Development of sustainable urban infrastructure, preservation of biodiversity, increased attractiveness of areas for eco-tourism

Smart waste management systems	Bigbelly Solar, Ecube Labs CleanCUBE, Enevo, SmartBin, Evreka	Improving waste collection efficiency through IoT-enabled monitoring, route optimization, and automated waste compaction	Reducing waste volume and pollution, optimizing municipal waste management costs
Analytics, Artificial Intelligence, and Decision Support			
Big Data Analytics	Apache Hadoop, Snowflake, IBM Cognos Analytics, Microsoft Azure Synapse Analytics, Google BigQuery, Smart Tourism Intelligence System (SIT), 3cixty, Smart Destinations Platform	Analysis of large datasets on tourist flows, visitor behavior, and infrastructure load; support for planning and management based on real-time insights.	Evidence-based load planning, prevention of over-tourism, optimization of tourism infrastructure, reduction of environmental impact, and enhancement of sustainability.
Artificial Intelligence (AI) and Machine Learning	ChatGPT (OpenAI), Google AI Platform, Bard (Google), Microsoft Azure AI, IBM Watson, TensorFlow, H2O.ai	Analysis of tourist data for demand forecasting; optimization of routes and logistics; service personalization; automatic monitoring of environmental and infrastructure conditions; decision support	Improved forecast accuracy, reduced overcrowding in tourist areas, resource optimization, minimized environmental impact, enhanced efficiency of urban ecosystem management

Source: summarized by the authors

uses digital technologies and intelligent systems to improve residents' quality of life, efficiently manage resources, develop infrastructure, ensure environmental sustainability, and promote economic growth [3].

The Smart City concept opens new opportunities to address major environmental and infrastructural challenges related to tourism. Within this framework, tourists are provided with highly automated services — ranging from transportation and booking to navigation. Digital services and intelligent systems enable the collection and pro-cessing of large volumes of real-time data, effective resource management, en-hancement of tourism service quality, and reduction of ecological footprints.

Digital solutions contribute not only to the improvement of urban infrastructure but also to the promotion of sustainable tourism principles through digital environ-mental management. An important component of developing environmentally re-sponsible tourism is the involvement of local communities, raising tourists' environ-mental awareness, and integrating innovative solutions into urban governance sys-tems, particularly through the implementation of digital monitoring systems, analysis of environmental indicators, and resource management.

The key directions for the use of digital technologies to develop environmentally responsible tourism within smart cities are summarized in Table 1.

According to the data in the table 1, it is important to highlight the multidimensionality and dynamism of digital technologies in shaping environmentally responsible tourism in smart cities.

One of the most effective tools in digital management of the tourism sector is artificial intelligence (AI). AI has long ceased to be merely an "optional feature" and is becoming a key element in the development of Smart Cities. Its applications are diverse, but special attention is given to chatbots. Many service companies implement intelligent widgets, such as FAQs, to provide prompt responses to common customer inquiries. AI-based chatbots assist tourists in planning their trips: suggesting routes, selecting hotels, optimizing expenses, booking tickets, processing documents, and more.

An example of successful chatbot implementation is TourHelperBot, developed by the Ukrainian Association of Travel Agencies. This bot provides tourists abroad with up-to-date information on accommodations, flight delays, and cancellations, as well as assists in resolving other issues that may arise during their travels.

There are numerous successful cases worldwide of implementing digital technologies within the Smart City concept that contribute to the development of environmentally responsible tourism.

According to the Smart City Index 2024 by PropttechOS, Paris topped the list of European smart cities. The city actively implements innovative digital solutions, combining modern technologies, infrastructure innovations, and environmental responsibility to achieve sustainable development. [14]

The city-state of Singapore is considered one of the most advanced Smart Cities in the world due to its effective digital governance. Singapore is known for its integrated environmental monitoring system that uses artificial intelligence and IoT sensors to control air quality, water resources, waste management, transportation, and security. The developed digital platforms help tourists plan routes with minimal impact on ecosystems and promote increased environmental awareness among the population. [4]

Vienna (Austria), Barcelona (Spain), and Amsterdam (Netherlands) actively use Big Data to forecast tourist flows and optimize transport infrastructure, as well as

IoT for air quality monitoring, smart lighting, water resource management, and providing digital services to residents. Smart solutions enable the distribution of tourist flows to prevent overtourism and also implement energy-efficient transportation and smart lighting in tourist areas. Toronto (Canada) employs digital technologies in construction, transportation, environmental monitoring, and integrates a Smart Grid system. [3]

One of the key methods for managing tourist flows is setting limits on the number of tourists who can simultaneously visit popular locations. Such measures are applied in many cities worldwide. For example, Venice has an online booking system that controls tourists' access to major attractions and natural sites, helping to avoid excessive strain on urban infrastructure and ecosystems.

These examples demonstrate that digital technologies can become a key tool in implementing environmentally responsible tourism practices in cities striving for sustainable development and improving the quality of life for residents and visitors. The most promising directions for the development of environmentally responsible tourism within Smart City frameworks are digital environmental monitoring, optimization of tourist flows, and integration of digital systems in city management. These digital solutions not only enhance the quality of the tourist experience but also significantly contribute to reducing the ecological footprint on cities.

However, it is important to remember that the use of digital technologies comes with certain challenges. First, there is the issue of data privacy protection: many services collect and process large amounts of personal information (names, contacts, passport and payment details, location, preferences, etc.), making tourists vulnerable to cyberattacks, fraud, and other criminal activities. Additionally, the implementation of digital technologies requires significant energy resources, with the solution being the production of additional energy from renewable sources. There is also a risk of creating social barriers due to inequality in access to digital technologies, particularly for financial reasons.

4. Conclusions

The study confirms that digital technologies serve as one of the key factors in the development of environmentally responsible tourism within the framework of the smart city concept. They contribute to increasing tourists' environmental awareness and the implementation of sustainable practices in the tourism industry. Through the use of mobile applications, online booking, virtual guides, and other digital tools, tourists are able to plan trips taking into account environmental criteria, selecting optimal routes based on time and distance. This promotes the enhancement of the quality of the tourist experience and significantly reduces the negative impact on the environment, ensuring the rational use of natural resources.

The integration of digital technologies into tourism organization contributes to the formation of a culture of conscious consumption of tourist services, which, in turn, supports the sustainable development strategies of cities and improves their environmental condition. It is recommended that Ukraine study the international experience of leading smart cities in the field of innovative and environmentally responsible tourism and actively implement digital tools to develop this sector.

At the same time, to minimize the negative impact of tourism on the urban envi-ronment, it is necessary to apply a comprehensive approach that combines govern-ment policies, local initiatives, technological innovations, and the transformation of tourists' behavioral patterns. Further scientific research should focus on the develop-ment of integrated digital environmental management systems, the evaluation of the effectiveness of implemented innovations, as well as the study of the impact of modern digital technologies on the sustainable development of tourist smart cities.

References

[1] Bingöl, S., & Yang, Y. (2025). Integrating smart technologies and artificial intelligence to build smart tourism destination ecosystems: A model for smart destination management. *Tourism Management Perspectives,* (58). https://doi.org/10.1016/j.tmp.2025.101380

[2] Chan, C.-S., Wong, S. Y., Agapito, D., & Tam V. (2025). The effect of pre-trip virtual reality and on-site smart device use on accessible tourism experiences. *Sustainable Futures,* (10), 100811. https://doi.org/10.1016/j.sftr.2025.100811

[3] European Commission: European Smart Cities. (2020). *Vienna University of Technology*. https://smart-cities.eu

[4] Grincheva, N. (2025). Towards creative and smart urban sustainability: Understanding smart cultural data intelligence (the case of Singapore). *Cities,* (166), 106216. https://doi.org/10.1016/j.cities.2025.106216

[5] Hashim, H. (2024). E-government impact on developing smart cities initiative in Saudi Arabia: Opportunities & challenges. *Alexandria Engineering Journal,* (96), 124–131. https://doi.org/10.1016/j.aej.2024.04.008

[6] Ionescu, A.-M., & Sârbu, F. (2024). Exploring the impact of smart technologies on the tourism industry. *Sustainability,* (16), 3318. https://doi.org/10.3390/su16083318

[7] Madeira, C., Rodrigues, P., & Gomez-Suarez, M. (2023). A bibliometric and content analysis of sustainability and smart tourism. *Urban Science,* 7(2), 33. https://doi.org/10.3390/urbansci7020033

[8] Moliner, Tena M. Á., Rodríguez, Artola R. M., Callarisa-Fiol, L. J., & Algueró-Boronat, M. (2024). Local government tourism officer satisfaction with the Smart Destination model: A case study with the Kano method. *Journal of Destination Marketing & Management,* (3)4, 100951. https://doi.org/10.1016/j.jdmm.2024.100951

[9] Nieves-Pavón, S., López-Mosquera, N., & Jiménez-Naranjo, H. (2024). The role emotions play in loyalty and WOM intention in a smart tourism destination management. *Cities,* (145), 104681. https://doi.org/10.1016/j.cities.2023.104681

[10] Nilsson, J., Jansson, J., Nicholas, K., & Zhao, C. (2025). Traveler perceived service quality and satisfaction with public transport: The influence of digital competence and environmental attitudes. *Transport Policy,* 103741. https://doi.org/10.1016/j.tranpol.2025.07.022

[11] Samancioglu, E., Kumlu, S., & Ozkul, E. (2024). Smart tourism destinations and sustainability: Evidence from the tourism industry. *Worldwide Hospitality and Tourism Themes,* 16. https://doi.org/10.1108/WHATT-07-2024-0167

[12] Sezer, S., & Ilban, M. Digital transformation in tourism: Opportunities and challenges for Türkiye and Mediterranean countries. (2024). *Journal of Tourism Management,* (1107), 62–83. https://doi.org/10.29329/jtm.2024.1107.5

[13] Stroumpoulis, A., Kopanaki, E., & Varelas, S. (2022). Role of artificial intelligence and big data analytics in smart tourism: A resource-based view approach. *WIT Transactions on Ecology and the Environment,* (259), 99–108. https://doi.org/10.2495/ST220091

[14] The Washington Post. (2025, March 23). Paris approves making 500 streets car-free. https://www.washingtonpost.com/world/2025/03/23/paris-car-free-vote-anne-hidalgo

[15] Tuo, Y., Wu, J., Zhao, J., & Si, X. (2024). Artificial intelligence in tourism: Insights and future research agenda. *Tourism Review,* 80 (8). https://doi.org/10.1108/TR-03-2024-0180

[16] Vanderhorst, H.R., Heesom, D., & Yenneti, K. (2024). Technological advancements and the vision of a meta smart twin city. *Technology in Society,* 79. https://doi.org/10.1016/j.techsoc.2024.102731

[17] Yasnolb, I., Demianenko, N., Galych, O., Gorb, O., Yehorova, O., Lipskyi, R., Borovyk, T., Mykolenko, I., & Protsiuk, N. (2023). Tourism of Ukraine as a type of business before and during the war. *Journal of Environmental Management and Tourism,* 14(2), 417–424. https://doi.org/10.14505/jemt.14.2(66).11

[18] Zhang, D., Pee, L.G., Pan, S.L., & Cui, L. (2022). Big data analytics, resource orchestration, and digital sustainability: A case study of smart city development. *Government Information Quarterly,* 39(1), 101626. https://doi.org/10.1016/j.giq.2021.101626

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ПОТЕНЦІАЛ ЦИФРОВИХ ТЕХНОЛОГІЙ ДЛЯ ОРГАНІЗАЦІЇ ЕКОЛОГІЧНО ВІДПОВІДАЛЬНОГО ТУРИЗМУ В РОЗУМНИХ МІСТАХ

Анотація. *У статті досліджується роль цифрових технологій у розвитку екологічно відповідального туризму в контексті розумних міст. Метою дослідження є виявлення основних напрямів застосування цифрових рішень у цій сфері та аналіз їхнього впливу на сталий розвиток туристичних smart-міст. Проведено огляд сучасної наукової літератури з метою виявлення основних тенденцій і напрямів подальших досліджень щодо впровадження цифрових технологій, а також узагальнено основні негативні наслідки традиційного туризму для міського середовища. Наукова новизна полягає у комплексному аналізі цифрових технологій у контексті екологічної стійкості туризму, зокрема у виокремленні чотирьох ключових напрямів їх застосування: інформаційно-комунікаційні технології для туристів; транспортні системи та логістика; системи моніторингу та управління міським середовищем; аналітика, штучний інтелект і підтримка прийняття рішень. Показано, що впровадження цих технологій не лише підвищує якість туристичного досвіду, а й дозволяє планувати подорожі з урахуванням екологічних критеріїв, суттєво знижує негативний вплив на довкілля та сприяє раціональному використанню міських ресурсів. Практична цінність статті полягає у формуванні теоретично-методичних основ для розвитку цифрових інструментів, які сприяють формуванню культури свідомого споживання туристичних послуг, підтримці стратегій сталого розвитку міст і покращенню їх екологічного стану. Подальші дослідження мають бути спрямовані на розробку інтегрованих систем цифрового екологічного менеджменту, оцінку ефективності інновацій та вивчення впливу сучасних технологій на сталий розвиток туристичних smart-міст.*

Ключові слова: *Міський туризм, Екологічно відповідальний туризм, Розумні міста, Цифрові технології.*

НАУКОВИЙ ЖУРНАЛ

СМАРТ-ЕКОНОМІКА, ПІДПРИЄМНИЦТВО ТА БЕЗПЕКА

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