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Digitalisation as a factor in the economic development of developing countries

Abstract. The relevance of this research arises from the need to assess the impact of digitalisation on the economic development of developing countries in the context of global challenges, such as economic inequality, limited access to modern technologies, uneven digital infrastructure, and low levels of digital literacy. The purpose of the article was to study the impact of digitalisation on the economic development of developing countries by identifying key digital indicators, analysing the clustering of countries by the level of digitalisation, and assessing the relationship between digital indicators and economic results. The research methods included cluster analysis to group countries by level of digital development, factor analysis to identify main drivers of digital transformation, and comparative analysis to identify key trends and features of digitalisation across countries. The analysis covered 90 countries with different levels of digital

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readiness and economic potential. The results of the study suggest that countries with a developed digital infrastructure, a high level of human capital and active government support demonstrate sustainable economic growth. It has been discovered that among main drivers of digital transformation are the following: access to high-speed Internet, digital education and the introduction of digital technologies in key sectors of the economy. Cluster analysis made it possible to identify four groups of countries that differ in the level of digitalisation, which helped to identify key priorities for each of them. The practical significance of the study is determined by the possibility of using the obtained results to develop recommendations for accelerating digital transformation in developing countries, taking into account their socio-economic conditions and potential

Keywords: cluster analysis; digital infrastructure; digital technologies; information and communications technology infrastructure; human capital

INTRODUCTION

Digitalisation is one of the key drivers of economic development, particularly for developing countries. The introduction of digital technologies contributes to increased productivity, improved business models, increased access to information and integration into global markets. Despite the overall benefits of digitalisation, developing countries face a number of challenges, including digital inequality, limited access to infrastructure and a low level of digital literacy. In the world where digital technologies play a key role in increasing competitiveness, attracting investment and ensuring sustainable development, middle- and low-income countries have the opportunity to reduce the economic gap considerably by implementing digital solutions. Ukraine, as a country with a significant potential for digital transformation, is also demonstrating progress in the implementation of digital technologies.

The digital transformation of national economies is no longer viewed merely as a technological innovation but rather as a strategic precondition for socio-economic growth. P. Winikoff (2024) focused on the operational dimension of digitalisation, defining it as the integration of digital technologies into business models to streamline processes, reduce transactional costs, and increase productivity. This interpretation grounds digitalisation firmly in corporate practice, presenting it as a functional tool for competitiveness rather than a holistic transformation of systems. In contrast, J. Clerck (2024) expanded the scope of the concept, arguing that digitalisation is a transitional phase on the path towards deep socio-economic reconfiguration. It was emphasised that digitalisation reshaped not only business processes but also cultural norms, institutional frameworks, and governance mechanisms. Together, these studies laid the theoretical groundwork for understanding digitalisation as a multilayered phenomenon with both technological and systemic implications.

Further empirical investigation into the link between digitalisation and economic performance has been provided by L.K. David *et al*. (2025). Their large-scale cross-country study quantifies the effect of digital readiness on economic growth by constructing a panel dataset covering indicators of information and communications technology (ICT) infrastructure, digital literacy, and e-government development across developing and emerging economies. The authors reported a statistically significant association between digital maturity and growth in sectors such as manufacturing, services, and education, concluding that digital investment yields long-term productivity gains and boosts national resilience to external shocks. Their work supports the idea that digitalisation plays a catalytic role in broader socio-economic dynamics. The relationship between digitalisation and GDP growth has also been rigorously examined by M. Sinha *et al*. (2025) in the context of South and Southeast Asia. Unlike previous macro-level studies, their approach incorporates institutional variables such as corruption control, bureaucratic quality, and legal effectiveness. The authors found that digitalisation alone does not guarantee economic improvement; rather, its positive effects materialise only in the presence of robust governance mechanisms. These findings highlighted that digital policy must be embedded in a stable institutional environment to generate sustainable development. This nuanced analysis contributes to the understanding that digitalisation is not a standalone driver, but one that is conditional on complementary policy frameworks.

The importance of institutional scaffolding is echoed in national-level studies conducted in Ukraine. H. Matviienko (2023) presented a case study on the interdependence between public-private collaboration and digital progress in Ukraine. It was argued that the development of the digital economy requires institutional commitment in the form of innovation grants, regulatory support, and public infrastructure investment. The study was based on an analysis of regional disparities and the impact of public procurement reforms on digital adoption. In a similar vein, N. Bobro (2024) analysed the structural coordination of Ukraine's digital policy, stressing the necessity for cross-sectoral integration to avoid fragmented implementation. A unified digital governance framework has been proposed to link ministries, local authorities and private organisations through shared performance metrics and interoperability standards. This recommendation is particularly relevant in the Ukrainian context, where overlapping mandates and institutional silos often hinder the scalability of digital initiatives.

A more geopolitical perspective is offered by S.V. Ivantsov (2024) who explored Ukraine's digital development within the framework of European integration. It outlined how alignment with EU digital standards – including the digital single market strategy – has prompted significant reforms in Ukrainian legislation, institutional design, and data protection policy. Modernisation was identified of ICT infrastructure and harmonisation of legal frameworks as two pillars that have facilitated Ukraine's integration into the European digital space. This study was especially valuable as it connects the technical aspects of digitalisation with the normative and legal standards that define cross-border cooperation in the EU. Digitalisation under wartime conditions in Ukraine represents a unique dimension of this research field. Y. Pereguda *et al*. (2024) documented how the Russian invasion has catalysed the rapid deployment of digital tools in government and finance, particularly in areas such as cybersecurity, remote authentication, and blockchain-based registries. This case study showed that in extreme conditions, digitalisation becomes not only a development vector but a mechanism of survival and continuity. The authors provide detailed analysis of how national agencies adapted their operations to wartime constraints by digitising essential services and protecting data infrastructure.

The broader implications of wartime digital adaptation are analysed by V. Levytskyi *et al*. (2024), focused on the emergence of remote work infrastructure and digital logistics networks as critical resilience tools. It was argued that these technologies have enabled business continuity and minimised economic disruption, especially in export-oriented sectors. This work added to the growing body of literature that positions digitalisation as a core element of economic defence strategy. As a result, it was established that the aspect of quantitatively assessing the relationship between the level of digital maturity and macroeconomic indicators remains insufficiently explored. Therefore, the aim of this study was to develop an integrated Digital Integral Index, to conduct cluster and factor analysis for grouping countries by the level of digitalisation, and to identify the key digital and institutional factors that contribute to economic growth in national economies.

MATERIALS AND METHODS

A set of empirical, theoretical and general scientific research methods was used to study the level of digitalisation processes development on a regional scale and in national economies of developing countries, as well as to analyse this world-transforming process as a factor of economic development. The general scientific methods included the following: analysis and synthesis (studying the pace of digital transformation in leading developing countries by examining various aspects of economies' digitalisation), extrapolation (used to forecast the export of computer services by Ukraine), deduction (transitioning from the analysis of a region's digital development to the characteristics of individual countries), rating estimation using the average multidimensional method (was used to construct rankings of countries by the Digital Integral Index and the integral index of intellectual capital).

Correlation analysis as a statistical method was used to study the degree of relationship between random variables, while regression analysis was used to assess the relationship between a dependent variable (Y) and one or more independent variables (X) to model their behaviour in the future. For a more objective study of the impact of digitalisation on the economic development of developing countries, the analysis relied on the results of global indices. Global Knowledge Index (2023) assessed the potential of knowledge in key development areas. The Network Readiness Index (2023) analysed the ability of countries to exploit the opportunities of the information society. It examined innovation potential using data from corporate and academic partners. The Global Cybersecurity Index (n.d.) evaluated cybersecurity commitments across five domains: legal, technical, organisational, cooperation, and capacity development. The Digital Integral Index measured the availability of digital technologies, infrastructure, education, and regulatory policy based on 20 key indicators. The World Digital Competitiveness Ranking (2023) analysed the implementation of digital technologies that transform the economy and society. A parameter E-Participation Index was included in the study.

Figure 1 presents the structure of the Digital Integral Index, calculated by the authors for a more objective comprehensive study of the national economy and the level of its digitalisation. The index is based on five components: the subindex "ICT" of the Global Knowledge Index; the subindex "Human Capital and Research" of the Global Innovation Index; the subindex "People", "Government" and "Impact" of the Network Readiness Index. The significance of each component in the overall result is estimated at 20%. These components are selected to correspond to five strategically important dimensions of digitalisation, namely: infrastructure provision, intellectual potential, inclusion, government support and impact on the economy, society and the sustainable development goals. The authors assessed 84 developing countries, based on 2023 data.

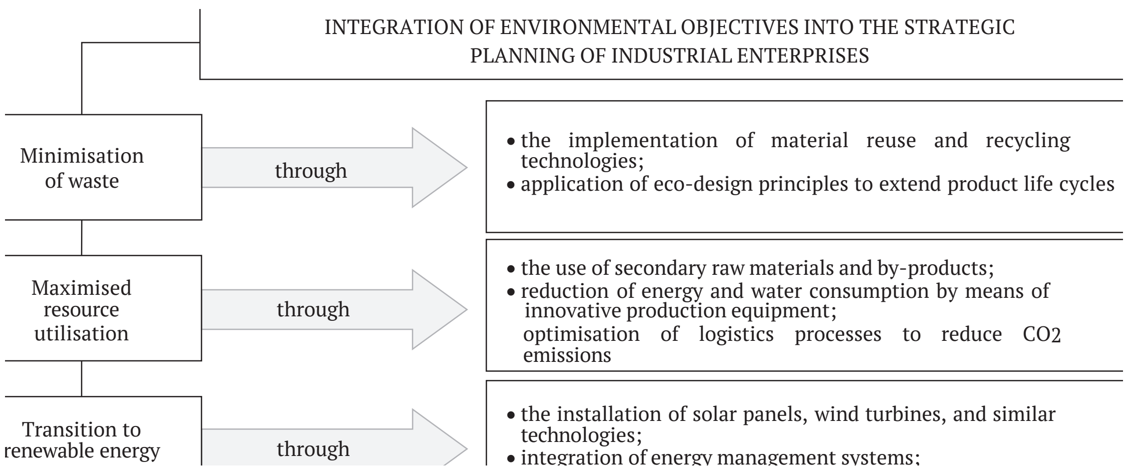

Figure 1. The structure of the Digital Integral Index

Source: prepared by the authors based on Global Knowledge Index (2023), Network Readiness Index (2023), Global Innovation Index (2023)

The calculation was based on the Human Development Index (n.d.) methodology with the following formula:

$$\text{Digital Integral Index} = \sqrt[5]{\bar{X}_1 \times \bar{X}_2 \times \bar{X}_3 \times \bar{X}_4 \times \bar{X}_5}, \quad (1)$$

where $\bar{X}$– the share of a country's value, calculated by attributing the country's value in a subindex to the average total value for all countries in that subindex. It should be mentioned that China's Digital Integral Index score differs from that of any other 83 countries in the ranking. This is due to China's lack of a value in the ICT subindex, resulted in a slightly different formula used for the calculation:

$$\text{Digital Integral Index (for China)} = \sqrt[4]{\bar{X}_2 \times \bar{X}_3 \times \bar{X}_4 \times \bar{X}_5}. \quad (2)$$

Correlation analysis was applied to explore pairwise statistical relationships between selected digitalisation indicators and economic outcomes. In particular, Pearson's correlation coefficients were calculated between the Digital Integral Index and individual economic indicators, such as GDP per capita, high-tech exports, value added in industry, and public expenditure on education. This analysis enabled the identification of the strength and direction of linear dependencies between variables across the 90-country dataset. Regression analysis was used to assess the predictive relationship between economic performance and selected digital variables. The dependent variable (*Y*) in the regression model was GDP per capita, while the independent variables (*X*) included Internet usage rate, fixed broadband subscriptions, mobile cellular penetration, ICT exports, and Digital Integral Index scores. Multiple linear regression models were tested to evaluate the explanatory power of digitalisation for economic outcomes. The regression diagnostics included R^2 values and significance levels to validate the robustness of the results.

RESULTS

Based on the analysis carried out in 2023-2024, this research formulates guiding principles of digitalisation to be considered in digital strategies across all levels (enterprise, industry, region, state). Table 1 summarises these key principles.

Table 1. Universal principles of digitalisation

Principle	Essence
Inclusivity	The digital strategy should provide for and guarantee equal access to services, information and knowledge provided based on digital technologies
Integration	All components of the digital environment, both software products and physical objects that make the technology work, must be combined and operate smoothly as a single mechanism
Security	Digital tools and technologies must prioritise the security of systems and each citizen. This applies to the protection of personal and confidential data, privacy and user rights, etc.
Continuous improvement	A technology that is revolutionary today will inevitably be dominated by another technology at some point in the future. Therefore, the technological development of any system must be subject to continuous improvement, if it is to be viable
Transparency	Digital solutions should ensure transparency of operations and provide authorised persons with the ability to monitor, control, analyse and respond to processes in a timely manner

Source: compiled by the authors

Ignoring any of the above principles undermines the likelihood of achieving long-term strategic results. Regardless of how innovative a particular technology may be, insufficient digital skills among personnel or the emergence of social stratification and associated risks limits its positive impact. A relevant example is the challenge of integrating systems and digital products. In the case of Ukraine, the absence of a unified methodology and the failure to ensure seamless interaction among the information and telecommunication systems of various governmental institutions clearly illustrate this issue. Digital transformation in the broad sense – from the digitisation of data on physical media to a radical change in existing business models – is possible in any national economy. However, it is worth emphasising that the pace of such transformation and its quality will vary significantly in different economic systems. This is explained by the influence of various factors, which by their origin can be divided into: exogenous – to which the system will adapt quickly and endogenous, which are subject to influence and adjustments. Generally, they are represented by the following categories: political, economic, institutional and social, and specific digital factors (Fig. 2). The factors presented in Figure 2 include: financial issues of the ability to incorporate digital solutions, inclusiveness of institutions and population, legal regulation of relations in the country and in the digital sector in particular, state credit and tax policy, ideological and educational activities aimed at creating an innovation culture of the population and many other aspects. These factors should be considered comprehensively and necessarily in connection with others. Thus, it is possible to produce knowledge, innovations and technologies only under the condition of reliable and fair legislation on intellectual property rights, data protection, e-commerce, cybersecurity. Otherwise, representatives of the intellectual sphere have no guarantees that the results of their intellectual and creative activities will be protected in such a country. There is no point in financing research and development for either private national or foreign investors if there is no sufficient legislative regulation. The loopholes in the legislation or the lag of the existing regulatory framework from modern realities inevitably leads to distrust of the country's population in authorities, government and, as a result, any attempts to change something can have negative consequences. Increasing competitiveness and attractiveness for foreign investors and partners is out of question in a system characterised by such features.

The fourth category is characterised by specific prerequisites for digital development, expressed in the availability and degree of preparation of digital infrastructure. Accelerated digital development is possible in a system that is provided with information and telecommunication networks, data centres, software and hardware, etc. It is worth mentioning that it is one thing when the digital infrastructure is available and quite another when the price for the internet connection allows households and business units to use the opportunities of the "digital time". The connection speed is acceptable, in other words, when the infrastructure support promotes the inclusion of users. Six leading countries were identified in the Digital Integral Index, China, which is not included in the ranking due to differences in the index calculation, and Ukraine, which is added for comparison. The parameters, according to which the study was conducted, have been systematised and grouped by the following areas: "inclusion", "government support", "intellectual potential" and "infrastructural support of the digital space". For a better visualisation of the obtained results, Figure 3 was constructed to present, which is presented below. Each axis represents a separate parameter (share of Internet users, employment in the ICT sector, share of mobile phone owners, etc.) and the country value corresponds to the symbol of the square painted in the corresponding colour. For most parameters, data by countries are given for the year 2022, except for the employment indicator in the ICT sector and in some cases where updated data is not available.

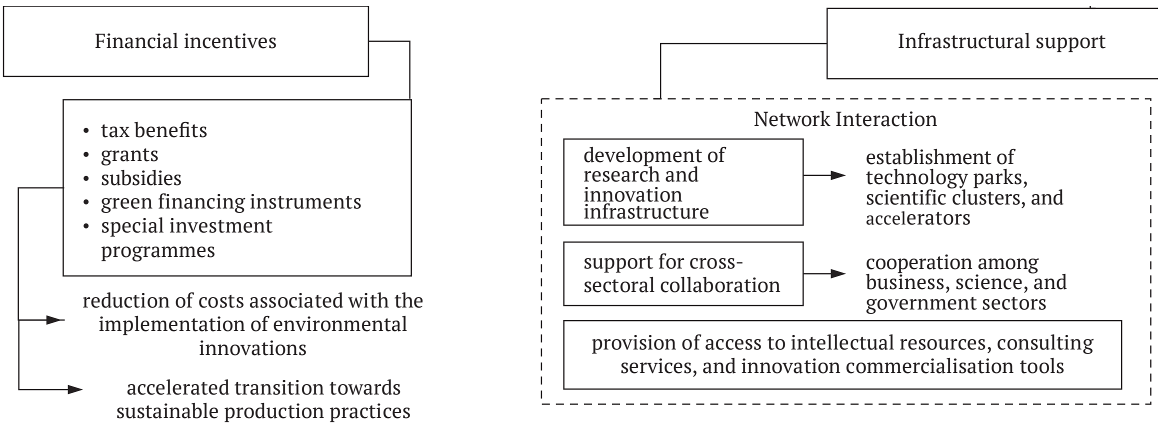

Figure 2. Key factors influencing digital transformation in the economic system
Source: prepared by the authors based on United Nations Development Programme (2022)

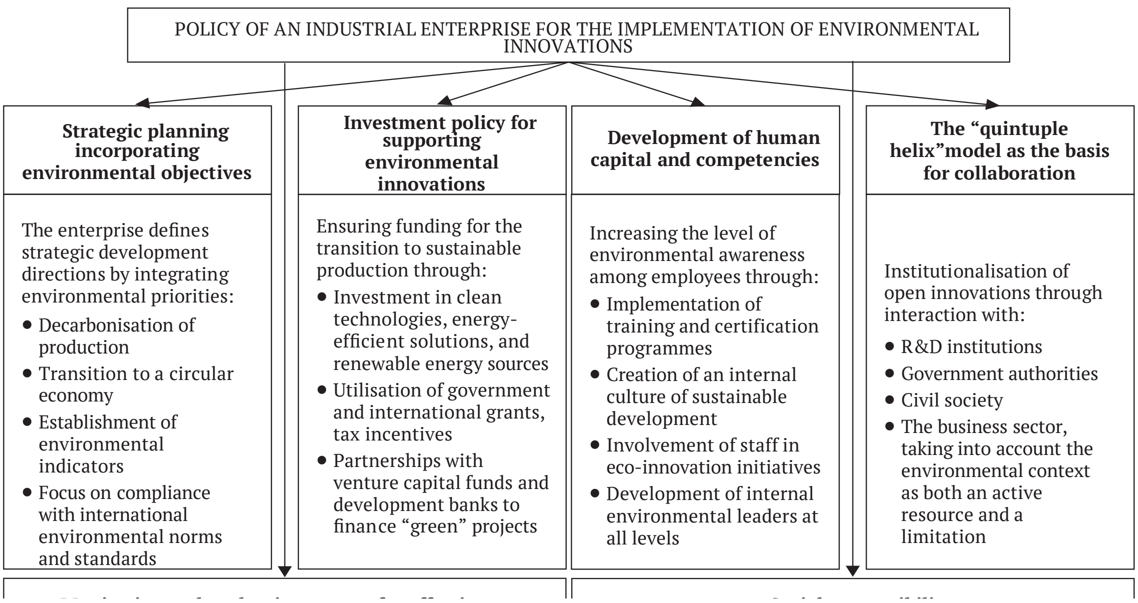

Figure 3. The values of the leading countries of the Digital Integral Index, China and Ukraine, in the area of "inclusion"
Source: prepared by the authors based on Global Knowledge Index (2023), Global Innovation Index (2023), United Nations E-Government Knowledge Base (2023), UN Trade and Development (UNKDAT) (2024)

As shown in Figure 3, all parameters assessed the degree of citizen involvement in digitalisation processes, including the availability of connection and communication, employment in the sector responsible for the digital transformation of the economy, and the E-Participation Index, which aimed to quantify how different countries utilised online tools to facilitate interaction between government and the population, as well as among citizens for the benefit of all (United Nations E-Government Knowledge Base, 2023). The values of the eight selected countries differ dramatically in several parameters, so it is expedient to analyse them in more detail. The shares of Internet users fluctuate in the range (68-100%) with the largest value in the UAE and, accordingly, the smallest in Mauritius (with the population of 1.27 million in 2021). These countries also have extremes in the parameter "share of households with the internet connection". It is logical that in order to use the Internet, a person must have both a connection and a mobile device. Figure 3 shows that countries with a higher number of mobile phone owners (the UAE, Malaysia, Kazakhstan) have both a higher share of Internet users and households with the internet connection. There was no doubt that the share of the active digital population was influenced by the price of internet connection. In Mauritius, the average monthly cost in 2023 amounted to 32.72 USD with a speed of 20.3 Mbps, whereas in the UAE it reached 98.84 USD, with an estimated average speed of 124.7 Mbps (BestBroadbandDeals, n.d.). In 2022, the percentage of Internet users in China and Ukraine was nearly identical; however, given the significant difference in population size, a substantial contrast in absolute user numbers was evident. Regarding the indicator "population covered by at least 3G mobile network", almost all of the analysed countries demonstrated acceptable levels, with values ranging from 92% to 100%, and the lowest level recorded in Ukraine.

Inclusion is evident in both the availability of a personal computer or smartphone and access to the Internet, as well as the effectiveness of its use. For this purpose, the parameter E-Participation Index was included in the study. The higher it is, the more the country's government is interested in using online tools to improve the efficiency of providing individual services, exchanging and accessing information, etc. In this case, the UAE lost the lead to China, which is actively promoting state strategies to increase the level of inclusion among its almost one and a half billion population. By most indicators, the only representative of the African continent, Mauritius, was among the outsiders, except for the parameter "employment in the ICT sector". This is explained by the international specialisation of the country and vectors outlined by the Mauritian government, in particular in the Mauritius National Export Strategy 2017-2021 (n.d.). Software development and arrangement of innovative approaches in all sectors of the national economy are among the key goals.

For digital transformation to occur not only at the level of individual enterprises but on a national scale, government support was essential. This included the adoption of comprehensive national digital strategies and the provision of adequate funding for sectors directly or indirectly related to the digital economy. In Figure 4, all parameters, with the exception of government spending on education, were provided for the year 2023. Since every citizen was expected to have at least a basic secondary education, the level of expenditure in this sector held significant strategic importance. A decline in education spending rendered the prospects for science and research development in the country increasingly unlikely. Among the analysed countries, the share of spending on education ranged from 3.9% to 5.7%. Notably, Ukraine recorded the highest share for this indicator, whereas the United Arab Emirates reported the lowest figure – 3.9%. According to the budget execution report, in absolute terms, the UAE Ministry of Education had spent AED 1.05 billion (USD 286.9 million) by 30 June 2021 (Ministry of Finance..., 2021).

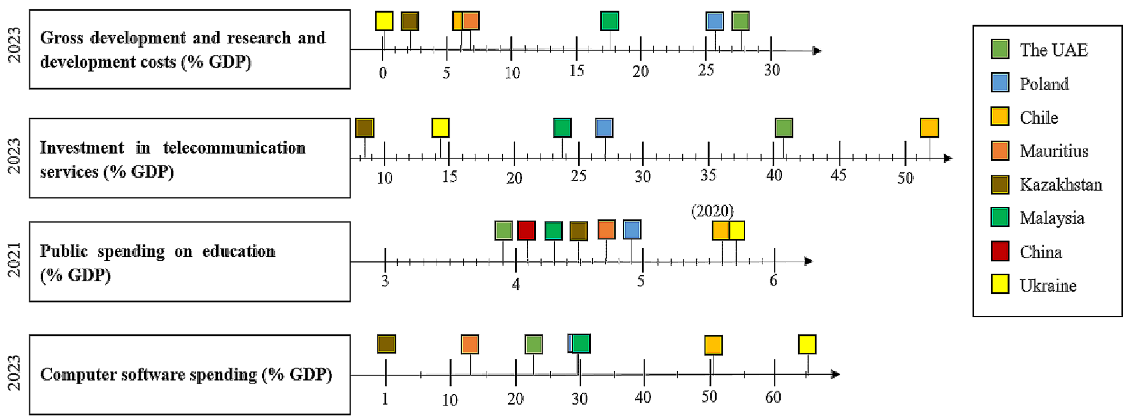

Figure 4. The values of the leading countries of the Digital Integral Index, China and Ukraine, in the area of "government support"
Source: prepared by the authors based on Global Knowledge Index (2023), World Bank Open Data (2024)

The telecommunications parameter is presented separately, since information is one of the national resources and constitutes the national wealth of the country. The informatisation of society and the digitalisation of sectors impose new requirements on the quality and efficiency of the telecommunications sector. The analysed countries took values in the range (8.5-51.9%) in 2023. Chile was identified as the regional leader in Latin America regarding the development of telecommunications infrastructure. Since the privatisation of the sector in the 1980s, telecommunications had demonstrated continuous year-to-year growth. However, the Telecommunications Infrastructure Index (a component of the E-Government Development Index) in Chile reached 0.79990 in 2022, which remained lower than in Uruguay (0.8543), the subregional leader (United Nations E-Government Knowledgebase, 2024; International Telecommunication Union, 2024). The share of investment in telecommunications as a percentage of GDP amounted to 51.9% in 2023. Despite these achievements, the government of Chile expressed concern about the persistent digital divide and outlined plans to increase funding in this sector (Privacy Shield Framework, 2024).

An important area of analysis was "intellectual potential". The experience of developed countries such as Switzerland, Singapore, and the Republic of Korea demonstrated that knowledge could serve as a driver of economic transformation and facilitate the creation of a knowledge-based economy. A favourable national environment was required to enhance intellectual capital, particularly through government-led initiatives aimed at eliminating illiteracy and expanding access to education. According to the Chart of the day: Education level in China up over past 20 years (2023), the demographic dividend of a country depends on the size of its population; however, the quality of population is more important. The adult literacy rate in 2023 was one of the primary indicators used for comparative assessment (Fig. 5). The values ranged from 89.2% to 100%, with Mauritius reporting the lowest rate and Ukraine the highest (World Bank Open Data, 2024). The average number of years of education was also considered informative. The difference between the highest and lowest performing countries – Poland and China, respectively – amounted to 5.4 years. Recognising this disparity, the Chinese government included in its 14th Five-Year Plan (2021-2025) the objective that all Chinese people will have better opportunities for education and the average duration of education among the working-age population will increase to 11.3 years (Asian Development Bank, 2021).

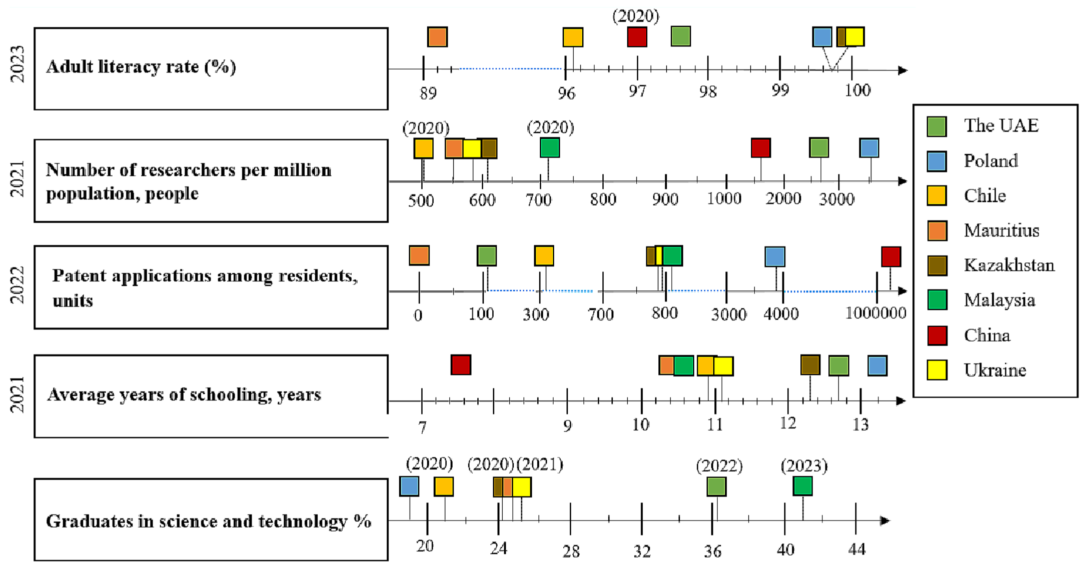

Figure 5. The values of the leading countries of the Digital Integral Index, China and Ukraine, in the area of "intellectual potential"

Source: prepared by the authors based on Global Knowledge Index (2023), World Bank Open Data (2024), UNESCO Institute for Statistics (2024)

Regarding the parameter "number of researchers per million population", a positive correlation was observed between the level of scientific engagement and factors such as the development of the education sector, legislative support, and adequate funding. In 2021, significant contrasts were identified across countries: Mauritius recorded 557 researchers per million people, while Poland reported 3,534 researchers (World Bank Open Data, 2024). For Mauritius, this figure was relatively high in proportion to its total population of 1.2 million. An analysis of the country's export commodity structure in 2021 indicated the dominance of low-tech sectors. Specifically, exports of foodstuffs amounted to USD 549 million and textiles to USD 600 million. In contrast, science-intensive sectors such as the chemical industry generated lower export volumes – USD 304 million (International Monetary Fund, 2024). Nevertheless, national research institutions, such as the Agritech Mauritius Research Centre (n.d.), highlighted the potential of digitalisation to transform the agribusiness sector. According to their projections, the adoption of digital technologies was expected to enhance competitiveness and increase the value-added component of agricultural products.

Regarding the number of patents granted to residents in 2022, Mauritius ranked the lowest, with no registered patented inventions, whereas China accounted for approximately 1.6 million patents (World Intellectual Property Organization, 2024). This result may have been linked to underdeveloped legal regulation in the field of intellectual property. As of 2022, Mauritius had not joined the Madrid Agreements Concerning the International Registration of Marks, the Hague Agreements Concerning the International Registration of Industrial Designs, or the Patent Cooperation Treaty. The respective accession treaties for

Mauritius entered into force on May 6, 2023, while the Patent Cooperation Treaty became effective on March 15, 2023 (World Intellectual Property Organization, 2024). In the final indicator included under the domain of "intellectual potential", Malaysia ranked highest, with 43.53% of university graduates in 2023 having specialised in science and engineering disciplines (World Intellectual Property Organization, 2023).

Infrastructure support of the digital sector is an important component of the digital transformation of countries around the world, covering a variety of aspects: the availability of hardware for the population (telephone, computer, etc.), databases, data centres and network capacity. One can wonder what the relationship between the localisation of infrastructure in the form of critical servers and computer subsystems and digital inclusion is. The relationship can be illustrated with the example of African countries, which need to solve the problem of affordability of internet connection in order to be included in digital processes or at least have access to the Internet. The most effective solution to guarantee the inclusion of each citizen is to have its own critical infrastructure with critical servers and computer systems with fully redundant subsystems. In 2023, Liquid Intelligent Technologies completed the Mauritius Telecom T3 submarine cable project, linking Mauritius and South Africa, thereby enhancing regional digital connectivity (South China Morning Post, 2023). In East, Southeast, and West Asia, China emerged as the regional leader in digital infrastructure development, actively competing with the world's most advanced economies. Technological advancement and cybersecurity were perceived by the Chinese government as key elements of national competitiveness and power. Consequently, substantial investments were directed towards national digital initiatives.

One of the most notable achievements in 2023 was the implementation of the Beijing-Wuhan-Guangzhou fibre-optic trunk line. This 3,000 km line, introduced under the national Future Internet Technology Infrastructure project, provided a data transmission speed of 1.2 terabits per second. According to South China Morning Post (2023), this speed equated to "the equivalent of 150 movies per second" and was approximately three times faster than that of the closest global competitor, the United States. Beyond national initiatives, China also engaged in international digital cooperation projects, particularly those focused on the development of digital infrastructure. In 2015, under the broader "One Belt, One Road" strategy, the "Digital Silk Road" initiative was launched. The framework of this project included partnerships aimed at enhancing terrestrial and submarine data transmission networks, exploring artificial intelligence, expanding the use of cloud computing, e-commerce, and mobile payment platforms, as well as developing surveillance technologies and satellite systems (South China Morning Post, 2023).

Table 2. The values of the leading countries of the Digital Integral Index and China, the size of their GDP (billion USD) and the contribution of the ICT sector to GDP (%)

Place in the ranking	The DII 2023	GDP 2023	The ICT contribution
1. China	1.5950	17,700	55% (2021)
2. The UAE	1.5122	509.18	2.2% (2020)
3. Poland	1.4720	842.17	3.77% (2020)
5. Malaysia	1.4682	430.9	23% (2021)
12. Chile	1.4433	344.4	3% (2015)
21. Kazakhstan	1.4299	259.29	3% (2021)
33. Mauritius	1.4041	14.82	5.8% (2019)

Source: prepared by the authors based on Information Society Outlook (2020), Global Knowledge Index (2023), Global Innovation Index (2023), Network Readiness Index (2023), World Bank Open Data (2024)

Table 2 systematised the data for the leading countries from seven global regions, including their Digital Integral Index values for 2023, national market size (GDP), and the ICT sector's contribution to GDP. In absolute terms, China ranked first across all three indicators. Based on the results of the correlation analysis conducted between the Digital Integral Index and GDP size, a strong positive relationship was observed. For the seven countries under analysis, the Pearson correlation coefficient equalled 0.853, indicating a significant link between the scale of the national economy and the level of digital development in 2023.

Figure 6 shows the place of Ukraine and Poland in the main international digitalisation indices. Ukraine demonstrates positive dynamics in most indices, especially in increasing the rating in the Network Readiness Index. In particular, from 2019 to 2023, Ukraine rose from the 67th to 43rd place. At the same time, compared to Poland, the gap remains significant, especially in the Digital Competitiveness Index. The smallest gap between countries is observed in the E-Government Development Index, where Ukraine ranked 46th out of 193 countries and Poland ranked 34th in 2022. These results indicate Ukraine's achievements in certain aspects of digitalisation, whereas require further strengthening of reforms to narrow the gap with the leaders of the European region.

Analysing the dynamics of computer technology exports, the authors discovered that the trend line has an upward direction, suggesting a positive trend in the growth of computer services exports by Ukraine in the period 2007-2022 (Fig. 7).

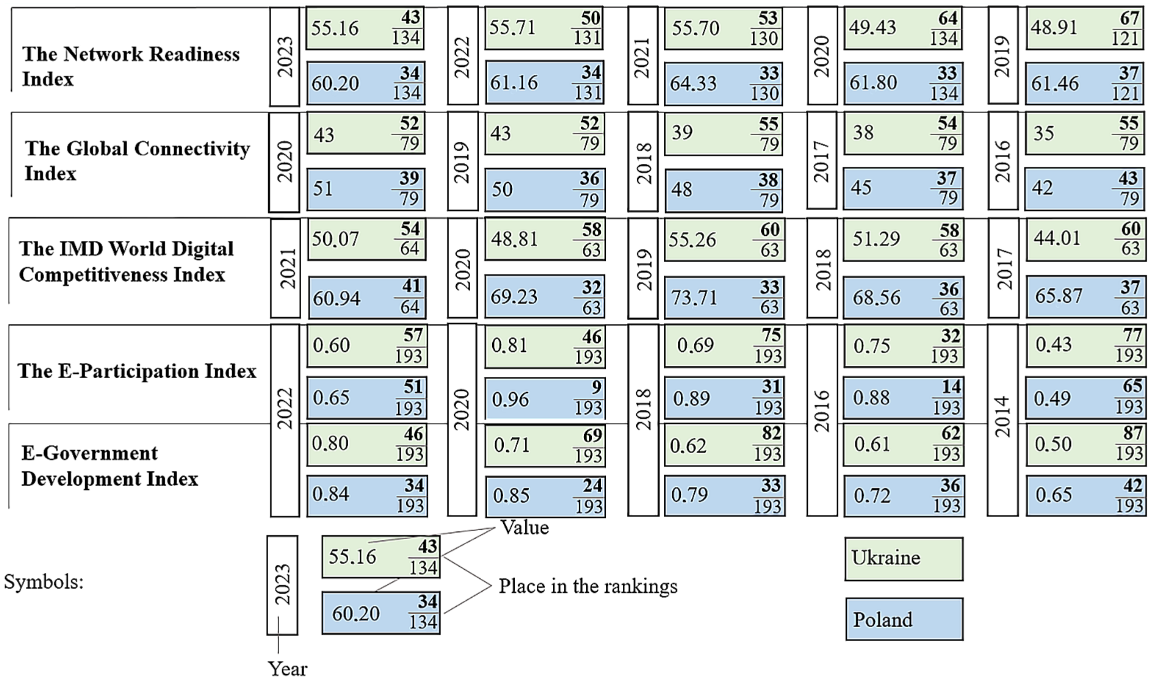

Figure 6. The values of Ukraine and Poland according to advanced indices in terms of digitalisation

Source: prepared by the authors based on Global Connectivity Index (2020), Network Readiness Index (2023), IMD World Digital Competitiveness Ranking (2024), E-Participation Index (2024), United Nations E-Government Knowledge Base (2024)

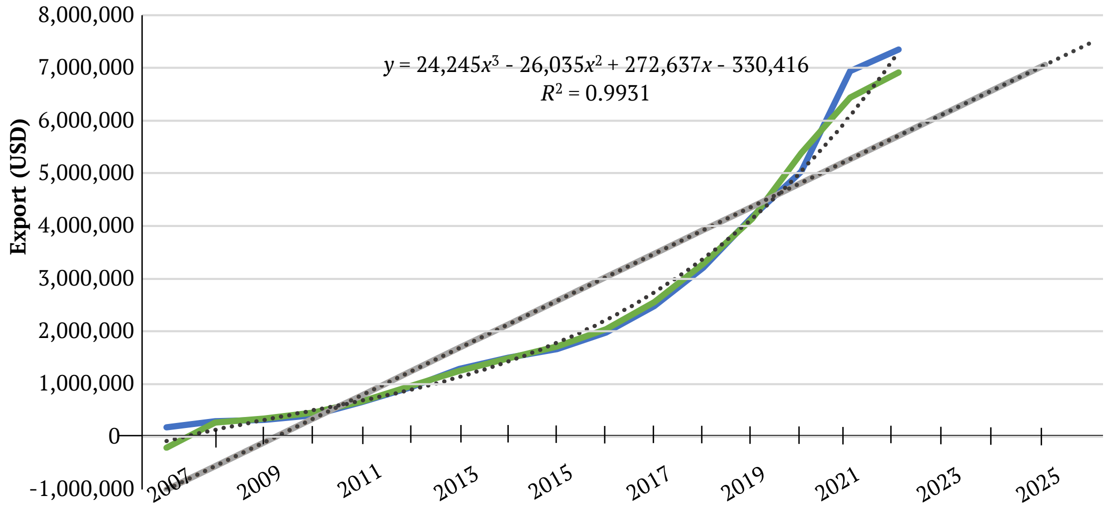

Figure 7. The dynamics of computer services export by Ukraine
(based on initial data and after smoothing the dynamic series) and a trend line

Source: prepared by the authors based on Trade Map (2024)

According to the data, export volumes demonstrate stable growth, despite the impact of crisis events, such as political instability in 2014-2015, the COVID-19 pandemic and the armed conflict in 2022. The conducted regression analysis indicates a high correlation between time and the increase in export volumes, which is proved by the coefficient of determination ($R^2 = 0.9931$). The constructed trend line suggests that the computer services sector in Ukraine is one of the key drivers of the economy, even during periods of turbulence. These data emphasise the importance of supporting and developing the IT sector in Ukraine, as it provides a significant contribution to national exports and remains one of the least vulnerable sectors during crises. The ICT sector was almost the only sector that gained even greater development during the period of full-scale invasion. The growing demand for remote services (medical, government, etc.), the need to track population movements, business online operations and many other factors have accelerated digitalisation in many sectors of the Ukrainian economy. Thus, digitalisation remains both a global trend and an effective rescue tool for citizens, business structures and the country itself. The result is presented in Table 3.

Table 3. Determined clusters and their composition

Cluster No. 1	Cluster No. 2	Cluster No. 3	Cluster No. 4
Malaysia, Vietnam, Philippines, China	The UAE, Saudi Arabia, Qatar, Bahrain, Kuwait, Brunei	Turkey, Iran, Tunisia, Thailand, Argentina, Brazil, Colombia, Costa Rica, Mexico, Panama, El Salvador, Trinidad and Tobago, Uruguay, Chile, India, Kazakhstan, Uzbekistan, Sri Lanka, Mauritius, Armenia, Bulgaria, Bosnia and Herzegovina, Georgia, Moldova, North Macedonia, Poland, Romania, Russian Federation, Serbia, Hungary, Ukraine, Montenegro, Belarus	Jordan, Egypt, Algeria, Iraq, Sudan, Indonesia, Cambodia, Mongolia, Azerbaijan, Guatemala, Honduras, Dominican Republic, Ecuador, Paraguay, Peru, Jamaica, Bangladesh, Pakistan, Angola, Benin, Botswana, Burundi, Ghana, Eswatini, Ethiopia, Zambia, Zimbabwe, Cabo Verde, Cameroon, Kenya, Democratic Republic of the Congo, Côte d'Ivoire, Lesotho, Madagascar, Mali, Mozambique, Namibia, Nigeria, South Africa, Rwanda, Senegal, Tanzania, Uganda, Albania, Gabon, Nicaragua, Togo

Source: prepared by the authors

It is necessary to pay attention to the fact that although the countries were systematised into groups based on the principle of similarity, the objects are characterised by inhomogeneity, which is visually proved by the clustering tree (Fig. 8).

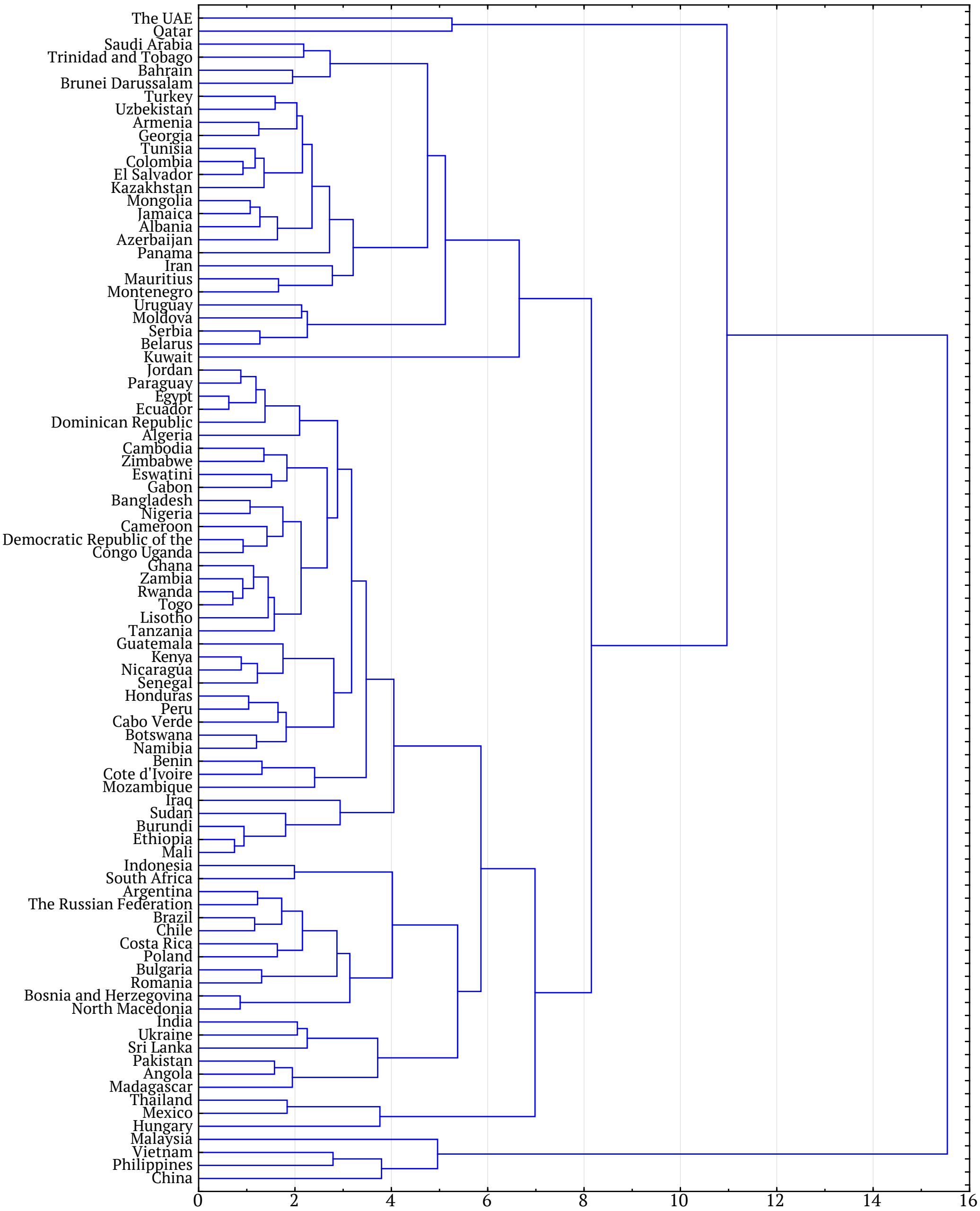

Figure 8. Clustering tree for developing countries by studied parameters

Source: prepared by the authors

Cluster No. 1 includes 4 countries of Southeast Asia (Malaysia, Vietnam, Philippines) and East Asia (China). In this group, the countries' GDP per capita fluctuates in the range from 3,500 to 12,800 USD. This cluster is a leader in terms of average share of high-tech exports from total sales (10.9%). All countries are competitors in terms of high-tech products, although Malaysia remains the flagship of the group (46.9%). Malaysia (0.75) and China (0.77) are the most distant from the centre of cluster No. 1. Cluster No. 2 grouped 6 Arab countries of the Middle East. Among all other clusters, this one stands out with an average value of 5.2 for GDP per capita, however the dispersion index within the group is quite low – 2.9. Although Brunei surpasses Saudi Arabia and Bahrain in terms of GDP per capita, the country is the last in terms of population (449,002 people). The greatest distance from the centre of cluster No. 2 is observed for the UAE and Bahrain. Cluster No. 3 includes 33 countries and is of a great interest to us, due to Ukraine's presence there. The objects of this group contrast in terms of the level of economic development, the GDP per capita of Uruguay (20,795 USD) is 9.2 times higher than that of Uzbekistan (2,255 USD). Hungary, Romania and Armenia are located further from the cluster centroid. Cluster No. 4 is characterised by the greatest contrast in terms of economic development and population number. In terms of GDP per capita, the Dominican Republic (10,111 USD) is 39 times ahead of Burundi (259 USD) and the difference between the population of Cabo Verde (593,149 people) and Bangladesh (171.2 million people) is significantly greater. Cluster No. 4 includes countries from almost all regions of the world: the average values in the cluster differ most in the share of public spending on education and gross fixed capital formation (1.02). Sudan, Burundi, South Africa and Indonesia are the most distant from the centre of cluster No. 4. Cluster average values in Figure 9 allow to compare the studied clusters across the entire set of parameters.

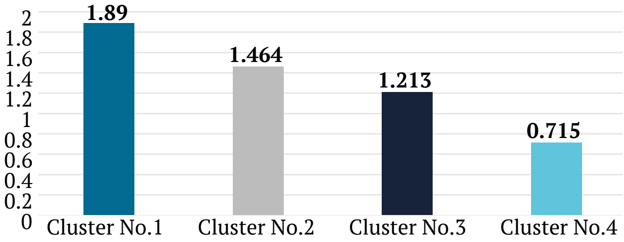

Figure 9. Average values across clusters for all parameters
Source: prepared by the authors

In addition, it can be assumed that each cluster is characterised by a corresponding level of digital development: Industry 2.0 and Industry 3.0, as well as two transition zones, referred to as Industry 2.5 and 3.5 in Figure 10.

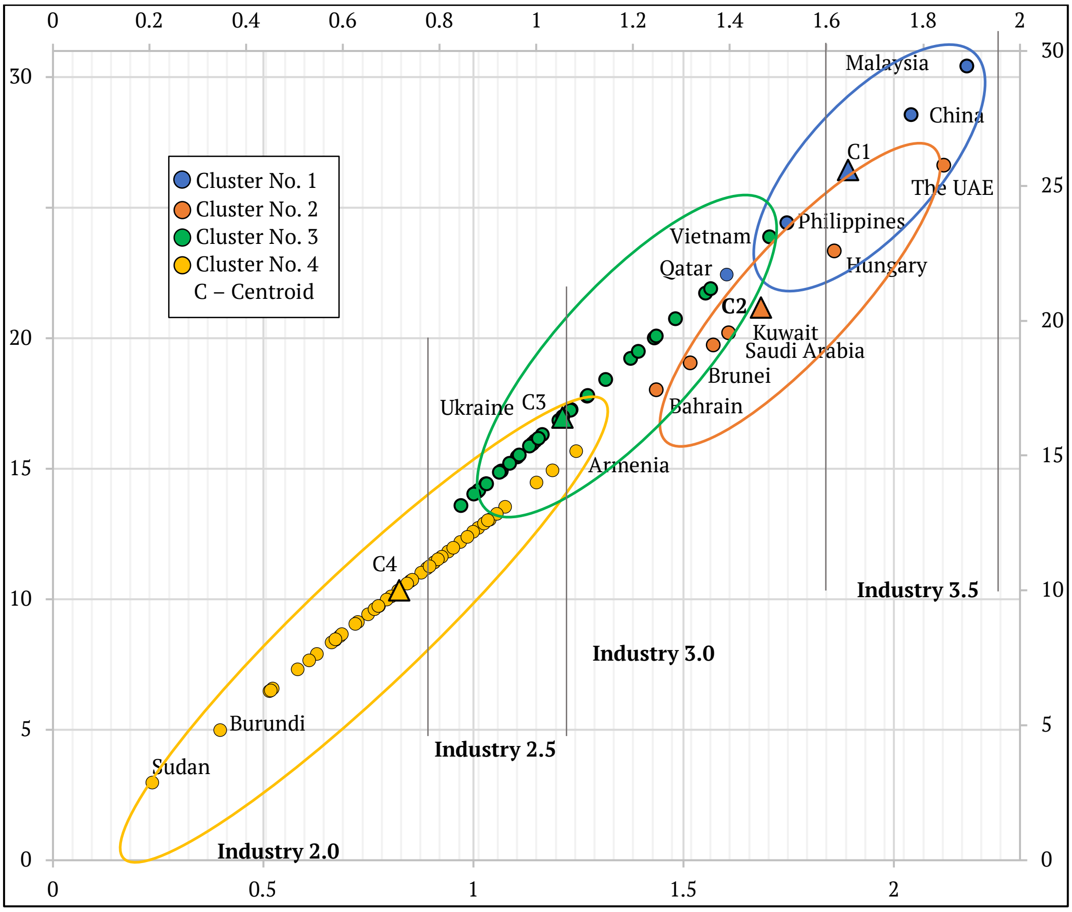

Figure 10. Cluster scatter diagram by average values for the studied parameters
Source: prepared by the authors

Malaysia, China and the UAE have already left the third technological revolution, which is characterised by robotic systems, total computerisation, the development of microelectronics, and are actively moving towards the next level of digital Industry 4.0. Ukraine is a vivid "transit" representative of Industry 2.5, characterised by a hybrid state of innovative and technical development. Despite experimental digital solutions in the form of government services digitisation and state registers, most industrial enterprises in the post-war period belonged to mechatronic systems. The latter refers to the synergistic combination of precision mechanics with electronic components, providing for reducing the workload on employees and increasing their productivity. Digital "experiments" should fit into the existing institutional environment, be accompanied by the creation of formal institutions and should not confront informal institutions that exist in society (corruptibility, traditions and people's perceptions, values, etc.).

Although Ukraine is well represented in the ranking of developing countries according to the parameters studied, the number of fixed broadband Internet subscriptions or the share of Internet users do not provide a qualitative assessment of the economy digitalisation level. Ukraine has experience in implementing successful digital projects only in certain high-tech sectors of the economy: telecommunications, IT or the production of electrical equipment and computer equipment. Similar to Ukraine, several other developing countries have achieved notable success through targeted digital policies and inclusive technology deployment. Recent studies suggest that digitalisation contributes to narrowing the development gap between countries and enhances economic resilience and growth (UN Trade and Development, 2024; World Bank Open Data, 2024). India, for instance, has emerged as a global leader in IT services by investing heavily in digital education and broadband infrastructure (Financial Times, 2024). Kenya's widespread adoption of the M-Pesa mobile payment system significantly improved access to financial services, particularly in underserved regions (GSMA, 2023). Such examples can serve as valuable references for Ukraine's digital trajectory. The "Diia" project, recognised internationally for its innovation in digital governance, reflects Ukraine's potential to apply best practices and accelerate its transformation (European Investment Bank, 2023).

The results of each country were formed under the specific circumstances of place, time and the ratio of resources to achieve the current level of digital development. For this reason, it is strategically important for the authority of Ukraine to work comprehensively with the economic system, which would cover both digital technologies and issues of infrastructure, the level of social institutions development and many other aspects. However, it is impossible to assign a certain level of digital development to each of the resulting clusters, since for a more substantive analysis it is necessary to increase the set of digitalisation indicators, including quantitative indicators of artificial intelligence application in economic systems, the volume of digital economy and the volume of the e-commerce market, whereas for most of the studied countries such data are absent, as well as a qualitative calculation methodology.

Digital technologies, which are used in combination with the most modern means of production, increase efficiency the most. Systems will have a radically different effect when digitalisation is combined with equipment and technologies, which physical properties are significantly limited in comparison with the best new models. Therefore, if different or even similar innovative and technological systems dominate within the studied clusters and different digital tools are applied, economic development in cluster countries will be different. As a result of the conducted factor analysis, which supplemented the cluster analysis findings, the percentage distribution between the two groups of factors was obtained (Fig. 11), namely, the percentage distribution between the two groups of factors.

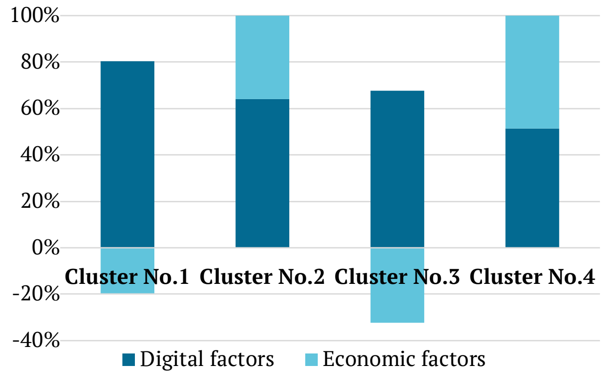

Figure 11. Percentage ratio of digital and economic factors by clusters
Source: prepared by the authors

In all cases, it was observed that the total factor loadings for digital variables are higher than for similar economic variables. The biggest difference is in clusters No. 1 and No. 3 – here digital factors reach 80%, the factor volume in cluster No. 2 is almost twice as large and in the last group it is almost balanced. These calculations statistically prove the statement that digitalisation is an influential factor in the economic development of developing countries, especially in the group characterised by the features of Industry 3.0. The findings of this study confirmed that digitalisation had a significant and multifactorial influence on the economic development of developing countries. These effects became most evident when digital transformation was supported by investments in infrastructure, human capital, effective institutions, and inclusive policies.

DISCUSSION

One of the most critical enablers of successful digital transformation was the availability and quality of digital infrastructure. S. Lin *et al.* (2025) used panel data from Chinese provinces and demonstrated that broadband infrastructure not only reduced regional disparities but also promoted industrial diversification and investment in less-developed areas. A consistency was observed between these findings and the cluster analysis results, where strong ICT infrastructure was identified as a key attribute of high-performing economies. At the firm level, evidence from X. Zhao & F. Dong (2025) indicated that infrastructure development under China's national broadband strategy resulted in improved innovation performance among non-state companies, thereby reinforcing the relationship between digital access and competitiveness. From a regulatory standpoint, E.J. Oughton *et al*. (2021) noted that broadband affordability continued to pose a significant policy challenge. To mitigate digital exclusion, particularly in low-income countries – a concern highly relevant to countries included in Cluster No. 4 – subsidies and price regulation mechanisms were recommended.

Alongside infrastructure, human capital was recognised as a fundamental component in translating digitalisation into sustainable growth. In particular, K. Bibi *et al*. (2025) demonstrated that digital transformation yielded the highest results when accompanied by strategic investment in education, which enhanced the capacity to absorb and apply technological solutions. This conclusion was supported by the findings of N. Xholo *et al*. (2025), who showed that digitalisation had a positive effect not only on income levels but also on innovation and economic complexity, particularly when supported by intellectual and technological development. These perspectives aligned with the results of the factor analysis, in which human capital was identified as a key component of the constructed Digital Integral Index.

Institutional quality also played a determining role in shaping the outcomes of digital transformation. In a study focused on the MENA region, M. Touitou & Y. Laib (2025) found that the effectiveness of digitalisation depended on political stability and the quality of governance. This observation correlated with the tendency of countries possessing strong institutions to be grouped in the same digital development clusters and to demonstrate higher levels of economic performance. Similarly, O.P. Olofin (2023) identified transparency and regulatory stability as essential prerequisites for leveraging the benefits of the digital economy in African and Asian contexts. The importance of institutional capacity was further underlined in the research of S. Shabnam & H.C. Rakibul (2025), where confirmed that the implementation of digital public services contributed to greater citizen trust and improved administrative efficiency. This provided empirical support for including platforms such as Ukraine's Diia as illustrative examples of institutional digitalisation. Beyond economic and institutional dimensions, the social implications of digital transformation were extensively addressed in recent literature. A study by S. Nosratabadi *et al*. (2023), based on data from EU-27 countries, demonstrated that inclusive digitalisation strategies improved labour market outcomes and reduced socio-economic inequality. Conversely, S. Qureshi (2023) emphasised the potential for digitalisation to reinforce existing inequalities if inclusive policy frameworks were not in place. These perspectives underscored the necessity of incorporating principles of equity and accessibility into national digital strategies, especially in developing contexts.

At the macro level, further empirical validation of the identified relationships between digitalisation and economic development was provided. According to H.Q. Vu *et al*. (2025), digital transformation in Vietnam had a significant positive impact on GDP growth, particularly in the manufacturing and services sectors. This finding corresponded to observations made in the case of Ukraine, where the expansion of ICT exports was linked to enhanced economic resilience. In a broader cross-country study, H. Asma *et al*. (2024) employed panel ARDL modelling for 78 developing economies and identified both short-term and long-term growth benefits of digitalisation, thereby supporting the inclusion of dynamic effects in national digital strategies. Additionally, a global comparative study by N. Mahikala *et al*. (2022) covering seven world regions confirmed a generally positive relationship between digitalisation and GDP, though the effects were weaker in areas with underdeveloped infrastructure. This pattern reinforced the differentiation established by the cluster analysis regarding digital readiness levels.

Environmental dimensions of digitalisation were addressed in the study by R. Li *et al*. (2025) who explored the intersection of digitalisation, human capital, and carbon efficiency in China. Using regional data and structural equation modelling, they show that investment in digital infrastructure and education correlates with improved energy productivity and reduced emissions intensity. Their findings suggest that digitalisation not only drives growth but can also align with environmental sustainability – a point that adds complexity to policy considerations in developing countries. O.Ya. Yurchyshyn *et al*. (2023) evaluated the territorial disparities of digital transformation in Ukraine. Through a regional comparative analysis, significant inequalities in broadband access, digital literacy, and institutional readiness across regions were identified. It was concluded that unless national policy is adjusted to address these imbalances, digitalisation risks deepening existing socio-economic divides. This recommendation focussed on targeted regional investment, digital capacity-building programmes, and multi-level governance mechanisms to foster inclusion. An important contribution to the discourse on national models of digital transformation is made by R. Ouyang *et al*. (2024), where an in-depth analysis of China's digital economy strategy was provided. The authors examined the structure and implementation of digital development under conditions of centralised political governance, noting that China's top-down approach enables rapid mobilisation of resources and large-scale investment in digital infrastructure. It was highlighted the strategic role of the state in initiating nationwide projects such as fibre-optic networks, cloud infrastructure, and 5G expansion, which have significantly boosted connectivity and technological capacity across provinces.

Given the growing relevance of digitalisation as a key determinant of economic development, recent academic discourse increasingly focuses on the relationship between digital readiness, infrastructure, and socio-economic outcomes in developing countries. Numerous studies highlighted the need to assess this impact within the broader context of global challenges – economic inequality, uneven technological access, and the accelerated pace of innovation. The findings of the study are supported by a growing body of international research across key dimensions such as infrastructure development, education and skills, institutional governance, social inclusion, and macroeconomic growth. A common conclusion emerges: digitalisation functions as a key enabler of sustainable development, provided it is supported by a favourable policy and social environment. The applied cluster and factor analysis, along with the proposed Digital Integral Index, contribute to this discussion by offering a structured analytical framework for assessing digital readiness and transformation capacity in developing countries.

CONCLUSIONS

The study confirmed that the introduction of digital technologies contributed to increased productivity, enhanced business process efficiency, and the integration of economies into global markets. To assess the level of digital transformation, the authors developed the Digital Integral Index, which incorporated five key components: infrastructure, intellectual potential, government support, inclusion, and the socio-economic impact of digitalisation. Based on the 2023 data, China (Index score: 0.772), Malaysia (0.754), and the UAE (0.749) demonstrated the highest levels of digital development among developing countries. In contrast, Ukraine's index score amounted to 0.589, indicating positive dynamics in digital readiness and inclusion, yet still revealing a considerable gap compared to European leaders such as Poland (0.702) and Romania (0.694).

The Global Knowledge Index, Network Readiness Index, and Global Innovation Index all pointed to the decisive role of access to knowledge, human capital development, and infrastructure availability as fundamental drivers of digital transformation. For instance, in 2023, Malaysia reported 43.53% of graduates in science and engineering, while Poland recorded 3,534 researchers per million people, reflecting strong intellectual capital. The cluster and factor analyses confirmed that countries with advanced digital infrastructure and active digital policy demonstrated greater prospects for sustainable economic growth. Specifically, Clusters No. 1 and No. 2, which included countries such as China, Malaysia, and the UAE, were characterised by a high share of ICT exports (up to 10.9%), broad 4G coverage (over 95%), and Internet penetration exceeding 90%. Conversely, Ukraine, assigned to Cluster No. 3, exhibited moderate digitalisation levels and required increased public investment and policy reforms.

Despite Ukraine's upward trend in indicators such as Network Readiness Index rank (from 67th in 2019 to 43rd in 2023) and growth in ICT service exports, significant challenges remained. These included underdeveloped digital infrastructure in rural regions, insufficient funding for ICT education, and low levels of digital literacy among older age groups. The findings thus indicated that further government support, enhancement of infrastructure, and comprehensive digital skills development were essential for bridging the digital divide. Further research could be aimed at analysing the impact of specific digital tools on the development of economic sectors such as agriculture, healthcare and education, as well as developing strategies for adapting successful international practices to Ukrainian conditions.

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Цифровізація як чинник економічного розвитку країн, що розвиваються

Анотація. Актуальність дослідження зумовлена необхідністю оцінки впливу цифровізації на економічний розвиток країн, що розвиваються, в умовах глобальних викликів, таких як економічна нерівність, обмежений доступ до сучасних технологій, нерівномірність цифрової інфраструктури та низький рівень цифрової грамотності. Метою статті було дослідити вплив цифровізації на економічний розвиток країн, що розвиваються, шляхом визначення ключових цифрових індикаторів, аналізу кластеризації країн за рівнем цифровізації та оцінки взаємозв'язку між цифровими індикаторами та економічними результатами. Методи дослідження включали кластерний аналіз для групування країн за рівнем цифрового розвитку, факторний аналіз для визначення основних факторів цифрової трансформації та порівняльний аналіз для виявлення ключових тенденцій та особливостей цифровізації в різних країнах. Аналіз охопив 90 країн із різним рівнем цифрової готовності та економічного потенціалу. Результати дослідження засвідчили, що країни з розвиненою цифровою інфраструктурою, високим рівнем людського капіталу та активною державною підтримкою демонструють стійке економічне зростання. Виявлено, що серед основних драйверів цифрової трансформації є такі: доступ до швидкісного інтернету, цифрова освіта та впровадження цифрових технологій у ключових секторах економіки. Кластерний аналіз дозволив виділити чотири групи країн, які відрізняються за рівнем цифровізації, що допомогло визначити ключові пріоритети для кожної з них. Практичне значення дослідження визначається можливістю використання отриманих результатів для розробки рекомендацій щодо прискорення цифрової трансформації в країнах, що розвиваються, з урахуванням їх соціально-економічних умов та потенціалу

Ключові слова: кластерний аналіз; цифрова інфраструктура; цифрові технології; інфраструктура інформаційно-комунікаційних технологій; людський капітал

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Introducing smart technologies into marketing logistics: Personalising the supply chain and improving the customer experience

Abstract. The implementation of Industry 4.0 smart technologies is particularly significant for enhancing the efficiency of marketing logistics, due to the multiplicative nature of their impact and the synergistic effects arising from the convergence of Logistics 4.0 and Marketing 4.0. This underscores the need for a rigorous scientific examination of the importance and distinctive features of Marketing Logistics 4.0, as well as the development of methodological approaches to identify effective strategies for integrating this concept into enterprise activities, which constituted the primary objective of this study. Cluster analysis was employed to segment a sample of 100 customers of a warehouse-store in Kyiv (Ukraine) into three clusters characterised by similar behavioural and logistical profiles, including order volume, purchase frequency, location, and satisfaction level. Incorporating both behavioural and logistical characteristics of customers served as the basis for developing recommendations on the prioritisation of strategies for implementing smart technologies in marketing logistics tailored to each identified cluster. The highest priority for smart technology implementation in marketing logistics was assigned to strategies aimed at retaining and incentivising loyal customers through the Internet of Things, big data, information systems, automation, and robotics. The next priority involves the application of machine learning, cognitive technologies, virtual and augmented reality, and digital twins to enhance transparency, trust, and engagement among profitable customers. Blockchain technology was deemed the lowest priority for low-potential customers, as its impact on loyalty and the financial attractiveness of the enterprise is limited. The proposed methodological approach for prioritising strategies offers significant practical value in contexts characterised by constrained financial resources and the high costs associated with implementing smart technologies

Keywords: digital business transformation; data analytics in marketing; Industry 4.0; Logistics 4.0; Marketing 4.0; key performance indicators

INTRODUCTION

In the context of large-scale intellectualisation of logistics and marketing as key areas of activity of any enterprise, the development of scientific approaches to managing the processes of implementing smart technologies in the

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marketing logistics of enterprises is of particular importance, the expected results of which are an increase in the level of personalisation of supply chains, improvement of logistics and marketing services, ensuring customer loyalty and overall business competitiveness. The use of smart technologies in marketing logistics allows enterprises to obtain a multiplicative effect from the optimisation of both marketing and logistics functions simultaneously. This is due to the fact that any smart technology has a multifaceted impact on all areas of enterprise activity, with marketing and logistics being the most sensitive to intellectualisation processes.

Analysing the prospects for the use of smart technologies, scientists highlighted the importance of certain innovations of Industry 4.0 in the transformation of modern marketing. A.T. Rosário & J.C. Dias (2022) emphasised that the greatest impact on marketing was made by technologies in the field of information processing, namely the Internet of Things (IoT), big data analytics, cloud computing, customer profiling and artificial intelligence (AI). The authors attributed the priority of these technologies to their great potential for collecting, analysing, interpreting and using customer data regarding their activity in the offline and online environment. Summarising the impact of Industry 4.0 on marketing, researchers noted the intellectualisation of marketing, the renewal of its basic principles (collaboration, conversation, co-creation, cognition, and connection).

A.T. Rosário & J.C. Dias (2022) emphasised that IoT technology plays a crucial role in collecting strategically important information about target markets. Cloud computing, in turn, significantly contributes to the development of the critical information infrastructure necessary for effective marketing, as it enables digital marketing professionals to remotely access data in various file formats, including real-time consumer feedback on products, services, and brands. Furthermore, big data has a critical role in gathering, aggregating, and commercialising personal and customer information, providing marketers with a comprehensive view of consumer behaviour patterns. This, in turn, allows them to create and implement customer-centric advertising content and marketing strategies that precisely respond to consumers' current needs and preferences. AI has had a revolutionary impact on marketing by enhancing the prediction of consumer behaviour, facilitating the generation of new ideas, and supporting decision-making processes regarding marketing initiatives and their progress.

As noted by M. Vijayakumar *et al*. (2025), the synergy of Industry 4.0 and Marketing 4.0 technologies is manifested in establishing a continuous connection, when smart data helps companies automatically sort customers, send relevant deals and predict their behaviour, improving the marketing effectiveness of the business. The authors recommended assessing improvements in marketing effectiveness by analysing the impact of smart technologies on key performance indicators (KPIs). They noted that return on investment (ROI) and customer lifetime value demonstrate efficiency gains in personalised marketing campaigns achieved through the use of AI and predictive analytics. Customer retention and churn indicators reveal increased effectiveness of push notifications resulting from the integration of customer relationship management (CRM) systems with the IoT. Moreover, the additional sales ratio and customer loyalty metrics, such as the Net Promoter Score, improve due to the synchronisation of enterprise resource planning (ERP) systems with machine learning, which strengthens customer loyalty. Conversion rates and customer return levels rise as a result of employing augmented and virtual reality (AR and VR) technologies for product testing, as well as digital twin technologies and cloud computing in the product creation process.

The unprecedented impact of Industry 4.0 technologies on logistics has also been studied by many scientists, including S. El Hamdi & A. Abouabdellah (2022). The summary of the scientific results of 47 publications allowed the authors to conclude that Industry 4.0 technologies support the logistics paradigm in two areas: physical operations and resource management, highlighting the importance of AI and big data analytics to support decision-making in logistics; the IoT for smart sensors to ensure the interconnection of logistics objects and their identification; IT systems and cloud computing to optimise information flows. S. El Hamdi & A. Abouabdellah (2022) consider the following as the main components of Logistics 4.0: big data, blockchain technology, radio-frequency identification, GPS, IoT, sensors (cameras and humidity/temperature sensors), 3D printing, AR and smart products, as well as investments, innovation management and value chain integration, automation of material flow in warehouse and transport, ERP, warehouse management system, smart transport systems (drones, robots and autonomous vehicles).

Therefore, the introduction of Industry 4.0 technologies into marketing and logistics activities has led to the intellectualisation of these concepts to the level of Logistics 4.0 and Marketing 4.0. At the same time, as E. Sós (2021) noted, the concepts of logistics and marketing are considered separately in most studies, despite the growing recognition that the implementation of a marketing logistics strategy is necessary to achieve customer satisfaction. The purpose of the article was to substantiate the importance and study the features of Marketing Logistics 4.0 and develop methodological approaches to determining effective strategies for implementing this concept in the activities of enterprises.

MATERIALS AND METHODS

The study was conducted in three stages. The first stage was devoted to substantiating the importance of implementing the concept of marketing logistics by modern enterprises. The second stage included a comparative analysis of the impact of smart technologies on logistics and marketing, identifying the synergistic effect of the impact of these technologies on marketing logistics, identifying the features and KPIs of Marketing Logistics 4.0. The third stage involved the development of a methodological approach to determining a strategy for implementing smart technologies in the marketing logistics of enterprises. This stage of the study included the empirical part, which contains the clustering of the sample, which is represented by 100 customers of the warehouse-store (Kyiv, Ukraine). The source of information was the data of the warehouse-store CRM system.

The main criteria for forming the sample were defined as follows. The target population consisted of warehouse-store customers who had placed at least one order during the 12 months of 2024, with the research limited to the Kyiv, including all its administrative districts. The inclusion criteria required that each customer record contain complete contact and logistics information (such as an address or district), as well as basic data on the number of orders placed during 2024, the total order volume or value, and a satisfaction assessment obtained through a survey. Additionally, only customers who were legally or physically active – meaning they had placed orders within the last 12 months of 2024 – were included.

Certain exclusions were also applied: duplicate entries of the same customer were removed, with the most recent or most complete record retained; "mosaic" records with more than 30% of key fields missing were excluded; and customer records showing abnormally small or large values, clearly caused by data errors (for instance, a zero amount despite recorded orders), were omitted. For the selection method, if the total customer list exceeded 100 entries, a stratified random sampling approach was used – either by city district to preserve spatial representativeness or by previous purchase frequency (high, medium, or low) – with proportional selection within each stratum. If the list contained exactly 100 customers, all were included in the sample. In cases where the list had fewer than 100 customers, all available records were used, and any sampling limitations were explicitly stated. The cluster analysis method was chosen to group customers. The clustering procedure was carried out using the k-means method and Nearest Neighbour Analysis, both performed with the IBM SPSS Statistics software package.

RESULTS

Based on modern definitions, marketing logistics is an approach to corporate management and a field of activity implemented on its basis, which permeates all corporate activities, integrates the results of both disciplines, and involves mutual knowledge of managers in related industries and is aimed at a synergistic effect (Barbosa-Povoa & Pinto, 2020; Sós, 2021). The importance of developing the modern concept of marketing logistics is due to its significant synergistic potential in the field of satisfying consumer needs, because marketing forms and manages demand, and logistics satisfies this demand in the most effective way. The transformation of the classic marketing 4 Ps into the modern 7 Ps (product, price, promotion, place, people, process, physical evidence) has increased the impact of marketing on logistics: the introduction of new products increases logistics costs; price changes affect the entire logistics system due to changes in demand; the promotion of goods and services leads to additional logistics costs and the expansion of logistics services due to increased turnover; the increase in distribution channels affects delivery times and logistics costs; personnel affects all logistics processes of the company; customer marketing service processes affect the technologies used, flexibility, order fulfilment times, inventories, etc.; the environment in which the product/service operates can determine the quality assessment (Sós, 2021).

Modern logistics and the concept of supply chain management affect all aspects of marketing, because the implementation of marketing decisions, both strategic and tactical/operational, takes place in supply chains. Considering the 7 Rs of logistics ("right" product, customer, time, place, cost, quantity and quality), each "R" has a special meaning precisely in that part of the supply chain where finished products go to the consumer, that is, in the marketing and logistics sales channels, the management of which is in the direct competence of marketing logistics. Compliance with all 7 Rs of logistics is a prerequisite for consumer satisfaction and fulfilment of the "ideal" order. The logistics strategy of any company is subordinate to the marketing strategy and contributes to its implementation in the most effective way.

Therefore, the mutual influence, close integration and interaction of two concepts, two strategies – marketing and logistics – ensure synergy in sales channels through the implementation of the most effective marketing logistics strategy. In the era of Industry 4.0, the integration of the two concepts of Marketing 4.0 and Logistics 4.0 leads to the transition of Marketing Logistics to the 4.0 level. The features of Marketing Logistics 4.0, due to the integration of technologies and concepts of Industry 4.0 into the management of the physical movement of goods, are aimed at increasing the efficiency, transparency and responsiveness of the supply chain and improving the overall effectiveness of marketing. The generalisation of literary sources allowed to identify the key features/indicators of Marketing Logistics 4.0 as a result of the implementation of Industry 4.0 technologies in logistics and marketing processes (Table 1).

Table 1. Key features and corresponding KPIs of Marketing Logistics 4.0 in terms of implementing Industry 4.0 technologies in marketing and logistics processes

Industry 4.0 technology/ concept	Logistics 4.0 integration result	Marketing 4.0 integration result	Key features of Marketing Logistics 4.0	KPIs Marketing Logistics 4.0
IoT	Ensuring the interconnection of logistics facilities and their identification (El Hamdi & Abouabdellah, 2022)	Gathering strategically important information regarding target markets (Rosário & Dias, 2022)	Improved visibility, transparency and predictability in sales channels	Customer retention, customer churn metrics (Vijayakumar *et al.*, 2025). Order execution time. Time to recovery. Order cycle time. Capacity utilisation. Risk assessment frequency. Supply and demand variation. Number of nodes in SC. Service level. On-time delivery. Equipment efficiency. Inventory movement speed. Inventory level. Forecast accuracy (Marinagi *et al.*, 2023)
Big data	Increased organisational efficiency; environmental, economic and social sustainability, supply chains (Lee & Mangalaraj, 2022)	Collection, aggregation, commercialisation of personal data and customer information (Rosário & Dias, 2022)	Data-driven decision-making, sustainable development of sales channels	ROI. Long-term customer value (Vijayakumar *et al.*, 2025). Order fulfilment time. Time to recovery. Capacity utilisation. Risk assessment frequency. Supply and demand variation. Number of nodes in the distribution channel. Proximity to suppliers and customers. Service level. On-time delivery. Equipment efficiency. Inventory turnover rate. Inventory level. Forecasting accuracy (Marinagi *et al.*, 2023)

Table 1. Continued

Industry 4.0 technology/ concept	Logistics 4.0 integration result	Marketing 4.0 integration result	Key features of Marketing Logistics 4.0	KPIs Marketing Logistics 4.0
AI	Rapid logistics decision-making, forecasting supply chain trends and logistical challenges. Reducing risks and increasing operational efficiency (Samuels & Motatsa, 2025)	Predicting consumer behaviour; generating new ideas, making decisions about marketing initiatives and progress (Rosário & Dias, 2022)	Increased flexibility, responsiveness and efficiency of sales channels	ROI. Long-term customer value (Vijayakumar *et al.*, 2025). Order fulfilment time. Time to recovery. Capacity utilisation. Risk assessment frequency. Supply and demand variation. Number of nodes in the distribution channel. Proximity to suppliers and customers. Service level. On-time delivery. Equipment efficiency. Inventory turnover rate. Inventory level. Forecasting accuracy (Marinagi *et al.*, 2023)
Machine learning and cognitive technologies	Accurate forecasting, automated decision-making, reduced operating costs, improved service quality and supply chain sustainability (Gafiatullin & Mukhanova, 2025)	Increasing customer loyalty (Vijayakumar *et al.*, 2025)	Personalised marketing logistics and on-demand marketing logistics	Cross-selling ratio. Customer loyalty system indicators (Vijayakumar *et al.*, 2025). Order fulfilment time. Time to recovery. Order cycle time. Capacity utilisation. Risk assessment frequency. Supply and demand variation. Number of nodes in the sales channel. Service level. On-time delivery. Equipment efficiency. Inventory turnover rate. Inventory level. Forecast accuracy (Marinagi *et al.*, 2023)
Automation and robotics	Transformation of warehouse and transportation processes, increased speed, accuracy and efficiency (El Hamdi & Abouabdellah, 2022)	Marketing automation can make the planning and management process easier, marketing programmes (Byba, 2023)	Improved customer experience, faster and more reliable delivery	ROI. Long-term customer value. Cross-selling ratio. Customer loyalty system indicators (Vijayakumar *et al.*, 2025). Order execution time. Time to recovery. Order cycle time. Capacity utilisation. Number of nodes in the sales channel. Service ratio. On-time delivery. Equipment efficiency. Inventory turnover rate. Inventory level. Forecasting accuracy (Marinagi *et al.*, 2023)
Supplemented/ VR, digital twin technologies	Monitoring, evaluation, forecasting, optimisation, control, system management, system integration and adaptation (Liu *et al.*, 2024). Increasing safety and reducing risks, increasing efficiency (Sariisik, 2025)	Product marketing testing	Improved customer experience, faster and more reliable delivery	Conversion rates, customer returns. Marketing budget optimisation metrics (Vijayakumar *et al.*, 2025). Order fulfilment time. Time to recovery. Capacity utilisation. Risk assessment frequency. Supply and demand variation. Number of nodes in the sales channel. Service level. On-time delivery. Equipment efficiency. Inventory turnover rate. Inventory level. Forecast accuracy (Marinagi *et al.*, 2023)
IT systems and cloud computing	Optimisation of information flows (El Hamdi & Abouabdellah, 2022)	Customer data management, real-time collaboration, reduced hardware and software costs, scalability and strategy correction, flexibility and adaptability (Besim & Sharma, 2023).	Decentralised decision-making to reduce overall costs in sales channels	Conversion rates, customer returns. Marketing budget optimisation metrics (Vijayakumar *et al.*, 2025). Order fulfilment time. Time to recovery. Capacity utilisation. Service cycle time. Supply and demand variation. Service level. On-time delivery. Equipment efficiency. Inventory movement speed. Inventory level. Forecast accuracy (Marinagi *et al.*, 2023)
Blockchain	Increased trust and transparency, improved monitoring and compliance (Kumar *et al.*, 2025)	Eliminating intermediaries, increasing transparency, privacy and security of consumers, customer loyalty programmes, social media channels, progressive, customer interaction skills. Customer influence in advertising and marketing (Adıgüzel, 2021)	Increased transparency, security and efficiency: improved product traceability, optimised supply chains and automated processes. Reduced fraud, increased resilience and customer-centricity of sales channels	ROI. Long-term customer value. Coefficient of additional sales. Customer Loyalty System Indicators (Vijayakumar *et al.*, 2025). Order execution time. Time to recovery. Order cycle time. Capacity utilisation. Frequency of risk assessment. Supply and demand variation. Number of nodes in the distribution channel. Service level. On-time delivery. Inventory level. Forecasting accuracy (Marinagi *et al.*, 2023)

Source: developed by the authors

The introduction of smart technologies into the marketing logistics of enterprises significantly affects its effectiveness, with each technology having a specific impact on certain KPIs (Table 1). When considering the prospects for implementing any Industry 4.0 technology, enterprises should consider the ROI in this technology. Therefore, the process of selecting the most promising smart technologies for business requires a well-founded approach, consistent with the marketing logistics strategy. Special attention deserves the preliminary use of mathematical modelling, in particular, cluster analysis, for the purpose of a well-founded implementation of certain smart technologies and the corresponding definition of marketing logistics strategies for certain groups of consumers/clients.In view of the above, a sample consisting of 100 customers of a warehouse-store (Kyiv, Ukraine) with certain behavioural and logistical characteristics (order volume, frequency of purchases, location, level of satisfaction) was formed for cluster analysis (Table 2). Grouping customers by similar characteristics will allow determining the most effective strategies for implementing smart technologies in marketing logistics that serve each of the formed groups.

Table 2. Data on customers of the warehouse-store for 2024

Customer	Purchase frequency	Average order amount ($)	Distance to warehouse (km)	Satisfaction level (1-5)
C001	89	8.22	3	4
C002	52	14.4	14	4
C003	64	18.56	24	5
C004	51	14.36	25	4
C005	56	13.11	11	5
C013	92	10.48	10	5
C014	53	17.73	27	5
…	…	…	…	…
C 100	67	16.84	4	5

Source: developed by the authors

The clustering procedure (k-means) was carried out using IBM software SPSS Statistics. After normalising the data and selecting the number of clusters, the k-means algorithm divided customers into three groups (Fig. 1). Cluster 1: customers with high purchase frequency, small amounts and high satisfaction level (regular buyers, loyal). Cluster 2: customers who are located a long distance from the warehouse have a low level of satisfaction (inactive or dissatisfied customers). Cluster 3: customers with average purchase frequency, large order amounts, and average satisfaction level (infrequent but large orders).

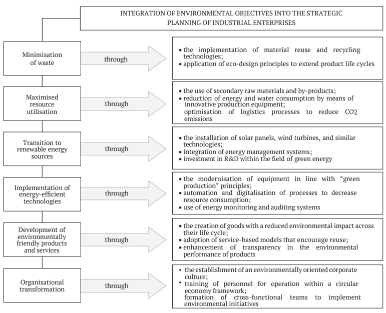

Figure 1. Characteristics of three clusters of warehouse-store customers using the k-means algorithm
Source: developed by the authors

It should be noted that the largest number of clients was in Cluster 1, the smallest in Cluster 2, and the average number in Cluster 3 (Fig. 2).

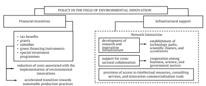

Figure 2. Number of warehouse-store customers in each cluster (obtained from IBM SPSS Statistics
Source: developed by the authors

Conducting cluster analysis using the Nearest Neighbour Analysis provided the opportunity to visualise the results of customer clustering. Graphical representation of cluster analysis using the Nearest Neighbour Analysis in Figure 3 shows several groupings (clusters).

A

B

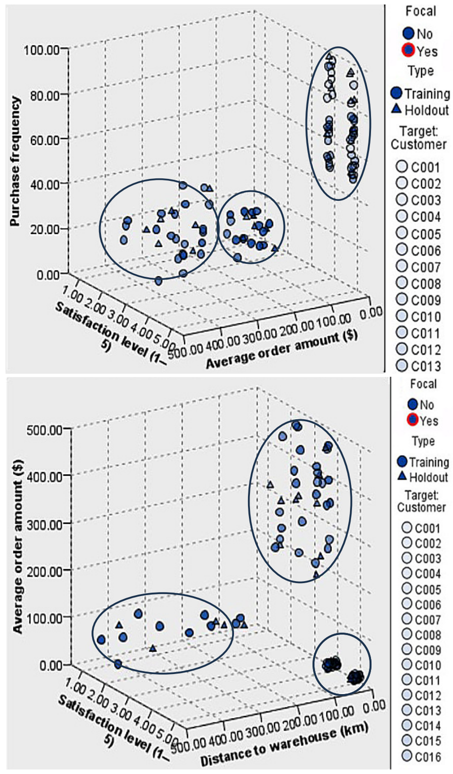

Figure 3. 3D scatter plot of warehouse-store customers
Note: the coordinate axes correspond to the clustering factors (*X* axis – satisfaction level; *Y* axis – purchase frequency in image A and average order size in image B; *Z* axis – average order size in image A and distance to the warehouse in image B); the points correspond to customers (blue circles – Training (training sample); blue triangles – Holdout (control sample); red points – Focal (focal customers)); the distinction between Training and Holdout shows that the data is used both to train the clustering model and to test its stability
Source: developed by the authors

Cluster 1. With a high level of satisfaction ($X = 4 - 5$) and small average orders (up to $50), a group of customers with a high frequency of purchases is visible (image A). Near the X axis (image B) = high level of satisfaction (4-5) and close proximity to the cluster of customers with a low average order (≈ up to $50). This is a typical profile of loyal regular customers. Cluster 2. At a low level of satisfaction ($X = 1 - 2$) and with small average orders (up to $100), with a long distance to the warehouse (⩾300 km), a group of customers with a low frequency of purchases is concentrated – low-prospect or "risky" customers. Cluster 3. At medium satisfaction values ($X = 2 - 3$) and short distances to the warehouse (⩽50 km), there are customers with medium or large order volumes (>$300-500) – perhaps these are strategic customers. The allocation of focal customers in each cluster made it possible to identify the most representative groups, and the division of data into Training and Holdout confirmed the stability and consistency of the model. Thus, the analysis results provide the basis for customer segmentation and the development of personalised logistics service strategies based on the implementation of smart technologies and aimed at increasing the company's loyalty and profitability. The conducted customer clustering allows to more accurately determine the needs of different customer segments and offer more effective strategies for implementing the recommended smart technologies of Marketing Logistics 4.0 (Table 3).

Table 3. Recommended smart technologies of Marketing Logistics 4.0 for warehouse-store customer clusters

Customer cluster	Smart technologies of Marketing Logistics 4.0							
	IoT	Big data	AI	Machine learning and cognitive technologies	Automation and robotics	Supplemented/ VR, digital twin technologies	IT systems and cloud computing	Blockchain
Cluster 1	+	+			+		+	
Cluster 2	+	+					+	+
Cluster 3	+	+	+	+		+	+	

Source: developed by the authors

The implementation of the following technologies for all three clusters is considered relevant: IoT, big data, IT systems, and cloud computing. These technologies are universal for marketing logistics and enhance visibility, transparency, and predictability within sales channels; enable data-driven decision-making; and support the decentralised adoption of optimal solutions under conditions of cost reduction across sales channels. For all clusters, under conditions of unstable demand and changing sales markets, the integration of clustering with a smart supply chain management system (including IoT sensors in warehouses, CRM systems, and analytical modules) is deemed advisable to ensure real-time adaptation of marketing logistics to each customer group. Regarding specific smart technologies, the following is proposed.

Cluster 1. Focus on retaining and encouraging loyal customers. Recommended smart technology is automation and robotics (pick-by-robot, conveyors, automated shelving). The use of this technology in a warehouse-store can significantly improve the quality of service for loyal regular customers. Due to faster order fulfilment, reduced errors, and stable deliveries, such customers receive a sense of reliability and care, which strengthens their commitment to the company. In addition, automated systems allow to personalise offers and more effectively take into account individual preferences. At the same time, it is important to maintain a balance between technological solutions and the "human factor" in order to maintain an emotional connection with customers, which is the basis of their long-term loyalty.

Cluster 2. It is necessary to improve the service for these customers or try to reduce the distance to the warehouse (for example, by opening new collection points or warehouses). Customer service can also be improved through the implementation of blockchain technology. The use of blockchain technologies in working with a warehouse-store can partially affect "risky" customers, who are characterised by low satisfaction levels, small orders and significant remoteness. Due to the transparency of supply chains, the ability to track each stage of delivery and the use of smart contracts, blockchain increases customer trust and reduces the risk of fraud. This is especially true for remote buyers who may doubt the reliability of the service.

Cluster 3. Since these are "profitable" customers, it is worth considering strategies to increase their purchase frequency, perhaps through personalised offers or advertising. Recommended smart technologies are AI; machine learning and cognitive technologies; AR and VR, as well as digital twin technologies. Using AI in warehouse-store operations can significantly increase the value of customers in this cluster. AI allows to personalise offers and recommendations, forecast demand and optimise inventory, as well as automate service through chatbots and virtual assistants, which ensures a quick response to customer requests. In addition, AI-based analytics helps identify high-potential customers and direct marketing and logistics resources to them. Together, these capabilities contribute to increasing loyalty, increasing order volumes and forming a strategically important customer segment for the enterprise;

The use of machine learning and cognitive technologies can provide personalisation of offers, forecasting needs and using intelligent support services, so customers receive a higher level of service (for example, related products, special discounts, chatbots, virtual assistants), which has a positive effect on their loyalty. Machine learning-based analytics allows to timely identify customers with high future potential (for example, those who gradually increase their orders) and focus marketing efforts on them. These technologies can turn this cluster into a more promising and strategically important one for the company. AR/VR solutions enable customers to interactively explore the range, virtually test products or processes, which improves their experience and engagement. Digital twin technologies, in turn, allow for the modelling of orders and logistics processes, providing transparency, predictability and reducing the risk of supply disruptions. Taken together, this strengthens the sense of partnership between the customer and the company and contributes to the transformation of this cluster into a strategically important one.

Therefore, generalising the prospects for implementing smart technologies in marketing logistics gives grounds to argue for the need for a certain prioritisation of strategies to determine the most important areas of action and tasks that ensure the achievement of the long-term goals of a trade organisation by ranking them by importance, timeliness, and expected effect. According to research results, the most promising strategy in the near future is the strategy for further retaining and encouraging loyal customers, based on the use of the following smart technologies: IoT; big data; IT systems and cloud computing; automation and robotics.

The next priority is the strategy of implementing machine learning, cognitive technologies, AR and VR, digital twin technologies to increase customer loyalty, transparency of information for customers (regarding the state of stocks, the process of picking and delivery), which strengthens trust in the supplier and reduces risks, creates a sense of involvement for customers. At the same time, these technologies require significant investments, which is not always justified if the cluster does not demonstrate the expected growth. The last priority is the strategy of using blockchain technology in working with the warehouse-store. This strategy received the lowest priority due to its limited effectiveness in the group of customers with low frequency and small order volumes; therefore, the implementation of this technology will not provide a significant increase in loyalty or financial attractiveness of this cluster of customers.

DISCUSSION

Marketing logistics is an integrated management approach that unites marketing and logistics to achieve synergy in fulfilling consumer needs. Within the framework of Industry 4.0, the concept evolves into Marketing Logistics 4.0, characterised by the adoption of smart technologies such as IoT, big data, AI, automation, and robotics to enhance efficiency, transparency, flexibility, and customer-centricity, driving sustainable business development and competitiveness. According to Y. Tiazhkun (2024), the modern integration of marketing and logistics is a key factor in forming a customer-oriented business model. The study highlights that the introduction of innovative technologies – in particular automation, blockchain, IoT, and green logistics – contributes to improving the efficiency of distribution channels, reducing logistics costs, and strengthening customer trust. Such a combination of marketing and logistics processes creates the foundation for the Marketing Logistics 4.0 concept. According to V. Parsyak & O. Zhukova (2022), modern marketing logistics is formed as an integrated system that combines marketing tools with digital technologies for managing material and information flows. The author emphasised that it is precisely the combination of big data analytics, cloud services, and automated management systems that forms the foundation of the "intelligent marketing logistics" concept, which enhances the competitiveness of enterprises in the digital marketplace. S.O. Kliuiev & B.V. Yurov (2021) investigated the transformation of transport logistics in Ukraine under Industry 4.0 conditions and emphasised that the implementation of IoT, 3D printing, and autonomous transport technologies is already reshaping logistics chains and product movement schemes. Their study highlighted that the integration of digital and cyber-physical technologies contributes to the creation of intelligent logistics systems capable of improving flexibility, transparency, and sustainability in supply chain management.

The obtained results of clustering of customers of a warehouse-store confirmed the feasibility of using behavioural and logistical characteristics for customer segmentation in order to personalise marketing logistics. As a result of the analysis using the k-means method, three clusters of customers were formed, differing in the frequency of purchases, order volume, location and level of satisfaction. This approach allowed developing targeted strategies for implementing smart technologies that increase the efficiency of logistics services and the level of customer loyalty. The study continues and expands upon previous research on the implementation of smart technologies in marketing and logistics processes conducted by various authors. Thus, the research of I. Lee & G. Mangalaraj (2022), which is devoted to the role of big data analytics in improving the efficiency of decisions and personalising supply chains, was expanded supplementing them with a marketing aspect and specifying the corresponding KPIs. A. Samuels & K. Motatsa (2025) in their work focused on AI in the context of environmental impact and sustainability of logistics systems, while the present study revealed the potential of AI to achieve customer personalisation and synergy of marketing logistics.

The results of the research of Y. Liu *et al*. (2024) and F. Gafiatullin & G. Mukhanova (2025), on the use of machine learning, cognitive technologies and digital twins in logistics were supplemented with applied solutions on customer clustering, improving customer experience and choosing Smart technology strategies. The works of V. Byba (2023), devoted to the impact of automation on marketing decision-making, and G. Sariisik (2025), focused on the use of VR/AR as smart technologies to enhance customer interaction, were supplemented with a logistical perspective, taking into account the synergistic effect achieved through the integration of marketing and logistics. The studies by R. Besim & B. Sharma (2023) on cloud technologies as a driver of digital business transformation, as well as S. Adıgüzel (2021) and N. Kumar *et al*. (2025) on the impact of blockchain in marketing and logistics, served as the basis for substantiating the role of these technologies in decentralised decision-making within sales channels and marketing logistics. In the article by C. Marinagi *et al*. (2023), the impact of Industry 4.0 on KPIs was assessed at the macro level, namely for supply chains. This research was extended by examining the impact at the micro level of the enterprise, with particular emphasis on Marketing Logistics 4.0.

The cluster analysis method is an effective and most frequently used method in similar scientific studies in recent years, such as P.S. Durga *et al*. (2023), M.A. Rani *et al*. (2024) and A.D. Rana *et al*. (2025). Regarding customer clustering, similar results were observed in the study by A.D. Rana *et al*. (2025), who also applied cluster analysis (RFM – T model clustering) for segmenting customers of trading companies. The authors proved that the use of a multifactor model (frequency of purchases, monetary amount, time of the last purchase and type of customer) provides a deeper interpretation of consumer behavioural patterns. The results obtained by them are consistent with conclusions about the effectiveness of clustering for the formation of personalised service strategies. At the same time, in the current study, a spatial component was added to the model – the location of customers, which allows to combine marketing and logistics aspects. Thus, the proposed segmentation model is more comprehensive and aligns more effectively with the objectives of Marketing Logistics 4.0.

P.S. Durga *et al*. (2023) confirmed the effectiveness of the cluster approach for increasing sales and improving customer service. They used the k-means method to group consumers by frequency and number of purchases, and used the results to optimise marketing campaigns. Compared to their findings, this study is different in that it focuses not only on increasing sales, but also on improving the efficiency of logistics processes, which integrates the principles of Marketing 4.0 and Logistics 4.0. In addition, in the current work, segmentation is used as a tool for prioritising the implementation of smart technologies, which allows taking into account the investment constraints of the enterprise. In turn, M.A. Rani *et al*. (2024) focused on the technical aspects of using the k-means algorithm for segmenting retail customers. They confirmed that this method provides reliable grouping of consumers according to their behavioural indicators and can be used to create more effective marketing strategies. This study develops the authors' approach, supplementing it with a logistical component – including the distance indicator to the warehouse and the level of customer satisfaction. This allows to apply the results of clustering not only for marketing, but also for operational decisions in the field of logistics, for example, optimising delivery routes, warehouse placement and improving service.

A comparative analysis of the above studies shows that they all confirm the universality of the clustering method for customer segmentation in different industries. A common feature is the emphasis on enhancing the customer experience, while the proposed approach is interdisciplinary, integrating both marketing and logistics variables. The difference also lies in the practical purpose: in the presented study, clustering is used to determine strategic priorities for the implementation of smart technologies in marketing logistics. This allows not only to understand customer behaviour, but also to reasonably invest in those technologies that most increase the efficiency of a particular segment. Thus, the study deepens the scientific discourse on the integration of smart technologies into marketing logistics, expanding the application of cluster analysis in the direction of intellectualisation of supply chain management. The results obtained are consistent with the conclusions of previous studies, but at the same time offer a practically oriented model that can be used by enterprises to develop personalised strategies for the digital transformation of marketing logistics.

CONCLUSIONS

The article substantiates the importance and features of Marketing Logistics 4.0 and develops methodological approaches to implementing this concept in the activities of enterprises. The study, conducted in three stages, confirmed the need to develop modern marketing logistics strategies, showed the synergistic effect of integrating smart technologies into marketing and logistics, and also allowed to clarify the key indicators of the effectiveness of Marketing Logistics 4.0. Based on the cluster analysis of warehouse-store customers, a methodological approach to the priority implementation of smart technologies was developed, which allows to increase customer loyalty, process transparency and the efficiency of enterprises.

The priority strategy for implementing smart technologies in marketing logistics is to retain and encourage loyal customers through IoT, big data, IT systems, automation and robotics. The next priority strategy according to the study is the use of machine learning, cognitive technologies, AR/VR and digital twins to increase transparency, trust and customer engagement, although they require greater investment. The strategy of using blockchain for low-potential customers received the lowest priority, since its effect on loyalty and financial attractiveness is limited. The results obtained can serve as the basis for the practical application of Marketing Logistics 4.0 and strategic planning of enterprise development in the digital era, as they provide the opportunity to: personalise service for different client segments; optimise investments in smart technologies taking into account the potential of each cluster; increase the level of customer loyalty, speed of order processing and transparency of supply processes. Further research expedient to direct on development integrated models digital marketing logistics, which will include elements AI for prognostication behaviour customers, analysis big data in mode real time and automatic adjustment logistic strategies depending from changes market conditions.

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Впровадження smart-технологій у маркетингову логістику: персоналізація ланцюга постачання та покращення клієнтського досвіду

Анотація. Впровадження інтелектуальних технологій Індустрії 4.0 має особливо важливе значення для підвищення ефективності маркетингової логістики завдяки мультиплікативному характеру їхнього впливу та синергетичним ефектам, що виникають внаслідок конвергенції Логістики 4.0 та Маркету 4.0. Це підкреслює необхідність ретельного наукового дослідження важливості та відмінних рис Маркетингової Логістики 4.0, а також розробки методологічних підходів для визначення ефективних стратегій інтеграції цієї концепції в діяльність підприємства, що було основною метою цього дослідження. Кластерний аналіз був використаний для сегментації вибірки зі 100 клієнтів складу-магазину в Києві (Україна) на три кластери, що характеризуються подібними поведінковими та логістичними характеристиками, включаючи обсяг замовлень, частоту покупок, місцезнаходження та рівень задоволеності. Врахування як поведінкових, так і логістичних характеристик клієнтів послужило основою для розробки рекомендацій щодо пріоритетності стратегій впровадження інтелектуальних технологій у маркетинговій логістиці, адаптованих до кожного визначеного кластера. Найвищий пріоритет у впровадженні розумних технологій у маркетингову логістику було надано стратегіям, спрямованим на утримання та стимулювання лояльних клієнтів через Інтернет речей, великі дані, інформаційні системи, автоматизацію та робототехніку. Наступний пріоритет включає застосування машинного навчання, когнітивних технологій, віртуальної та доповненої реальності, а також цифрових двійників для підвищення прозорості, довіри та залученості серед прибуткових клієнтів. Технологія блокчейн була визнана найнижчим пріоритетом для клієнтів із низьким потенціалом, оскільки її вплив на лояльність та фінансову привабливість підприємства обмежений. Запропонований методичний підхід до визначення пріоритетних стратегій має значну практичну цінність в контексті обмежених фінансових ресурсів підприємств та високих витрат, пов'язаних з впровадженням розумних технологій

Ключові слова: цифрова трансформація бізнесу; аналітика даних у маркетингу; Індустрія 4.0; Логістика 4.0; Маркетинг 4.0; ключові індикатори ефективності

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Meta-analysis of postwar recovery financing in Ukraine: Key public documents overview

Abstract. The aim of this paper was to conduct a meta-analysis of institutional assessments (2022-early 2025) to identify sectoral needs, funding gaps, and institutional obstacles that influence recovery timelines. A structured review and meta-analysis of more than 20 reports and sector studies were applied, along with comparative scenario design (Baseline, Accelerated, Delayed) and the creation of a diagnostic screening tool for the investment environment. Research found that total needs exceed USD 524 billion, mainly in energy, housing, transport, industrial assets, and agriculture; rising estimates reflect both additional damage and the adoption of EU technical, decarbonisation, and digital standards. It was noted that grants and concessional loans are necessary but not enough: key constraints include bankable project preparation, procurement quality, concession structure (risk sharing, step-in, foreign exchange risk), and donor coordination. Three scenario options were developed based on data: a Baseline path (15+ years) with limited private

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involvement; an Accelerated path (8-10 years) relying on standardised preparation, scalable guarantees, political-risk insurance, local-currency funding, and a strong coordination platform; and a Delayed path with longer timelines and growing regional disparities. An operational framework is proposed, comprising a network of Reconstruction Project Preparation Facilities, model concessional agreements aligned with EU standards, a blended-finance approach (including guarantees, local-currency facilities, and social bonds labeled), and a national reconstruction dashboard that links budgeting, procurement, and monitoring. It is shown that transparency does not equal absorption: digital procurement platforms increase contestability but do not ensure executable capital expenditure without engineering support, standardised documentation, and independent goal verification. The findings offer practical guidance for governments and municipalities to prioritise sectors, standardise project preparation, and deploy blended-finance tools that shorten recovery time and boost investment multipliers

Keywords: reconstruction financing; blended finance; donor coordination platforms; public investment; reconstruction framework; macrofinance

INTRODUCTION

The 2022 escalation of Russia's war against Ukraine caused one of the most severe humanitarian and economic shocks in Europe since the mid-20th century. The destruction of transportation, energy, housing, and productive capital turned recovery financing into a challenge of government capacity, donor coordination, and private risk tolerance. Overall needs increased alongside cumulative damage and growing reconstruction goals – rising from about USD 349 billion in 2022 to roughly USD 524 billion by early 2025 (World Bank, 2025). At the same time, policy goals shifted from emergency replacement to resilience, "build back better", decarbonisation, and alignment with EU rules and standards (European Commission, 2023). The shock spread across borders through trade, relative prices, and expectations: multi-regional models show significant spillovers across European regions (Almazán-Gómez *et al.*, 2023), input-output analysis reveals diverse territorial disruptions within Ukraine (Haddad *et al.*, 2023), and research on the global food system highlights environmental and supply chain impacts radiating from the region (Zhang *et al.*, 2024).

Research on external finance and markets highlights both the importance and limitations of capital inflows when institutional quality is lacking. Postwar reconstruction studies, such as R.J. Moore (2021) and O. Pustovoit (2022) identified external aid and foreign direct investment as key triggers, showing that their growth effects depend on stable political and legal environments and credible property rights enforcement. Evidence from markets after 2022 further emphasises the need for risk-sharing frameworks. European equity markets show asymmetric sensitivity to conflict shocks (Aliu *et al.*, 2023; Kumari *et al.*, 2023). Hospitality-related equities have been more heavily impacted (Balli *et al.*, 2022). Conflict sentiment influences FinTech, blockchain, and cryptocurrency assets in complex, state-dependent ways (Abakah *et al.*, 2023; 2024; Hamouda *et al.*, 2024).

W. Abbassi *et al.* (2023) noted that, at the firm level, vulnerability varies: balance-sheet weaknesses (such as leverage, liquidity reserves, and supply-chain concentration) increase exposure to war shocks, strengthening the need for targeted guarantees and liquidity backstops in recovery plans. Expectations have also shifted: survey data show war-related changes in inflation expectations that make monetary policy transmission more complicated (Afunts *et al.*, 2023), while comparative analysis reveals different policy responses across euro and non-euro countries (Aliu *et al.*, 2025). Overall, these findings suggest that guarantees, insurance, and blended-finance arrangements are essential, not optional, parts of a cost-of-capital reduction strategy for Ukrainian projects.

Governance, coalitions, and resource politics show that markets are shaped by political processes. EU-Ukraine integration advances not only through legal approximation but also through coalition building around access to and governance of natural resources, thus "making markets" in a literal sense, as noted by A. Buzogány & M. Varga (2025). The success of recovery tools – guarantee schemes, procurement frameworks, local-content rules, and concession models – depends on how well they align with coalition incentives, ensuring that reforms and capital mobilisation support each other. In this context, the present study does not aim to produce a new "headline" estimate of reconstruction needs. Instead, it conducts a structured synthesis of assessments, institutional diagnostics, and policy proposals published between 2022 and 2025, with the goal of identifying recurring patterns, key constraints, and gaps in the emerging recovery framework. The aim was to conduct a meta-analysis of institutional data on Ukraine's recovery finance to characterise sectoral needs, identify funding gaps by instrument type, and assess the readiness of the institutional framework to plan, execute, and monitor large, multi-year investment flows under uncertainty.

MATERIALS AND METHODS

This study used a mixed-method meta-analytical approach to analyse, compare, and interpret the changing financial estimates, institutional capacities, and policy responses related to Ukraine's postwar recovery. The method was designed to combine both quantitative sector-specific data and qualitative institutional evaluations, allowing for a thorough assessment of recovery financing trends, challenges, and strategic options. The core dataset was built from over 10 influential reports published between 2022 and early 2025 by international financial institutions – IMF (2024), EBRD (Bennett, 2024), World Bank (2025), IFC (2025), multilateral organisations (European Commission, 2023; UNDP, 2024), and Ukraine's government agencies. Key inputs included the Third and Fourth Ukraine Rapid Damage and Needs Assessments (World Bank, 2025), budget documents from Ministry of Finance of Ukraine (2024), and sector-specific studies on infrastructure, housing, and energy reconstruction. Inclusion criteria specified that sources must provide either: official cost estimates and sectoral breakdowns of recovery needs; empirical or scenario-based assessments of financing flows; evaluative content on institutional readiness, legal frameworks, or investment mechanisms. Public media publications from Reuters (Reuters, 2025; Shalal, 2025) and The Guardian (Clinton *et al*., 2025) were used selectively to cross-reference updated figures and confirm the timeline of critical announcements, but the core of the analysis is grounded in institutional and government-issued data.

A structured framework was employed to organise and compare cost estimates across five key recovery sectors: housing, transport, energy, industrial infrastructure, and agriculture. These sectors were chosen based on their recurring appearance in damage assessments and the size of their financial needs. For each sector, funding estimates were triangulated from at least two independent sources, ensuring both temporal consistency (2023-2025) and validation across institutions. In addition to aggregating cost estimates, sectoral cost structures – distinguishing between emergency repairs, modernisation components (e.g., green technologies, EU alignment), and logistical or geopolitical constraints – provide deeper insight into the quality and feasibility of proposed investments. To simulate potential recovery pathways, the study developed three recovery scenarios (Baseline, Accelerated, Delayed) based on different assumptions about donor support, institutional reform, and private sector participation. These scenarios were created through logical extrapolation from existing investment commitments and reform trajectories, guided by international benchmarks and past postwar reconstruction cases. Annual investment requirements, timelines, and key assumptions were detailed for each scenario. While the scenarios model is not econometric, it functions as a comparison tool to demonstrate how different policy and coordination environments could affect Ukraine's long-term recovery prospects.

To evaluate Ukraine's readiness to absorb large-scale recovery financing, a diagnostic scorecard was created. This scorecard focused on five key institutional enablers: legal framework for public private partnerships (PPPs), risk-sharing mechanisms, project pipeline readiness, donor coordination, and investment promotion capacity. Each category was rated on a 0-10 scale using semi-quantitative methods, supported by qualitative descriptions from primary reports (SIGMA, 2024; Transparency International, 2024; IFC, 2025). Scores were verified against sectoral data and project implementation trends to identify discrepancies between legal frameworks and actual execution. This hybrid diagnostic aimed to highlight both structural strengths and important gaps in Ukraine's current recovery governance system. The meta-analytical approach inherently depends on the availability, quality, and transparency of secondary data. While every effort was made to use the most current and validated figures, some discrepancies in sectoral classifications and assumptions between reporting agencies may still exist. Additionally, the scenarios developed are illustrative rather than predictive; they aim to inform strategic thinking, not forecast specific outcomes.

RESULTS AND DISCUSSION

An analysis of the most reliable assessments of Ukraine's reconstruction needs shows a consistent rise in projected costs over time. The total funding required for complete recovery and rebuilding now exceeds USD 524 billion, according to the February 2025 update issued by the Ukrainian government in partnership with the World Bank, the UN, and the European Commission (World Bank, 2025). This is a substantial increase from the USD 486 billion estimate in 2023, which accounted for both the continued destruction caused by the war and broader development goals including energy transition, climate resilience, and EU integration (European Commission, 2023). The extent and severity of the damage are not evenly distributed across different sectors. The most heavily impacted categories are the energy sector (USD 68 billion), housing (USD 84 billion), and transportation infrastructure (USD 78 billion), with industrial and commercial assets (USD 64 billion) and agriculture (USD 55 billion) following closely behind (World Bank, 2025). These five sectors collectively account for more than two-thirds of the total projected needs. The rise in estimates over time can be attributed to both the adoption of more ambitious policy goals, such as sustainable and equitable development standards, and additional damage that has occurred since the initial assessments (CEPR, 2022).

Large-scale infrastructure recovery and modernisation will require a significant portion of the funding, according to a closer examination of the sectoral data. The extent of the humanitarian disaster is evident in the loss of nearly 2 million dwelling units, particularly in the East and South regions (UNDP, 2024). To comply with EU standards, reconstruction plans are increasingly incorporating seismic resilience and energy-efficiency criteria, which can lead to higher prices per unit (European Commission, 2023). Roads, railroads and port infrastructure have all sustained significant damage. In the case of the railway network, the requirement for gauge conversion and electrification drives up expenses. Dredging and mine clearance are also integral to port reconstruction, particularly in the south (Bandura *et al*., 2024). Damage in the energy sector occurs at every stage of production, transmission, and distribution.

Despite the recovery strategy's focus on innovative grid development and renewable energy, emergency repairs and stabilisation of current infrastructure account for more than half of the estimated expenses (IEA, 2024). Logistical limitations, persistent security threats and price volatility in international labor and building material markets aggravate these sectors' needs (Bennett, 2024). Given these constraints, financing will need to blend grants, concessional loans, and risk-sharing instruments to bring in private capital where feasible. Sequencing is critical: stabilise and de-mine first, then rebuild to EU codes and resilience standards. Investing in project preparation (feasibility studies, E&S assessments and standardised procurement) will save time and reduce overruns at scale. Domestic capacity building and transparent digital tracking should be treated as core components of every major programme. Based on the open-source analysis, three financing scenarios were developed to explore potential recovery paths (Table 1). These scenarios reflect different levels of private sector participation, progress in internal reforms, and international support.

Table 1. Recovery scenarios based on meta-analysis of publicly available reports

Scenario	Annual investment	Recovery timeline	Assumptions
Baseline	USD 10-12 billion	15+ years	Moderate donor support, limited private investment, partial reform implementation
Accelerated	USD 25-30 billion	8-10 years	Robust donor commitment, successful PPP legislation, and effective project pipeline development
Delayed	< USD 7 billion	20+ years	Declining donor engagement, macroeconomic instability, poor coordination

Source: developed by authors based on CEPR (2022), European Commission (2023), UNDP (2024), R. Bandura *et al.* (2024), IEA (2024), V. Bennett (2024), Reuters (2025), A. Shalal (2025), J. Clinton *et al.* (2025), World Bank (2025)

According to the baseline scenario, which most closely matches current financing levels (World Bank, 2025), the entire restoration process might take more than 15 years. The expedited scenario, on the other hand, could significantly shorten the recovery timeline and is only achievable with increased institutional capacity and private sector involvement (IFC, 2025). Conversely, the delayed scenario would likely entail a longer reconstruction period, a substantial decline in the country's GDP, and a widening of regional inequality (IMF, 2024). This meta-analysis's main conclusion is that the difficulty of absorbing and efficiently allocating this funding equals the size of the financial need. A major challenge remains institutional inadequacy. Many implementing agencies and local officials lack the administrative and technical resources needed to create projects ready for financing. Less than 10% of project ideas submitted in 2023-2024 met the requirements set by foreign donors and investors, according to internal evaluations by the World Bank and Ukraine's Ministry for Communities (World Bank, 2025).

Recovery financing faces greater challenges due to procedural and legal issues. Ukraine's legislation related to PPPs is still only partly aligned with international standards and remains unclear in areas like concession rights and dispute resolution procedures. While there has been some progress in reforming public investment management and procurement, especially through the digitalisation of tender processes such as the ProZorro system, oversight mechanisms are still insufficient, and accountability for major infrastructure projects remains uneven (Transparency International, 2024). Data from SIGMA and Transparency International indicate that up to one in four public contracts at the subnational level may be at risk from procurement-related hazards (SIGMA, 2024). These risks deter private investment and lead donor organisations to question whether current financing sources are sustainable.

Ukraine's recovery environment remains largely dependent on donor and public financing. Around USD 4.5 billion in donor funds were allocated to Ukraine's national budget in 2024 for recovery efforts, mainly to rebuild critical infrastructure systems (Ministry of Finance of Ukraine, 2024). Although only a small part of the roughly USD 6.5 billion in donor commitments was given as grants, the rest was provided as financial aid or concessional loans (European Commission, 2024a; 2024b). Private sector involvement remains limited. The IFC predicts that less than USD 2 billion of the total infrastructure financing in 2024 will come from privately financed projects, including PPPs (IFC, 2024). A lack of legislative guarantees, currency risk, an underdeveloped secondary capital market, and limited scalable insurance options are some of the barriers to increasing private investment (MIGA, 2023). A diagnostic scorecard based on five important enablers to evaluate Ukraine's preparedness to deploy blended financing for post-war recovery needs was created. Table 2 shows the indicators used based on the institutional reports and publicly available data that were used to assign scores on a scale of 0 to 10.

Table 2. Scorecard of preparedness for absorbing large-scale recovery financing

Indicator	Score (2025)	Comments
Legal framework for PPPs	4.5 / 10	Progress on alignment with EU standards is incomplete
Risk-sharing mechanisms	3.0 / 10	Instruments such as partial guarantees and political risk insurance (PRI) remain underutilised
Project pipeline readiness	4.0 / 10	Lack of technical assistance and feasibility studies hampers quality
Donor coordination	7.0 / 10	Coordination platforms exist but remain donor-driven
Investment promotion capacity	5.5 / 10	Fragmentation across agencies reduces effectiveness

Source: developed by authors based on CEPR (2022), MIGA (2023), European Commission (2023; 2024a), UNDP (2024), R. Bandura *et al.* (2024), IEA (2024), V. Bennett (2024), IMF (2024), Transparency International (2024), SIGMA (2024), World Bank (2025)

On the one hand, these results suggest that Ukraine has advanced in some of the institutional categories (particularly around donor coordination), though there remain notable holes in its ability to attract, manage and retain diversified types of funding. The findings of the meta-analysis show that by itself raising enough financial resources is not sufficient for postwar reconstruction in Ukraine; an institutional and strategic capacity to absorb, as well as distribute, that funding has to be established. The reconstruction demands, estimated over USD 524 billion, are so large and complex that an approach is needed integrating international coordination, institutional renovation and fiscal innovation. Considering the facts, the following policy recommendations are offered to further enhance the effectiveness and sustainability of Ukraine's recovery efforts.

The inability to generate projects that are investment-ready is a serious barrier for Ukrainian institutions at the subnational level. The Ukrainian government should establish a network of specialised Reconstruction Project Preparation Facilities (RPPFs) in close cooperation with foreign development organisations to address this. While preparing feasibility studies, environmental assessments, and procurement documents, they need support from these units of cooperation, as developed by municipalities and line ministries. The experience of the Marshall Plan and the Western Balkans Investment Framework, both of which have clearly accelerated infrastructure delivery through project pipeline development, offers valuable lessons.

Ukraine's current institutional framework does not align with donor interests or the early participation of private companies in the market. There is a need to encourage long-term private investments. This includes immediately aligning Ukraine's PPP legislation with EU standards, streamlining approval processes, and increasing transparency in concession terms and dispute resolution mechanisms. Establishing a PPP Guarantee Facility supported by global financial institutions, such as EBRD and IFC, especially for transportation, energy, and water infrastructure, can help mitigate perception-based risks and potentially boost investor confidence in these sectors. As of 2025, private participation in infrastructure projects remains limited; most financing is provided by public funds and donor organisations (European Commission, 2024b; Ukraine Facility, 2025). Increasing private investment directly depends on the availability of scalable guarantees and clear PPP regulations. To close this gap, Ukraine and its international partners should expand the use of blended finance models that combine grants, concessional loans, and equity capital. This approach should also include greater use of guarantees, political risk insurance, and local currency lending facilities offered by organisations like EBRD. Additionally, Ukraine can consider issuing green bonds or reconstruction bonds to the diaspora to tap into ethical finance market potential.

International aid is only as effective as the coordination and accountability that ensure its delivery. Ukraine needs to formally establish and strengthen the Multi-Agency Donor Coordination Platform, which should be empowered with the authority to evaluate disbursements, reduce duplication, and align financial sources with national policy priorities. A results-based framework for all major donor programmes, using sector-specific performance indicators, can increase transparency and foster confidence among both local and international stakeholders. Ukraine's ambition to join the EU, along with the need to achieve long-term sustainability, requires that reconstruction efforts focus on creating a more modern and resilient economic base. From this perspective, the green and digital transitions must be incorporated into all major reconstruction projects, especially those related to energy, housing, or transportation. Ukraine should leverage all available EU funding sources, such as the Digital Europe Programme and the Green Deal Investment Plan. Additionally, local governments need more technical assistance to develop recovery efforts centered on digital solutions, and support the private sector in integrating energy efficiency guidelines or climate risk assessments into their designs.

The national reconstruction dashboard would consolidate information on cash flows, milestone achievements, and performance outcomes from all funds and sectors in Ukraine – building on lessons learned from systems like ProZorro and Digital Restoration Ecosystem for Accountable Management (DREAM). Oversight mechanisms should at least be broad-based and include civil society, local communities, and foreign observers to offer an independent perspective on the process. Table 2 summarises policy recommendations, particularly regarding absorption issues related to postwar recovery financing.

Table 3. Policy recommendations on efficient absorption of recovery financing under current recovery framework

Policy Area	Lead Actor	Timeline	Expected Impact
Institutional capacity building	Government of Ukraine + IFIs	Short-term (2024-2026)	Improved project pipeline and donor absorption
Legal reform (PPPs Law)	Parliament of Ukraine + Ministry of Economy	Short-term (2024-2025)	Increased investor confidence and PPP mobilisation
Blended finance instruments	Ministry of Finance + IFC + EBRD + MIGA	Medium-term (2025-2028)	Higher private capital inflow and reduced fiscal burden
Donor coordination mechanisms	Government of Ukraine + Donor Platform	Immediate & ongoing	Efficient donor engagement and reduced fragmentation
Green & Digital transition	Ministry of Infrastructure + EU Partners	Medium-term (2025-2030)	Long-term competitiveness and EU alignment
Monitoring & Transparency	Ministry of Digital Transformation + Civil Society	Immediate & ongoing	Greater transparency and reduced corruption risks

Source: developed by authors based on CEPR (2022), MIGA (2023), European Commission (2023; 2024a), UNDP (2024), R. Bandura *et al.* (2024), IEA (2024), V. Bennett (2024), IMF (2024), Transparency International (2024), SIGMA (2024), World Bank (2025)

The evidence shows that Ukraine's recovery is limited as much by institutional capacity as by funding levels. Total needs now surpass USD 524 billion, mainly in energy, housing, transport, industry, and agriculture. However, key challenges include project preparation, procurement transparency, PPP and concession design, and coordination among donors. Scenario analysis suggests different timelines: without legal alignment with EU standards and proper execution capacity, recovery could take over 15 years; however, a faster path (around 8-10 years) requires standardising pipeline preparation, implementing risk-sharing measures like guarantees, PRI, and local-currency options, and establishing a strong coordination platform. Therefore, the recovery plan should follow these steps: stabilisation and demining; rebuilding using EU technical codes with resilience features; and integrating green and digital initiatives systematically. Operationally, setting up RPPFs, aligning PPP laws and dispute-resolution systems with EU standards, expanding blended finance options (grants, concessional loans, equity, guarantees), and creating a national reconstruction dashboard based on ProZorro, DREAM are essential for turning commitments into practical, investable projects. With these measures, external funding can be used to develop resilient infrastructure, competitive businesses, and improved urban systems; without them, even large amounts of money risk being wasted through slow spending and low impact.

The meta-analytic findings – that the main constraints on Ukraine's recovery are institutional (such as procurement quality, PPP and concession design, project preparation capacity, and coordination) – align broadly with recent comparative and Ukraine-specific literature. Synthesis work emphasises that increasing funds without matching improvements in governance and pipeline quality results in weak absorption and limited impact (Becker *et al.*, 2025). Institutional diagnostics also supports this conclusion and needs assessments that show rising headline requirements alongside uneven delivery capacity (European Commission, 2023; UNDP, 2024; World Bank, 2025). Regarding programme design, sustainable finance, and firm adaptation, conceptual and Ukraine-focused analyses agree that recovery finance must be integrated into corporate-finance strategies with clear incentives and measurable outcomes (Pustovoit, 2022; Aleksin, 2024; Aleksin & Dyba, 2024). Incorporating ESG, SDG markers and labeled instruments within blended-finance vehicles enhances accountability and can reduce the cost of capital when paired with reliable monitoring (Becker *et al.*, 2025). At the entrepreneurial level, Latvia's experience demonstrates how green-enterprise ecosystems (advisory services, credit lines, incubation) turn policy goals into local investment and jobs – an approach easily adaptable to Ukrainian regions (Arbidane *et al.*, 2024).

Multi-regional and input-output studies show that the war's effects are uneven across regions, with strong interregional spillovers in Europe and varied territorial shocks within Ukraine (Almazán-Gómez *et al.*, 2023; Haddad *et al.*, 2023). Sector analyses for energy and logistics highlight that sequencing is important: stabilisation and emergency repairs, followed by modernisation for resilience and EU standards, improve multipliers and lower long-term costs. Global supply chain and environmental impacts (such as food system effects) support the need for climate-focused reconstruction (Zhang *et al.*, 2024). Recovery instruments operate within coalition structures that "make markets" around natural-resource access and governance; EU-Ukraine integration thus requires aligning incentives so that legal approximation, procurement rules, and local-content and competition policies pull in the same direction (Buzogány & Varga, 2025). Historical perspectives echo this architecture-first logic: durable successes of post-war programmes stemmed from institutional arrangements – decision rules, coordination platforms – rather than financing volumes alone (Achenui, 2021; Onah *et al.*, 2023; Martinez, 2025).

Market-based studies document asymmetric vulnerability across European equities, sector-specific drawdowns (e.g., hospitality), and transmission to FinTech, blockchain and crypto assets with nonlinear dynamics; these patterns validate the need for guarantees and contingent liquidity to stabilise investment pipelines (Abbassi *et al.*, 2023; Abakah *et al.*, 2023; 2024). Shifts in inflation expectations and heterogeneous monetary policy responses across currency areas further shape the cost of capital and timing of issuance for Ukraine-linked instruments (Afunts *et al.*, 2023; Aliu *et al.*, 2025). City-scale rebuilding must balance heritage conservation with modern infrastructure, highlighting the need for integrated conservation planning in Ukrainian municipalities facing complex reconstruction decisions (Dimelli & Kotsoni, 2023). Recovery outcomes are also socially varied; refugee and displacement literature emphasises the importance of addressing diverse needs in programme design, especially for vulnerable groups (Vella, 2024). Incorporating these aspects into project planning enhances absorption and legitimacy. Programme design is crucial for durability. Evidence from Ukraine shows that investments in innovation capacity and firm-level adaptation generate more lasting productivity improvements than short-term construction spending. In this context, governance quality acts as a de-risking tool: combining public and donor resources with transparent conditions on integrity, compliance, and ESG goals increases private sector involvement and enhances absorptive capacity (Aleksin & Dyba, 2024). Given the scope of the task, relying solely on grants and budget funding is insufficient; financing must be integrated into corporate-finance strategies aligned with the SDGs, using instruments that combine sources and motivate firm-level performance (Aleksin, 2024).

Measurement frameworks and institutional structures influence both perspectives and implementation. Business-sector needs seem exaggerated when only compared to direct asset losses: RDNA (February 2023) reports USD 120 billion in business needs for 2023-2033 versus USD 34 billion in direct damages, reflecting severe decapitalisation in 2022 (approximately -42% of book value) and suggesting that early-stage priorities should focus on recapitalisation and compensation rather than additional leverage (Zymovets, 2023a; 2023b). An actionable response involves a specialised facility that consolidates funding streams and provides standardised payouts based on a unified registry of direct losses, with distribution, where possible, managed through local financial institutions under donor oversight. Past experience supports this approach: the European Recovery Programme's most lasting contributions were institutional – decision rules, allocation procedures, and coordination platforms – rather than volume-based (Achenui, 2021; Onah *et al.*, 2023). Country-level evidence (e.g., Italy) shows that adaptable, locally specified instruments outperform uniform loan schemes (Martinez, 2025).

Recovery is socially differentiated, spatial, and aligned with climate considerations. Outcomes differ across demographic groups; evidence from refugee and displacement research highlights complex, gender-specific needs and barriers to access that – if left unaddressed – weaken programme effectiveness (Vella, 2024). Urban recovery must balance heritage preservation with modern infrastructure and land-use pressures; integrated conservation planning developed for complex postwar contexts (e.g., Aleppo) offers a transferable approach for Ukrainian cities (Dimelli & Kotsoni, 2023). On the growth front, green-entrepreneurship ecosystems – including incubation, specialised credit lines, and advisory services – can transform energy-efficiency and circular-economy opportunities into employment and exports, with Latvia's experience serving as a nearby example for programme design and sequencing (Arbidane *et al*., 2024). When integrated with Europe-wide spillovers and Ukraine's internal input-output structure, these insights support a recovery plan that is spatially aware, institution-led, climate-compatible, and attentive to distributional differences.

CONCLUSIONS

Ukraine's post-war reconstruction depends as much on institutional capacity as on financing. Current estimates exceed USD 524 billion, mainly for energy, housing, transport, industry, and agriculture. The pace of recovery hinges on the ability to design bankable projects, structure public-private partnerships (PPPs), and coordinate donor flows through a unified framework. Three scenarios (Baseline, Accelerated, and Delayed) illustrate that outcomes vary chiefly by legal alignment and implementation capacity. Without reform, recovery could take over 15 years; with professionalised project preparation, risk-sharing tools, and effective coordination, it may shorten to 8-10 years. Transparency reforms alone are insufficient. Digital procurement and open data enhance integrity but cannot ensure capital formation without robust RPPFs providing feasibility studies, due diligence, and standardised procurement packages. PPP and concession frameworks must align with EU norms – step-in rights, dispute resolution, and risk allocation – to reduce uncertainty and enable limited-recourse project finance.

A layered financing model is required. Grants and concessional loans should fund social infrastructure, while guarantees, political-risk insurance, and local-currency mechanisms de-risk revenue assets. Green, sustainability, and diaspora bonds should operate within blended-finance vehicles embedding ESG-SDG metrics and covenants. Sequencing is essential: stabilisation and de-mining, reconstruction to EU technical codes, and integration of green and digital components to improve resilience and efficiency. Institutional design remains the core constraint. A strengthened multi-agency coordination platform linked to a national reconstruction dashboard should align donor funds, enforce preparation standards, and track outputs. Embedding labour-market modules within sector programmes can mitigate capacity shortages.

Policy priorities include establishing RPPFs, finalising PPP legislation, expanding guarantee and liquidity instruments, institutionalising results frameworks, and developing integrated data systems. Effective institutional frameworks, not funding volumes, will determine Ukraine's ability to transform commitments into resilient infrastructure and competitive, sustainable growth. Future work should assemble a harmonised project-level dataset linking preparation milestones, procurement attributes, risk-sharing terms, and ex-post delivery outcomes to estimate "absorption elasticities" with granular causal designs (event studies, matched difference-in-differences); integrate political-economy and coalition metrics – e.g., sectoral lobbying intensity, local content provisions, and EU acquis alignment scores – into financing models to test how governance shifts reduce the cost of capital; extend scenario analysis with dynamic multi-regional input-output and spatial general-equilibrium modules to quantify regional spillovers, supply-chain re-routing, and distributional effects across regions.

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Мета-аналіз фінансування повоєнного відновлення України: огляд ключових загально доступних документів

Анотація. Метою цієї роботи було провести метааналіз інституційних оцінок (2022 – початок 2025) для визначення галузевих потреб, фінансових розривів і інституційних перешкод, що впливають на терміни відновлення. Було застосовано структурований огляд і метааналіз понад 20 звітів і секторних досліджень, а також порівняльне моделювання сценаріїв («Базовий», «Прискорений», «Відкладений») і створено діагностичний інструмент для оцінки інвестиційного середовища. Дослідження показало, що загальні потреби перевищують 524 мільярди доларів США, здебільшого у сферах енергетики, житла, транспорту, промислових активів і сільського господарства; зростання оцінок відображає як додаткові збитки, так і впровадження технічних, декарбонізаційних і цифрових стандартів ЄС. Зазначено, що гранти та пільгові кредити є необхідними, але недостатніми: ключові обмеження включають підготовку банківських проєктів, якість закупівель, структуру концесій (розподіл ризиків, механізм step-in, валютні ризики) та координацію донорів. Було розроблено три варіанти сценаріїв на основі даних: «Базовий» шлях (15+ років) з обмеженою участю приватного сектору; «Прискорений» шлях (8-10 років), що спирається на стандартизовану підготовку, масштабовані гарантії, страхування політичних ризиків, фінансування у національній валюті та потужну координаційну платформу; і «Відкладений» шлях із довшими термінами та зростаючими регіональними диспропорціями. Запропоновано операційну рамку, яка складається з мережі Центрів підготовки проєктів відновлення, типових пільгових угод, узгоджених зі стандартами ЄС, підходу змішаного фінансування (включно з гарантіями, інструментами в національній валюті та соціальними облігаціями з маркуванням), а також національної панелі моніторингу відновлення, що поєднує бюджетування, закупівлі та контроль. Показано, що прозорість не дорівнює ефективності освоєння коштів: цифрові платформи закупівель підвищують конкуренцію, але не забезпечують реалізацію капітальних видатків без інженерної підтримки, стандартизованої документації та незалежної верифікації цілей. Результати дослідження пропонують практичні рекомендації для урядів і муніципалітетів щодо визначення пріоритетних секторів, стандартизації підготовки проєктів і застосування інструментів змішаного фінансування, що скорочують час відновлення та підвищують інвестиційні мультиплікатори

Ключові слова: фінансування відбудови; змішане фінансування; платформи координації донорів; державні інвестиції; рамка відбудови; макрофінансування

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Integrated assessment of economic vulnerability in the European Union: A multi-criteria sensitivity-adaptability approach (2000-2023)

Abstract. With the increasing frequency and magnitude of global shocks (financial crises, pandemics, geopolitical conflicts), traditional macroeconomic indicators are proving insufficient to assess how national economies respond to and recover from external shocks. There is an urgent need to develop a comprehensive tool that simultaneously captures the sensitivity of economies to shocks and their adaptive capacity. The aim of the study was to develop and apply an integrated economic vulnerability index for European Union countries for the period 2000-2023 to comprehensively assess their structural weaknesses. To achieve this goal, a multifactor sensitivity-adaptability model was used, combining 29 macroeconomic indicators from the real, financial, public, and external sectors. To increase the objectivity of the assessment, multiple objective weighting methods were applied, including Entropy, CRITIC, and Gini indices. A new assessment approach has been developed that quantitatively reflects the economy's capacity for self-recovery and flexibility, unlike models with fixed weightings. Significant heterogeneity in levels of economic vulnerability and resilience among European countries has been identified, driven by structural and macroeconomic factors. In particular, the Netherlands, Germany, and Estonia show lower vulnerability due to industrial diversification and financial sector resilience, while Romania, Greece, and Italy are the most vulnerable. The key systemic drivers of vulnerability are identified as the current account balance, foreign trade dynamics, industrial value added, and banking sector capitalisation, which consistently dominate in all objective weighting methods. The critical role of integrating multiple weighting methods to ensure reliable and nuanced vulnerability assessments in heterogeneous economies has been confirmed. The research results provide experts (government agencies, international organisations) with practical recommendations for developing context-oriented strategies to reduce systemic risks and increase the long-term sustainability of the real sector

Keywords: financial fragility; economic resilience; responsiveness-flexibility framework; composite index; structural risk

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INTRODUCTION

In an era marked by periodic financial crises, pandemics, and geopolitical upheavals, understanding the structural weaknesses that make economies vulnerable is more relevant than ever. Traditional macroeconomic indicators often fail to capture how economies respond to shocks and their ability to recover from them. In the context of the increasing frequency and magnitude of economic shocks, there is a growing need for a comprehensive approach to assessing the vulnerability of national economies.

The existing scientific literature provides several critical insights. The study conducted by C.P. Nguyen & T.D. Su (2021) represented the first comprehensive investigation into the influence of financial development, as a component of the institutional framework, on economic vulnerability across a global sample of 76 countries over the period 1997-2017. Researcher S.K. Gnangnon (2025) examined the concept of structural economic vulnerability, defining it as the risk of a nation's development being impeded by external or environmental shocks. It was emphasised that this vulnerability remains a critical barrier to sustainable economic growth, and the reliance on single indicators for national assessments may overlook crucial vulnerability aspects, potentially restricting opportunities for the state and its citizens. The article by A. Sánchez *et al*. (2023) examined the level of socio-economic vulnerability of European Union regions at the NUTS-2 level by constructing a composite Socioeconomic Vulnerability Index (SEVI) that combines economic, social and demographic indicators. The authors found significant regional differences: northern and western regions show greater resilience, while southern and eastern regions remain more vulnerable. The Euoripean Union's cohesion policy contributes to reducing these disparities, but its effectiveness is uneven and depends on the institutional capacity of the regions. Insufficient attention has been paid to the dynamics of adaptability and the role of managerial and environmental factors in shaping resilience.

Certain multilateral organisations, such as the United Nations (UN), have thus recognised the limitations of single-indicator approaches and employ composite measures, including the Economic Vulnerability Index (EVI), to consolidate multiple dimensions into a single metric. Recent studies have also drawn attention to the omission of financial vulnerability from the broader definition of economic vulnerability, underscoring the necessity of integrating financial dimensions into analytical frameworks. Focusing on the fiscal dimension, N.H. Dau *et al*. (2024) investigated the stability of the financial system, arguing that it largely depends on its capacity to correct fiscal imbalances, particularly the mismatch between government revenues and expenditures. The researchers contended that this approach ensures effective national debt management and minimised fiscal deficits, underscoring the importance of understanding the intricate relationship between debt structure, exposure to economic shocks, and economic vulnerability. Furthermore, the dual role of trade openness has been interpreted in the literature, which suggests that while trade openness promotes export diversification and access to resources, it also causes commodity shocks to affect countries' economic growth, thereby increasing vulnerability.

Regarding alternative methodologies for index construction, the employment of the CRITIC approach was advanced by X. Wei *et al*. (2025) during the screening of uncalibrated priority pollutants using the enhanced Analytic Hierarchy Process-Criteria Importance Through Intercriteria Correlation (AHP-CRITIC) methodology. Their study demonstrated an integrated Multi-Criteria Decision Analysis (MCDA) protocol combining AHP and CRITIC, which was validated as a method of diminishing excessive reliance on subjective or data-driven methodologies, affirming its adaptability to any multi-indicator index. Concurrently, in the field of credit risk assessment, Y. Li & W. Chen (2021) proposed a novel LNN-Entropy credit scoring model that integrates data pre-processing, feature selection, neural networks, and logistic regression using an entropy-based framework. Their empirical analysis demonstrated that this hybrid model surpasses both individual algorithms and several state-of-the-art benchmarking models in terms of classification accuracy and predictive performance, illustrating the potential of entropy-driven optimisation in enhancing model robustness. Moreover, O. Pala (2023) introduced an innovative objective criterion weighting approach known as the ROCOSD method, which simultaneously considers robustness, correlation, and standard deviation. Comparative analyses undertaken by the author demonstrated that ROCOSD surpasses traditional weighting techniques in both robustness and accuracy, validating its practical utility and adaptability to policy assessment frameworks. Overall, these methodological developments underscore the necessity of adopting flexible, transparent, and statistically robust weighting schemes in the construction and interpretation of composite indices. The purpose of this study was to develop and apply a composite EVI for European Union countries.

MATERIALS AND METHODS

The primary innovation pertained to the objective weighting of 29 macroeconomic indicators encompassing the real, financial, government, and external sectors. The application of seven distinct weighting schemes was employed in this study: equal weighting, entropy, standard deviation (SD), coefficient of variation (CV), CRITIC, Gini coefficient, statistical dispersion, with a sensitivity-adaptability model for assessing economic vulnerability. The methodology employed was designed to minimise subjectivity and ensure that the composite index reflects both the dispersion and the unique contribution of each indicator. The analysis encompassed key macroeconomic indicators such as Gross Domestic Product (GDP) growth rate, inflation, unemployment, and savings rate, examined across a selection of European countries. The study period spans from 2000 to 2023, enabling a thorough evaluation of structural vulnerabilities within the real, financial, public, and external sectors of the economy. The assessment of economic vulnerability across European countries was performed using a comprehensive composite index, integrating indicators from the real, financial, government, and external sectors. This multi-criteria approach allowed for a nuanced analysis of both sensitivity to economic shocks and the adaptive capacity of national economies.

Several methodological approaches were adopted in line with contemporary practices in composite index construction. First, the aforementioned methods were integrated prior to the final aggregation stage to ensure methodological robustness and to mitigate potential biases associated with any single weighting technique. Second, within the established hierarchy of indicators, a clear conceptual and analytical distinction was drawn between sensitivity (defined as volatility in response to external shocks) and adaptability (interpreted as resistance to long-term adverse trends). This classification enabled a more nuanced understanding of the structural dimensions of economic vulnerability. Finally, the VIKOR method was employed to synthesise the weighted scores and to implement a compromise ranking algorithm. This approach facilitated the comparative analysis of the EVI across countries, allowing for the identification of relative performance patterns and the assessment of inter-country disparities in economic resilience. Given that the EVI under consideration utilises seven objective weighting schemes (equal, entropy, SD, CRITIC, Gini, variance, CV), it was appropriate to employ Equal Weighting/Minimax Method (EW/MM) results to assess the sensitivity of the EVI ratings to the simple mixing of all indicators at equal weightings. Next, adaptive methods were used to determine if EVI behaves more like Data Envelopment Analysis (DEA) (unstable with many indicators) or EW (stable). To convert the weights into a consistent ranking scale, the VIKOR compromise ranking method was employed, with the pyrepo-mcda Python package being utilised for implementation. The data were obtained directly from the World Bank (n.d.) via the wbgapi interface, and all calculations are performed using Python scripts to ensure full reproducibility. The standardisation of sensitivity (i.e. the annual volatility around long-term averages) and adaptability (i.e. the resistance to regression-based trends) prior to the construction of the index is undertaken to ensure the comparability of indicators between countries.

In addition to quantitative analysis, qualitative research methods were also employed to deepen the understanding of the underlying nature of the studied phenomenon. Synthesising the approaches reviewed in the literature, the article primarily focuses on the structural vulnerabilities of the real, financial, and public sectors of the economy. To achieve this, a composite indicator was developed based on a set of key variables (Table 1).

Table 1. Variable coding map

Code	Variable	Impact
C1	Current account balance (% of GDP)	+
C2	Foreign direct investment, net inflows (% of GDP)	+
C3	S&P Global Equity Indices (annual % change)	+
C4	Stocks traded, total value (% of GDP)	+
C5	Stocks traded, turnover ratio of domestic shares (%)	+
C6	Bank nonperforming loans to total gross loans (%)	-
C7	Bank capital to assets ratio (%)	+
C8	Bank liquid reserves to bank assets ratio (%)	+
C9	Broad money (% of GDP)	+
C10	Broad money growth (annual %)	+
C11	Inflation, consumer prices (annual %)	-+
C12	Deposit interest rate (%)	-
C13	Lending interest rate (%)	-+
C14	Domestic credit to private sector (% of GDP)	+
C15	Central government debt, total (% of GDP)	-
C16	General government final consumption expenditure (% of GDP)	-
C17	Final consumption expenditure (annual % growth)	+
C18	Exports of goods and services (annual % growth)	+
C19	Gross fixed capital formation (% of GDP)	+
C20	Imports of goods and services (annual % growth)	+
C21	External balance on goods and services (% of GDP)	+
C22	Trade (% of GDP)	+
C23	Industry (including construction), value added (% of GDP)	+
C24	Services, value added (% of GDP)	+
C25	GDP growth (annual %)	+
C26	GDP per capita (current US$)	+
C27	Gross savings (% of GDP)	+
C28	Price level ratio of Purchasing Power Parity (PPP) conversion factor (GDP per capita)	+
C29	Unemployment, total (% of total labour force)	-

Source: compiled by the authors based on World Bank (n.d.)

To provide a clearer understanding of the distribution and variability of the selected indicators, descriptive statistics were calculated for each variable. Table 2 presents the statistical description of the indicators, including measures such as the mean, minimum, maximum, quartiles, and standard deviation, which together allow for an assessment of cross-country differences and potential outliers over the studied period.

Table 2. Statistical description of indicators

Variable	N	Mean	Min	25%	50%	75%	Max	Std
Current account balance (% of GDP)	636	-0.62	-25.74	-4.05	-0.35	2.71	19.16	5.79
Foreign direct investment, net inflows (% of GDP)	646	13.65	-440.13	1.73	3.56	7.64	452.22	56.35
S&P Global Equity Indices (annual % change)	579	6.83	-73.02	-14.06	4.86	26.07	189.23	31.47
Stocks traded, total value (% of GDP)	449	22.62	0.01	1.12	7.40	31.05	264.76	35.01
Stocks traded, turnover ratio of domestic shares (%)	413	46.04	0.05	6.25	30.98	68.23	377.25	53.24
Bank non-performing loans to total gross loans (%)	396	6.77	0.15	2.40	4.06	7.97	47.75	7.65
Bank capital-to-assets ratio (%)	402	7.65	-1.26	5.50	7.26	8.93	34.60	3.25
Bank liquid reserves to bank assets ratio (%)	161	17.33	0.20	0.29	13.38	22.49	77.21	15.62
Broad money (% of GDP)	168	59.12	26.13	46.34	60.28	67.89	93.83	15.42
Broad money growth (annual %)	168	9.78	-11.09	5.07	8.74	13.01	48.42	8.47
Inflation, consumer prices (annual %)	648	3.03	-4.45	1.12	2.28	3.55	45.67	3.77
Deposit interest rate (%)	150	3.44	0.01	1.18	2.34	3.73	33.11	4.32
Lending interest rate (%)	170	7.68	1.47	4.49	5.92	9.44	53.85	6.45
Domestic credit to private sector (% of GDP)	584	82.97	7.13	50.51	77.75	104.21	254.67	42.54
Central government debt, total (% of GDP)	330	67.43	3.81	38.09	60.81	92.60	249.37	41.72
General government final consumption expenditure (% of GDP)	648	19.88	11.06	18.17	19.44	21.67	27.82	2.93
Final consumption expenditure (annual % growth)	647	2.24	-16.80	0.86	2.17	3.81	17.02	3.30
Exports of goods and services (annual % growth)	647	5.34	-23.19	1.98	5.26	9.08	41.02	7.78
Gross fixed capital formation (% of GDP)	648	22.30	10.97	19.83	21.85	24.31	53.22	4.11
Imports of goods and services (annual % growth)	647	5.20	-30.89	1.30	5.47	9.34	41.30	8.50
External balance on goods and services (% of GDP)	648	2.14	-21.79	-2.04	1.24	5.04	41.69	8.75
Trade (% of GDP)	648	119.30	45.14	77.76	105.64	148.41	394.22	59.00
Industry (including construction), value added (% of GDP)	648	23.50	9.97	19.80	23.74	27.20	40.68	5.75
Services, value added (% of GDP)	648	62.59	42.33	57.62	62.15	66.65	80.60	6.56
GDP growth (annual %)	648	2.50	-16.04	0.90	2.57	4.51	24.62	3.90
GDP per capita (current US$)	648	30,921.66	1,621.26	14,792.16	24,665.99	43,772.63	133,711.79	22,590.00
Gross savings (% of GDP)	636	22.31	4.60	18.74	22.67	26.14	36.85	5.23
Price level ratio of PPP conversion factor (GDP) to market exchange rate	648	0.78	0.25	0.58	0.76	0.97	1.56	0.26
Unemployment, total (% of total labour force) – national estimate	648	8.34	1.81	5.53	177,326.00	10.04	27.69	4.27

Source: compiled by the authors based on World Bank (n.d.)

Within the framework of this study on economic vulnerability, an extended set of quantitative indicators was developed to encompass key aspects of the external, financial, banking, and real sectors of the economy. Each selected variable plays a critical role in the comprehensive analysis of economic structure and facilitates the identification of potential threats to macroeconomic stability. The current account balance (% of GDP) reflects the overall external equilibrium of a country, where positive values are indicative of financial resilience. Foreign direct investment (% of GDP) serves as a proxy for investor confidence and, accordingly, exerts a positive influence on economic dynamics. Stock market indicators, such as changes in global equity indices, total value of stocks traded, and turnover ratio of domestic shares, provide insights into the depth and liquidity of financial markets, which are positively correlated with economic activity. The condition of the banking system is assessed through the share of non-performing loans, the capital-to-assets ratio, and the level of bank liquidity reserves. A low proportion of problematic assets, high bank capitalisation, and substantial reserves are indicative of financial system resilience. Additionally, indicators of monetary policy were considered: broad money (% of GDP) and its annual growth rate, which allow for the evaluation of the level of monetary activity. The equal weights method is employed in sensitivity and reliability studies that utilise equal weights/minimax methods to construct composite social indicators (Shi & Land, 2021).

Particular attention was given to domestic credit to the private sector, which reflects the level of access to financial resources, and to central government debt (% of GDP), where exceeding critical thresholds may pose risks of debt instability. The analysis also incorporated indicators of government consumption and final consumption expenditure, which reflect fiscal policy and domestic demand, respectively. External economic activity was assessed through export and import growth rates, the external balance of goods and services, and total trade (% of GDP). These indicators capture the degree of a country's integration into the global economy and its dependence on external conditions.

From a structural perspective, the study examines value added in industry (including construction) and the services sector, providing insight into the sectoral composition of GDP. Core macroeconomic indicators, such as annual GDP growth, GDP per capita (current US$), gross savings (% of GDP), and unemployment rate, offer a general overview of economic activity, population welfare, and socio-economic balance. Additionally, the price level index (defined as the ratio of the purchasing power parity conversion factor to nominal GDP) was considered, enabling an assessment of real purchasing power in comparison with other countries. Taken together, this set of indicators enabled a comprehensive evaluation of both internal and external factors contributing to economic vulnerability, helping to identify potential risks and structural weaknesses in national economies. This approach provided a foundation for the development of an integrated EVI and for ranking countries according to their level of structural resilience.

Methodology for assessing economic vulnerability. The vulnerability of an economic system was assessed through a "sensitivity-adaptability" function. The formula for calculating vulnerability presented as follows:

$$Vulnerability = Sensitivity - Adaptability, \quad (1)$$

where V, S, A – system's vulnerability, sensitivity, and adaptability, respectively. The vulnerability of the system is influenced by both its sensitivity and adaptability. Sensitivity reflects the degree to which the system responds to external disturbances, while adaptability indicates the system's capacity to maintain and restore its structure when faced with such disturbances. For instance, taking GDP growth rate (a key indicator of the macroeconomic system) its sensitivity is measured through the annual volatility over the period in dataset.

The formula for calculating sensitivity is as follows:

$$Sensitivity_j = \frac{\sum_{i=1}^{n} |F_i - \bar{F}|}{\bar{F}}, \quad (2)$$

where F_i – value of index j in the year i; $\bar{F}$ – the average value of index j from 2000 to 2023. $Sensitivity_j$ – the variable rate of index j, which reflects the degree of dispersion of the average value of index j within the relatively specific time from 2000 to 2023.

Formulas (3) and (4) were used in this research methodology to quantitatively assess the adaptability of the economic system, which is a key component of the developed EVI. The formulas describe the application of linear regression to measure the long-term trend of variability for each indicator:

$$y = \beta_0 + \beta_1 x + \epsilon; \quad (3)$$

$$\beta_1 = \frac{cov(x,y)}{var(x)}, \quad (4)$$

where β_1 – regression coefficient, representing the change in the dependent variable y associated with a one-unit change in the independent variable x; ε – error term, capturing the unexplained variation in yyy not accounted for by the regression model; $cov(x,y)$ – covariance between x and y, measuring the degree to which the two variables vary together; $var(x)$ – variance of x, indicating the dispersion or spread of the variable around its mean.

The variable x denotes the ordinal time period, spanning from 2000 to 2023, while captures the intercept. The objective variable, denoted by y, is calculated for each indicator j by subtracting the mean value of j, calculated over the period 2000 to 2023, from its actual value. Additionally, as the sensitivity and adaptability values calculated from the preceding formula may vary in magnitude, it is essential to standardise these results separately before calculating vulnerability. This step ensures comparability and facilitates the analysis of regional differences in vulnerability. The equal weighting method is the simplest and entirely objective approach to determining the weights of criteria. Under this method, all criteria are considered equally important, regardless of data variability, informational richness, or statistical characteristics:

$$w_j = \frac{1}{n}, \forall j = 1,2, \dots, n. \quad (5)$$

It is important to note that this approach effectively neutralises the statistical significance or characteristics of individual indicators. Nevertheless, it is suitable in cases where expert judgment is unavailable or when there is no substantiated information regarding the relative importance of specific criteria. In essence, it represents a maximally neutral approach to assigning weights and evaluating the influence of indicators on the final assessment outcome. The Entropy Weight Method (EWM) is a widely recognised objective evaluation approach that is considered to be more reliable than those based on subjective methods. The principal benefit of this approach is that it reduces the potential for human bias, thereby enhancing the objectivity of comprehensive evaluation outcomes. At present study, EWM was employed in a multitude of disciplines, including engineering, technology, and socio-economic studies. The EWM calculates the entropy weight of each indicator using information entropy based on variation levels. Subsequently, each indicator's weight is adjusted according to the entropy value, thereby achieving a more accurate weight assignment. In general, a lower entropy weight, as determined by this method, indicates a higher degree of variation and richer information content, thereby contributing more significantly to the overall assessment and obtaining a larger weight. Consequently, this study employed EWM to determine the weight of each indicator within the economic system vulnerability assessment, given the method's suitability and effectiveness. The first step in EWM is standardisation. The positive and negative standardised formulas are as follows:

$$x'_{ij}(+) = \frac{x_{ij}-\min(x_j)}{\max(x_{ij})-\min(x_{ij})}; \quad (6)$$

$$x'_{ij}(-) = \frac{\max(x_j)-x_{ij}}{\max(x_{ij})-\min(x_{ij})}, \quad (7)$$

where x'_{ij} – initial value of indicator j for alternative/country i. y_{ij} is generated by:

$$y_{ij} = \frac{x_{ij}-\min(x_j)}{\max(x_{ij})-\min(x_{ij})}. \quad (8)$$

In EWM, – the entropy, is defined as:

$$entropy_j = -\frac{\sum_{i=1}^{n} y_{ij}\ln(y_{ij})}{\ln(n)}, \quad (9)$$

where n – number of observations.

It is necessary to mention that $y_{ij}=0 => y_{ij}\times ln(y_{ij})=0$. e_j lies in the [0,1] domain. In EWM the weight w_j is calculated as:

$$w_j = \frac{1-entropy_j}{\sum_{j=1}^{m} 1-e_j}, \quad (10)$$

where m – number of criteria/features; e_j – the entropy of criterion j, which measures the degree of uncertainty or dispersion of data for this criterion among all alternatives.

Comprehensive score calculation is as follows:

$$Score = \sum_{j=1}^{m} w_j y_{ij}. \quad (11)$$

The standard deviation weighting method belongs to the category of objective approaches for determining criterion weights. Its core principle lies in using the degree of data variation as an indicator of the informational value of each criterion. The greater the dispersion (or standard deviation) of a criterion's values across alternatives, the higher the weight it receives in the decision-making process. The standard deviation for each criterion is calculated as follows:

$$\sigma_j = \sqrt{\frac{1}{m}\sum_{i=1}^{m}\left(x_{ij}-\bar{x}_j\right)^2}, \quad (12)$$

where σ_j – the standard deviation of the j-th feature (or variable). It measures how spread out the values of this feature are from the mean; m – the number of observations (or data points) in the dataset.

Subsequently, the weights are derived using the formula:

$$w_j = \frac{\sigma_j}{\sum_{k=1}^{m}\sigma_k}, \quad (13)$$

where w_j – is the weight of the j-th feature (or variable). It shows the relative importance of that feature compared to the others; k – an index variable used inside the summation. It just counts through all the features (1, 2, 3, ..., m).

The logic of this method was based on the assumption that criteria with higher variability carry greater informational weight, as they are more effective in differentiating between alternatives. Conversely, criteria with low variation were assigned lower weights due to their limited contribution to comparative analysis. The CRITIC method is an objective approach to determining criterion weights that accounts for both the degree of data variation and the interdependence (correlation) among criteria. The underlying idea is that more important criteria are those that exhibit greater dispersion in values and do not duplicate the information provided by other criteria. That is, they are less correlated with others. In the first stage of this method, minimax normalisation was applied to the indicators (as per formulas (6) and (7)), resulting in standardised values x'_{ij}. The standard deviation for each criterion was then calculated as follows:

$$\sigma_j = \sqrt{\frac{1}{m}\sum_{i=1}^{m}\left(x'_{ij}-\overline{x'}_j\right)^2}. \quad (14)$$

Next, the correlation between each pair of indicators is computed:

$$r_{jk} = \frac{\sum_{i=1}^{m}(x'_{ij}-x'_j)(x'_{ik}-x'_k)}{\sqrt{\sum_{i=1}^{m}\left(x'_{ij}-\overline{x'_j}\right)^2\left(x'_{ik}-\overline{x'_k}\right)^2}}. \quad (15)$$

The resulting correlation values from formula (15), together with the standard deviation from formula (14), allowed for the estimation of the informational strength of each criterion:

$$C_j = \sigma_j \sum_{k=1}^{n}(1-r_{jk}). \quad (16)$$

Thus, each criterion is evaluated based on two parameters: its variability and its degree of independence from other criteria. Finally, the weights are calculated as:

$$w_j = \frac{C_j}{\sum_{k=1}^{m} C_k}. \quad (17)$$

This method objectively incorporates both the intensity of variation and the avoidance of excessive correlation, thereby preventing information redundancy. It is well-suited for complex multi-criteria decision-making tasks, although it is sensitive to the choice of correlation calculation method.

Gini coefficient-based weighting method. This method is based on the use of the Gini coefficient as a measure of inequality in the distribution of indicator values for each criterion. The greater the variation among alternatives for a given criterion, the higher its informational weight. It is an objective weighting approach that does not require expert input. For each criterion $j = 1,2,..n$, the Gini coefficient G_j is calculated to reflect the degree of inequality in the distribution of values across all alternatives $i = 1,2,...m$. The general formulation is as follows:

$$G_j = \frac{1}{2m^{2-}}\sum_{i=1}^{m}\sum_{k=1}^{m}\left|x_{ij}-x_{kj}\right|, \quad (18)$$

where G_j – the Gini coefficient for criterion j, representing the degree of inequality or dispersion of criterion j across all alternatives; m – the number of alternatives under evaluation; n – the number of criteria considered in the assessment; x_{ij} – the value of alternative i with respect to criterion j; $\bar{x}_j$ – the mean value of criterion j across all alternatives.

Once the values of are computed, the weights for each criterion are determined by normalising the vector of Gini coefficients:

$$w_j = \frac{G_j}{\sum_{k=1}^{m} G_k}, \quad (19)$$

where w_j – the normalised weight assigned to criterion j, derived from the corresponding Gini coefficient.

This method provides an objective mechanism for evaluating the relative importance of criteria based on distributional inequality, and is particularly useful in contexts where expert judgment is unavailable or undesirable.

Statistical variance weighting method. The statistical variance weighting method is based on the assumption that criteria with greater variability in their values carry more informational weight and should therefore be assigned higher importance in a multi-criteria model. Unlike subjective approaches, this method provides an objective means of determining weights solely based on the statistical properties of the input data. In the initial stage, minimax normalisation is applied (as per formula (6)).

In the next step, the statistical variance for each normalised criterion is calculated as follows:

$$var_j = \frac{1}{m}\sum_{i=1}^{m}\left(x'_{ij} - \bar{x}'_j\right)^2. \quad (20)$$

Once the variances are computed, the weight of each criterion is determined as the ratio of its variance to the sum of variances across all criteria:

$$w_j = \frac{var_j}{\sum_{k=1}^{m} var_k}. \quad (21)$$

The advantages of this method, as with other objective approaches, include its simplicity, transparency, and independence from expert judgment. However, it does not account for interrelationships between criteria, focusing solely on their individual variability.

Coefficient of variation weighting method. The coefficient of variation method is an objective approach to determining criterion weights that considers both the mean value of an indicator and the degree of its variability. A high ratio between the standard deviation and the mean is interpreted as a high informational significance of the criterion.

In this approach, data are standardised using sum normalisation:

$$b_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}}, \quad (22)$$

where b_j – average.

This results in a normalised matrix , where the sum of each column equals one. For each criterion j, the mean is calculated as:

$$\bar{b}_j = \frac{1}{m}\sum_{i=1}^{m} b_{ij}\,, \quad (23)$$

and the standard deviation is computed as:

$$\sigma_j = \sqrt{\frac{1}{m-1}\sum_{i=1}^{m}\left(b_{ij} - \bar{b}_j\right)^2}\,. \quad (24)$$

Following formulas (21-23), the coefficient of variation is calculated using:

$$e_j = \frac{\sigma_j}{\bar{b}_j}. \quad (24)$$

This metric reflects the intensity of fluctuations relative to the average level. Final weights are then determined by normalising the coefficients of variation:

$$w_j = \frac{e_j}{\sum_{k=1}^{m} e_k}. \quad (25)$$

This method offered a transparent and objective means of weighting, particularly useful when both variability and average performance are relevant.

RESULTS

In an era of increasing information availability, composite indicators satisfy the need for consolidation by combining multiple indicators into a single number that encompasses and summarises all this information. This key feature elucidates the reasons for their success and the reasons why they have been adopted on a global scale by organisations, scientists, the media and politicians. Despite their usefulness, these indicators should be used cautiously, especially when drawing significant conclusions. The validity of these accounts is contingent upon their construction, which, as previously discussed, contains no elements beyond critique. Each approach, at each individual stage, has both advantages and disadvantages, and during the weighting stage, developers select from a range of subjective and objective approaches.

The selection of components for the construction of a composite index invariably presents a dilemma, whereby alternative choices appear to be either disadvantageous or impractical. Despite its frequent oversight, it is imperative that reliability analysis is conducted after the construction of the index. This instrument is an excellent quality assurance tool for developers, with the additional advantage of enhancing overall transparency. However, it should not be mistakenly interpreted as a guarantee of the sensitivity of the composite index. Indeed, the reliability of the construction can be assured by ensuring that each choice is linked to the purpose of the construction. The results of assessment of economic vulnerability across European countries, classified using a natural breaking point method, revealed clear regional clusters and heterogeneity in economic resilience across Europe. The findings demonstrated that the advancement of financial systems – including financial depth, access, efficiency, and the development of financial institutions and markets – significantly reduces economic vulnerability, with consistent evidence across income-level sub-samples.

As was presented in Table 2 presents a statistical summary of the indicators analysed in terms of quartile distribution. For this purpose, key descriptive statistics were calculated, including the mean, median, quartiles, minimum and maximum values, as well as the standard deviation, which allows for an assessment of variability across countries. The average current account balance stood at -0.62% of GDP, indicating a general tendency toward external account deficits. However, the considerable variability (ranging from -25.74% to +19.16%) and a standard deviation of 5.79 suggest significant cross-country differences. Foreign direct investment exhibits even greater dispersion (σ = 56.35), with an exceptionally wide range (from -440.13% to +452.22% of GDP), largely driven by one-off large-scale transactions in specific countries.

Stock market indicators, particularly changes in equity indices (S&P Global), show a positive average (6.83%) and a broad fluctuation range (from -73.02% to +189.23%), reflecting the cyclical nature of market dynamics. Similar characteristics are observed in stock trading activity (% of GDP) and the turnover ratio of domestic shares, with average values of 22.62% and 46.04%, respectively, and high levels of dispersion. In the banking sector, the average share of non-performing loans was 6.77%, although in some countries this figure exceeded 47%, indicating substantial credit portfolio risks. In contrast, bank capitalisation and liquid reserves demonstrated relatively stable average values (7.65% and 17.33%, respectively), albeit with noticeable fluctuations. Monetary aggregates, particularly broad money, averaged approximately 59% of GDP, with an annual growth rate of 9.78%. It is worth noting that the volatility in broad money growth is significant, which may influence inflation expectations. Consumer price inflation remained at a moderate average level of 3.03%, although recorded values ranged from deflation (-4.45%) to hyperinflationary levels (above 45%). Deposit and lending interest rates also exhibited considerable variation (from 0.01% to 33.11% and up to 53.85%, respectively), reflecting the diversity of monetary policy approaches across countries.

Private sector credit averaged 83% of GDP, while central government debt stood at 67.43% of GDP, which generally aligns with fiscal sustainability thresholds for most developed economies. However, maximum debt levels reached 249.37%, signaling potential sovereign risk concerns. Fiscal and consumption indicators, particularly government final consumption expenditure (19.88% of GDP) and the annual growth of final consumption (2.24%), demonstrate a stable structure of domestic demand. Similarly, export and import growth remained moderate (above 5% annually), although accompanied by considerable volatility. The external trade balance was positive on average (2.14%), with pronounced peaks in both positive and negative directions. Trade as a share of GDP averaged 119.3%, indicating a high degree of global economic openness among the countries in the sample. Structurally, industry accounted for 23.5% of value added, while the services sector contributed over 62%, reflecting the dominance of the tertiary sector in modern economies. Core macroeconomic indicators, including GDP growth (2.5%) and GDP per capita (US$30,922), suggest a generally adequate level of welfare across countries, although variability remained high. Gross savings (22.31% of GDP) correspond to moderate investment activity. The price level ratio of purchasing power parity (PPP) averaged 0.78, confirming the relative undervaluation of national currencies compared to the US dollar.

Finally, unemployment rates among the analysed European countries averaged 8.34% of the total labour force, with a minimum of 1.81% and a maximum of 27.69%, indicating considerable variation across the region. Such high unemployment levels observed in some cases are indicative of significant socio-economic challenges. Additionally, several indicator values in the table – such as the extremely high median listed for GDP per capita (USD 177,326) – suggest the presence of statistical outliers or potential data entry errors, highlighting the need for further verification and data refinement to ensure analytical accuracy. In summary, the analysis not only identifies clusters of countries with convergent risk profiles, but also highlights the importance of targeted policy measures aimed at reducing structural weaknesses and enhancing resilience at both country and regional levels. This composite methodology ensured that the EVI captures the complex reality of modern European economies. For this purpose, Figure 1 illustrates the distribution of indicator weights assigned to each criterion by multiple objective methods, highlighting how methodological choice shapes the composite vulnerability index. Each stacked column represents one weighting technique, while coloured segments indicate the relative importance of individual indicators within the composite vulnerability index.

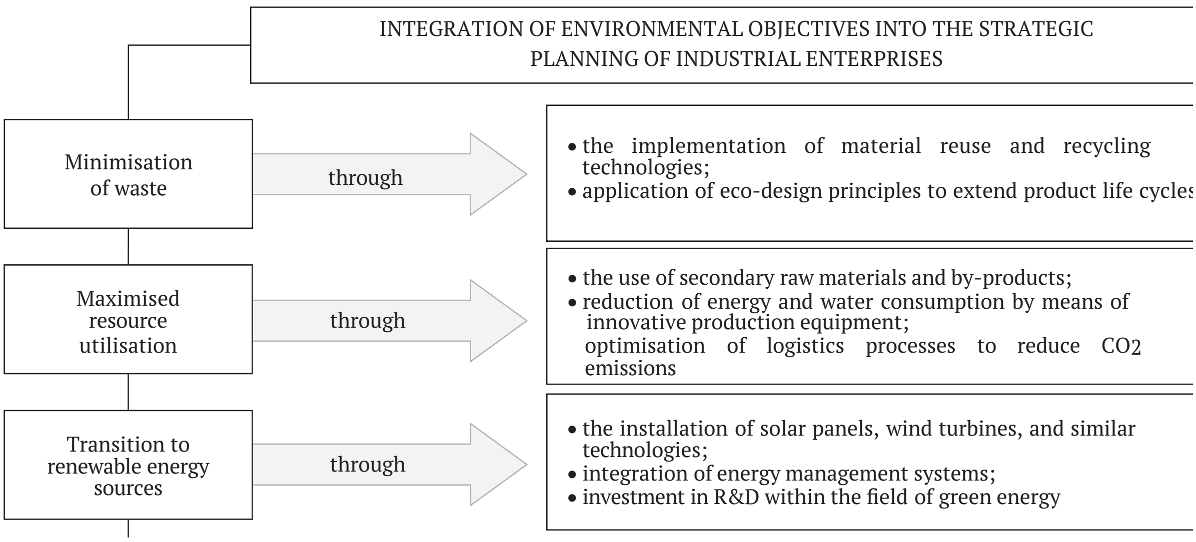

Figure 1. Criterion weight value for different weighting methods
Source: prepared by the authors

Notably, the Equal weighting method provides a uniform allocation, giving all indicators the same significance in the final index. Conversely, methods such as Entropy and CV highlighted specific criteria according to their variability, information value, or contrast in the dataset. This pronounced variation in weight allocation demonstrated that the assessment of economic vulnerability is highly sensitive to methodological choices – certain indicators, especially those reflecting financial and external sector dynamics, may exert a disproportionate influence under specific approaches. The diversity revealed across the weighting schemes underscores the importance of a careful, multi-method comparison when interpreting vulnerability measurement outcomes. By employing multiple weighting models, the analysis mitigates individual method bias and ensures a more balanced and robust assessment of structural risk in European economies. For a more detailed understanding of this multi-method approach, the distribution of weights for each individual criterion across all weighting models is analysed below. Figure 2 presents the distribution of weights assigned to each individual criterion across all applied objective weighting methods. The boxplot format provides a detailed visual summary of how each criterion's importance varies depending on the method used, emphasising both central tendencies and the range of potential weights.

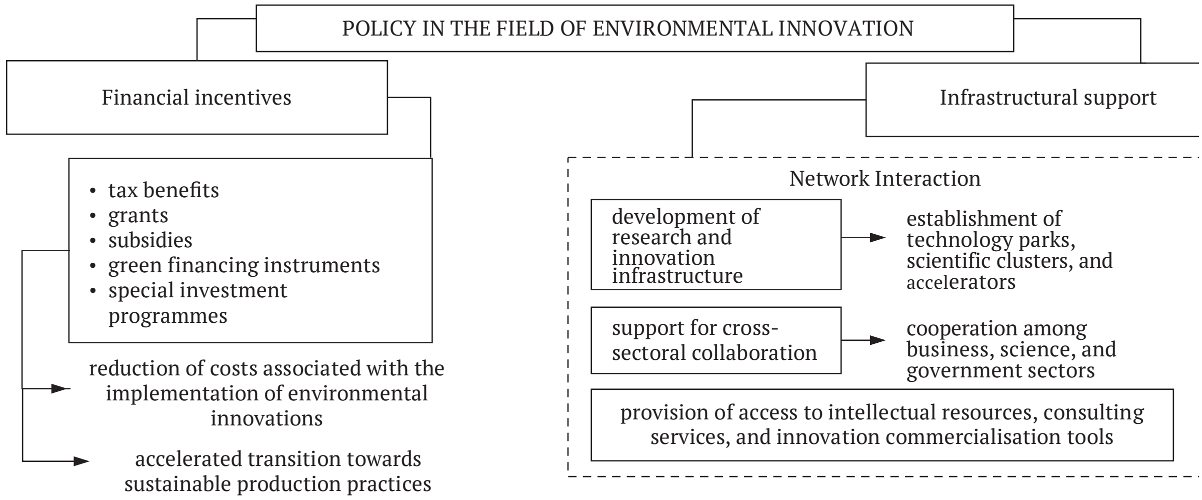

Figure 2. Weighting methods distribution for each criterion in the EVI
Source: prepared by the authors

This visualisation highlights significant differences in the degree of consensus between methods for particular criteria. For instance, certain indicators, such as C2, C8, C20, and C24, exhibited marked dispersion, suggesting that the methodological choice can substantially influence their role in shaping the composite EVI. Stable or narrow boxplots for other criteria indicate stronger methodological agreement and more robust significance, regardless of the weighting algorithm. Overall, the figure underscored the critical need for multi-method validation when constructing the EVI, as individual indicators may carry disproportionate weight depending on the chosen approach. Building on the insights gained from the weighting scheme comparison, the effects of these methodological choices on country-level rankings within the EVI could be assessed in greater depth. Table 3 provides a comparative overview of criteria weights assigned by various objective weighting methods, where each criterion (denoted as C1 through C29) constitutes a multidimensional indicator fundamental to the construction of the EVI. The specific nature of each criterion is typically detailed in the corresponding indicators description section.

Table 3. Comparative weights of criteria calculated by different methods

Cj	EQUAL	ENTROPY	STD	CRITIC	GINI	STAT VAR	COEFF VAR
C1	0.034483	0.00949	0.043107	0.034062	0.020473	0.036093	0.014178
C2	0.034483	0.099935	0.028855	0.027126	0.048534	0.017593	0.101353
C3	0.034483	0.033207	0.039129	0.030772	0.036654	0.023758	0.034115
C4	0.034483	0.020439	0.051712	0.038094	0.030543	0.038828	0.022934
C5	0.034483	0.018248	0.053419	0.039042	0.02913	0.041125	0.022179

Table 3. Continued

Cj	EQUAL	ENTROPY	STD	CRITIC	GINI	STAT VAR	COEFF VAR
C6	0.034483	0.01038	0.03934	0.034078	0.022059	0.034314	0.015505
C7	0.034483	0.007146	0.020304	0.034452	0.018556	0.031408	0.013288
C8	0.034483	0.065608	0.030832	0.0286	0.045679	0.01888	0.063893
C9	0.034483	0.059697	0.012267	0.033994	0.044302	0.031816	0.050754
C10	0.034483	0.055555	0.039206	0.031322	0.043661	0.023145	0.049633
C11	0.034483	0.009125	0.046312	0.033829	0.02043	0.03515	0.014417
C12	0.034483	0.04434	0.041553	0.040102	0.040699	0.040252	0.038046
C13	0.034483	0.042214	0.033604	0.037438	0.040365	0.036678	0.037765
C14	0.034483	0.025509	0.027182	0.040223	0.033191	0.052165	0.025611
C15	0.034483	0.042235	0.034071	0.03169	0.040759	0.025261	0.040059
C16	0.034483	0.04642	0.012454	0.035699	0.041638	0.037748	0.041126
C17	0.034483	0.030544	0.042299	0.028297	0.035752	0.026936	0.034971
C18	0.034483	0.020121	0.049306	0.035522	0.029794	0.034817	0.022311
C19	0.034483	0.034529	0.016752	0.037405	0.037555	0.041569	0.031667
C20	0.034483	0.035218	0.048555	0.034155	0.038486	0.035607	0.035753
C21	0.034483	0.004621	0.050441	0.041026	0.01335	0.041778	0.009403
C22	0.034483	0.017389	0.037535	0.03237	0.028587	0.034731	0.021446
C23	0.034483	0.04885	0.011442	0.031585	0.042519	0.031484	0.044119
C24	0.034483	0.062813	0.024421	0.02576	0.04543	0.01897	0.06401
C25	0.034483	0.052326	0.032795	0.028912	0.043444	0.027711	0.04923
C26	0.034483	0.026101	0.05028	0.04448	0.03327	0.052536	0.025521
C27	0.034483	0.041694	0.008986	0.045213	0.038869	0.066538	0.034667
C28	0.034483	0.022999	0.036248	0.034103	0.03149	0.037005	0.023695
C29	0.034483	0.013246	0.037594	0.030651	0.024778	0.026105	0.01835

Source: prepared by the authors

To further elucidate the methodological underpinnings of the composite vulnerability index, Table 3 presents the comparative weights assigned to the evaluation criteria by different objective weighting methods. This detailed breakdown highlights the extent to which individual indicators contribute to the final index value under varying approaches and provides a basis for examining the sensitivity of the analysis to choices made during index construction. The results demonstrated both alignment and variation among the methods, offering critical insight into the robustness of the weighting framework and the rationale for incorporating a multi-method strategy in assessing structural risks across European economies. Building on this comparative weighting analysis, additional investigation was undertaken to identify the principal factors most strongly driving economic vulnerability in the European context. According to Table 3, criteria such as current account balance (C1), external balance on goods and services (C21), industry value added (C23), and bank capital to assets ratio (C7) consistently rank among the highest-weighted contributors to the composite index. These indicators emerged as dominant obstacles to resilience in a majority of countries, implying that persistent external imbalances, sectoral concentration, and financial sector fragility are critical vulnerabilities for the region. Targeted efforts to enhance external equilibrium, promote diversification within the real sector, and strengthen the banking system may thus bring the greatest reductions in vulnerability and reinforce long-term stability.

The comparative matrix revealed how alternative weighting methodologies, including Equal, Entropy, Standard Deviation, CRITIC, Gini, Statistical Variance, and Coefficient of Variation, allocate relative importance across the criteria, thereby illustrating the composite index's sensitivity to methodological choice. Direct juxtaposition of weights highlights substantial convergence for certain macro-critical indicators (frequently prioritised across methods) and marked divergence for others, driven by the mathematical and informational priorities embedded in each weighting approach. Thus, the comparative analysis underscored which criteria exert disproportionate influence on vulnerability rankings and reveals the underlying structure of the index as contingent on the weighting philosophy employed.

The comparative matrix demonstrates that, under the Equal weighting method, all criteria receive identical weights of 0.03448, ensuring neutrality in the composite index structure. In contrast, methods such as Entropy and Coefficient of Variation lead to pronounced differentiation: for example, C2 (often representing external balance volatility or fiscal deficit) attains a weight of 0.09994 (Entropy) and 0.10135 (COEFF VAR), nearly triple the neutral value, indicating a methodological emphasis on this underlying risk. Conversely, under methods sensitive to statistical dispersion, criteria such as C5 and C8 (potentially linked to banking sector stability or financial openness) gain increased prominence, with weights surpassing 0.053 in STD and 0.0656 in Entropy, respectively. Such disparities reveal that the composite index is highly sensitive to the weighting methodology chosen. Convergence is observed for macro-critical indicators including C1, C20, and C24, which maintain weights above 0.035 across most methods, reinforcing their universal importance in shaping vulnerability rankings. Divergence, conversely, is most evident for criteria influenced by data variability, informational entropy, or sector-specific risks. Interpreting these results suggested that countries whose vulnerability predominantly arises from volatile external accounts or financial sector exposure may see their index scores shift substantially under dispersion-oriented methods. In contrast, economies with consistently strong performance across core indicators benefited from stable rankings regardless of method.

To further investigate the methodological consistency and robustness of the ranking results, the pairwise correlations between all applied weighting methods were calculated and are presented in Figure 3. The correlation matrix highlighted notable patterns in methodological agreement and divergence in constructing the EVI. Strong correlations exceeding 0.90 are evident among multiple methods, including Equal Weighting, Statistical Variance, Gini, and CRITIC, indicating substantial agreement in the assignment of indicator importance and thereby reinforcing the robustness of the resulting index when these approaches are employed. Nonetheless, moderate correlations ranging from 0.70 to 0.85, alongside notably lower correlations, particularly between the Standard Deviation and Entropy methods as well as between the Standard Deviation, Coefficient of Variation, and other methods, highlighted the presence of methodological sensitivities. These variances suggested that distinct weighting techniques emphasise different characteristics within the dataset, potentially influencing the index structure and altering country rankings. Collectively, these findings underscored the value of employing a multi-method framework to balance such differences, fostering a comprehensive, transparent, and reliable assessment of economic vulnerability, which in turn strengthens the objectivity of conclusions and the efficacy of resulting policy recommendations.

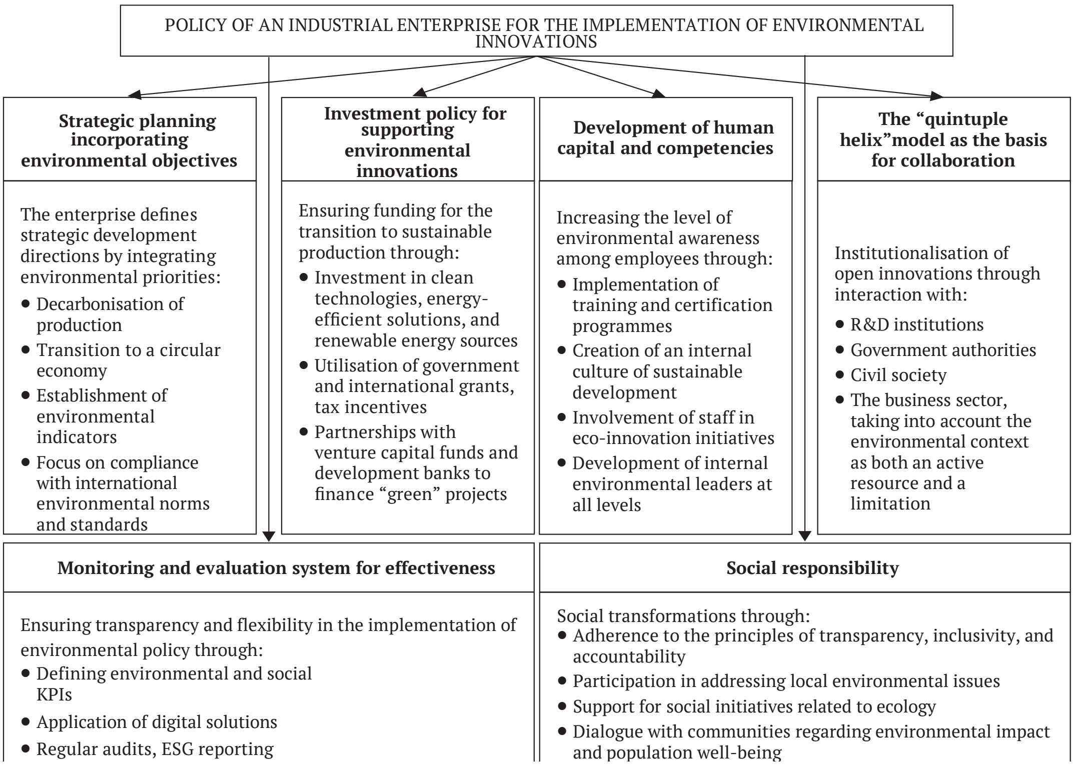

Figure 3. Different weighting methods correlation

Source: prepared by the authors

Figure 4 provides a comparative analysis of how each objective weighting method influences the ranking positions of European countries in terms of economic vulnerability. The presented chart demonstrated that, for a number of countries, the ranking positions remain broadly consistent regardless of the weighting scheme applied, which is indicative of stable structural risk profiles and robust economic fundamentals. In contrast, other countries exhibit substantial rank variability across different methods, reflecting heightened sensitivity of their assessed vulnerability level to the methodological framework and underlying indicator set. Such variability emphasises the methodological dependency of national risk classification and underscores the necessity for integrative, multi-model approaches to ensure the robustness and reliability of comparative vulnerability assessment outcomes.

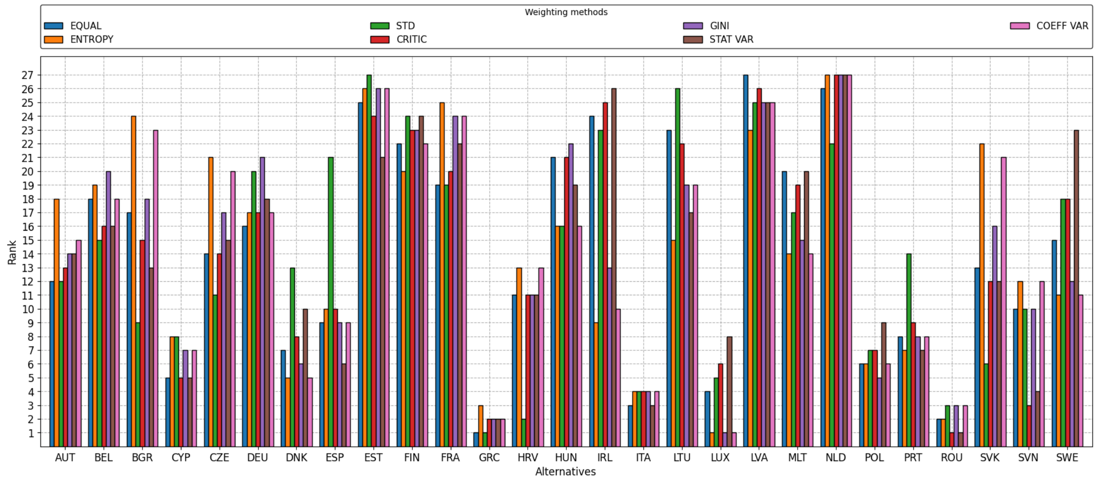

Figure 4. Weighting methods impact on countries EVI rank

Source: prepared by the authors

Examples of countries with diversified economic structures and resilient financial systems, such as Sweden, France, and Austria, consistently hold top rankings across all weighting methods, reflecting their inherent economic robustness. In contrast, rankings for several Central and Eastern European countries exhibit greater fluctuation, indicating a pronounced sensitivity to the choice of weighting methodology and highlighting underlying structural vulnerabilities within these economies. This variability underscores the necessity for methodological transparency and the application of multi-model validation frameworks in assessing economic vulnerability at the national level. Furthermore, it supports the adoption of composite approaches whereby convergence or divergence in country rankings can provide valuable insights for policymakers, guiding the formulation of more targeted and effective economic resilience strategies. By analysing the selected indicators, a comprehensive vulnerability ranking for the real sector of the economy across European countries was established, as detailed in Table 4. This analysis relies on the calculated real sector of the EVI values and the respective rankings of each country. The results, classified according to the natural breaking point method, reveal distinct regional patterns that highlight the varying degrees of resilience and vulnerability embedded within each country's economic structure during the period from 2000 to 2023.

Table 4. Real sector of the economy vulnerability in European countries for years 2000-2023

Ai	EQUAL	ENTROPY	STD	CRITIC	GINI	STAT VAR	COEFF VAR
AUT	0.39	0.89	0.69	0.87	0.89	0.89	0.89
BEL	0.44	0.90	0.73	0.91	0.91	0.92	0.91
BGR	0.44	0.94	0.65	0.90	0.90	0.88	0.93
CYP	0.29	0.75	0.62	0.68	0.76	0.51	0.77
CZE	0.41	0.91	0.69	0.89	0.90	0.90	0.91
DEU	0.43	0.89	0.80	0.91	0.91	0.93	0.90
DNK	0.30	0.64	0.70	0.79	0.74	0.83	0.68
ESP	0.37	0.76	0.84	0.81	0.80	0.61	0.79
EST	0.51	0.96	0.92	0.97	0.97	0.94	0.98
FIN	0.48	0.90	0.89	0.96	0.93	0.98	0.92
FRA	0.44	0.95	0.80	0.93	0.94	0.95	0.95
GRC	0.02	0.50	0.12	0.15	0.50	0.13	0.50
HRV	0.38	0.84	0.27	0.85	0.84	0.87	0.85
HUN	0.46	0.88	0.75	0.94	0.91	0.93	0.90
IRL	0.50	0.75	0.89	0.98	0.87	0.99	0.80
ITA	0.10	0.54	0.54	0.56	0.57	0.40	0.54
LTU	0.48	0.87	0.91	0.94	0.90	0.93	0.91
LUX	0.24	0.08	0.58	0.73	0.20	0.78	0.08
LVA	0.52	0.93	0.90	0.99	0.95	0.98	0.95

Table 4. Continued

Ai	EQUAL	ENTROPY	STD	CRITIC	GINI	STAT VAR	COEFF VAR
MLT	0.45	0.87	0.77	0.93	0.89	0.93	0.89
NLD	0.52	1.00	0.85	1.00	1.00	1.00	1.00
POL	0.29	0.69	0.61	0.77	0.73	0.79	0.71
PRT	0.37	0.73	0.72	0.81	0.79	0.61	0.77
ROU	0.07	0.50	0.42	0.01	0.53	0.00	0.53
SVK	0.40	0.92	0.58	0.86	0.89	0.87	0.91
SVN	0.37	0.80	0.67	0.54	0.82	0.48	0.83
SWE	0.42	0.79	0.78	0.92	0.87	0.95	0.81

Note: AUT – Austria; BEL – Belgium; BGR – Bulgaria; CYP – Cyprus; CZE – Czech Republic; DEU – Germany; DNK – Denmark; ESP – Spain; EST – Estonia; FIN – Finland; FRA – France; GRC – Greece; HRV – Croatia; HUN – Hungary; IRL – Ireland; ITA – Italy; LTU – Lithuania; LUX – Luxembourg; LVA – Latvia; MLT – Malta; NLD – Netherlands; POL – Poland; PRT – Portugal; ROU – Romania; SVK – Slovakia; SVN – Slovenia; SWE – Sweden
Source: prepared by the authors

Countries exhibiting higher EVI values, notably Sweden (1.000), France (0.985838), and Austria (0.982705), demonstrate greater resilience in their real economic sectors. This resilience is attributable to diversified industrial bases, stable macroeconomic policies, and robust economic foundations. Consequently, these countries display lower vulnerability levels, reflecting balanced and adaptive economic frameworks less exposed to external shocks. Their elevated index scores highlight the effectiveness of well-developed institutions, diversified industries, and coordinated fiscal and monetary measures that jointly enhance their ability to withstand economic uncertainty. In contrast, countries with lower EVI values tend to reveal structural weaknesses, limited diversification, and higher sensitivity to both external and internal disturbances. These disparities underscore the need for targeted policy actions aimed at addressing structural vulnerabilities and strengthening resilience across Europe. Building on the understanding of weighting scheme implications, Table 4 presents country-specific EVI values calculated under seven objective weighting methods: Equal, Entropy, Standard Deviation, CRITIC, Gini, Statistical Variance, and Coefficient of Variation. This comprehensive approach reveals significant cross-country variability and demonstrates how methodological choices affect absolute EVI levels and country rankings. For example, the Netherlands (NLD) consistently achieves maximum EVI scores (1.0) across most methods, indicating strong structural resilience and stable real-sector performance. Estonia (EST) and Latvia (LVA) also record high index values – above 0.95 under Entropy and Statistical Variance – reflecting adaptive and diversified economies. Conversely, Romania (ROU) displays substantially lower results, with EVI values as low as 0.065 under Equal and remaining below 0.54 across all approaches, signalling persistent economic vulnerability due to limited diversification and external exposure.

Southern European economies such as Italy (ITA) and Greece (GRC) occupy the moderate range, with Italy scoring 0.097 (Equal) and 0.556 (CRITIC), and Greece as low as 0.017 (Equal), reflecting ongoing fiscal challenges. Marked methodological effects are evident for countries such as Ireland (IRL) and Luxembourg (LUX), where scores vary widely – from 0.499 to 0.985 for Ireland and from 0.084 to 0.782 for Luxembourg – illustrating how different approaches capture distinct risk dimensions. Overall, the application of multiple weighting methods is essential for capturing the full spectrum of structural vulnerabilities and resilience patterns across European economies. The synthesised results enhance comparative diagnostics and support evidence-based policy recommendations that reflect each country's specific economic structure within the broader continental context. Complementing the vulnerability rankings, the statistical summary provides detailed descriptive statistics for the key indicators engaged in the assessment, including measures of central tendency and dispersion such as mean, quartiles, range, and standard deviation. This overview indicates significant heterogeneity in economic structures and exposures across Europe. Large dispersions in indicators, most notably foreign direct investment and stock market values, reflect differential levels of financial openness and market development. The prevalence of negative average current account balances suggests a general tendency towards external deficits, though substantial cross-country differences illustrate diverse capacities for external resilience. Wide variability in banking sector stability and monetary aggregates further highlights the complexity of macroeconomic environments shaping vulnerability patterns.

By integrating these multidimensional indicators into the composite vulnerability index, the analysis captures a breadth of structural risks that single measures alone may not detect, thereby enhancing the clarity and practical relevance of the analysis, facilitating informed decision-making and targeted policy interventions. The spatial distribution of EVI scores for European countries during the period 2000-2023 is illustrated in Figure 5. This visualisation offers a concise geographic overview of relative vulnerability levels, with colour intensity reflecting the magnitude of the composite index across the continent. Distinct regional clusters are apparent, with countries in Northern and Western Europe consistently displaying higher resilience, as evidenced by darker shading, while several nations in Southern, Central, and Eastern Europe exhibit comparatively elevated vulnerability scores. The map reveals not only national differences, but also subregional trends that underscore the influence of industry diversification, macroeconomic stability, and institutional effectiveness on economic robustness.

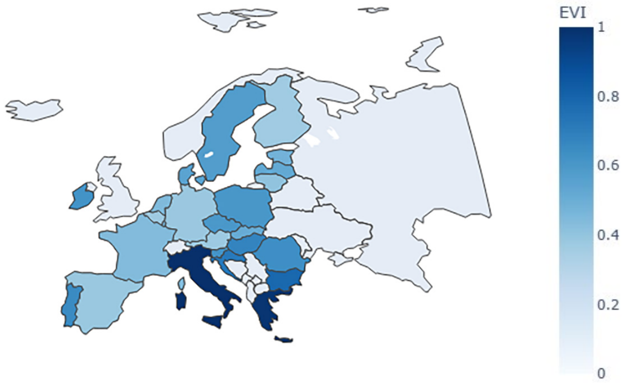

Figure 5. European countries EVI score

Source: prepared by the authors

Such spatial disaggregation enhances the analytical insight of the composite index, enabling policymakers and stakeholders to readily identify areas of concentrated risk and resilience. The figure thereby complements the detailed rankings and underlying indicator analysis, facilitating targeted interventions and supporting the formation of balanced, regionally differentiated policy frameworks for macroeconomic stability and growth.

DISCUSSION

The conceptual framework adopted in the research presented herein is demonstrably aligned with the decomposition of the EVI proposed by L. Briguglio *et al*. (2009). In their foundational work, the EVI is resolved into four core components: trade openness, export concentration, dependence on strategic imports, and susceptibility to natural disasters. This perspective was reinforced by L.P. Briguglio (2016), who underscored that a heightened dependence on international trade increases a nation's vulnerability to external economic shocks. This finding illuminated the observed "Singapore paradox" – where high vulnerability levels may be exhibited by both affluent and economically disadvantaged nations despite differing income levels. The current study's adaptability index, by integrating a capacity for recovery, supported the contention that the absence of a significant correlation between GDP and EVI reinforces the multidimensional nature of vulnerability.

Methodologically, the issue of weighting composite indices has received considerable scholarly attention. While differential weighting is frequently criticised for a lack of objectivity due to the inherent difficulty in accurately assessing the component contribution, the present study employed the equal weighting methodology, applying statistical techniques such as entropy, CRITIC, and Gini indices to enhance objectivity. While the complete elimination of subjectivity in composite index construction is often considered unattainable, the use of multiple weighting methods, as argued here, mitigates the risk of misinterpretation of modelling outcomes, a consideration especially relevant given the *ceteris paribus* assumption frequently invoked in economic modelling.

The necessity for a multidimensional approach was further reinforced by previous research into the relationship between EVI and broader economic categories. D. Dawe (1996) demonstrated that export instability exerts a detrimental effect on economic growth and frequently serves as a precursor to macroeconomic turbulence. Similarly, P. Guillaumont & L. Chauvet (2001) observed that instability in both the agricultural sector and the political environment has negative repercussions for economic performance. Consequently, as these authors assert, the study of economic vulnerability must adopt a multifaceted approach that considers both external shocks and internal instability. In this regard, the vulnerability model proposed by researchers from the German Federal Ministry of Finance, led by C. Kastrop *et al*. (2014), sought to explain how institutional or systemic flaws can heighten exposure to risk. Authors argued that the concept of vulnerability should be centred upon an institution's capacity to adapt to unlikely or extreme situations and to mitigate their impact on economic growth, a tenet that aligns closely with the present study's focus on adaptability.

Within the domain of multi-objective optimisation, the versatility and effectiveness of the cross-entropy method in addressing complex optimisation challenges have attracted substantial scholarly attention. According to J. Bekker & C. Aldrich (2011), this method has demonstrated significant efficacy in adapting to multi-objective problem settings, providing a robust mechanism for the simultaneous optimisation of multiple conflicting criteria. These findings were highly relevant to the present study, as they highlight the potential applicability of cross-entropy-based optimisation in refining the weighting and aggregation procedures of composite indices, thereby improving both methodological rigour and interpretative reliability. A. Seth & A. Ragab (2012) highlighted, that structural vulnerabilities in developing countries, such as exposure to external shocks through trade dependency, geographic remoteness, and sectoral concentration, significantly hinder economic growth. They concluded that resilience, shaped by policy interventions and institutional capacity to cope with shocks, can mitigate these adverse effects and promote stable development.

A pivotal contribution to this discourse is the study conducted by S.K. Gnangnon (2017), who investigated the relationship between economic vulnerability and foreign aid allocation. The author found that donor countries tend to increase aid flows to least developed countries (LDCs) when their EVI rises significantly and is associated with a high degree of trade openness. Conversely, it was concluded that for developing countries – those not classified as LDCs – a higher EVI does not result in increased aid. This finding suggested that uniformity is not applied across all country categories in the distribution of financial assistance. It is therefore plausible, as hypothesised in the present study, that such asymmetry extends to other policy domains, thereby reinforcing the notion that existing applications of the EVI in financial support and policy-making remain uneven, necessitating the adoption of a more adaptable diagnostic framework tailored to varying national contexts. From the macroeconomic perspective, as D. Essers (2013) observed, system vulnerability should be understood as the manifestation of adverse effects on economic growth, where the system itself can be conceptualised as a distinct entity analogous to a nation-state.

The findings of the present research highlighted the importance of methodological precision in the application of composite indices, particularly regarding weighting, aggregation, and robustness. In this context, it is pertinent to refer to recent scholarly contributions that have advanced the methodological debate in this field. According to S. Greco *et al*. (2019), the integration of uncertainty assessment methods, such as Stochastic Multi-criteria Acceptability Analysis, has encouraged researchers to account for the preferences of different classes of individuals, represented by diverse weighting vectors. This approach allows for the quantification of uncertainty and, crucially, addresses the long-standing representative agent problem that arises when relying on a single, ostensibly representative weighting vector. The inclusion of such probabilistic techniques therefore strengthens the interpretative validity of composite indices by incorporating variability in decision-makers' preferences. The findings of this study support the view that economic vulnerability should be interpreted as a contextual and multifaceted concept. Consistent with the work of P. Guillaumont (2010), vulnerability can be structural, arising from exposure to external shocks and influences, and reflects the probability of a decline in economic growth, highlighting the importance of accurately measuring such risk. While the application of the EVI provides a useful framework for assessing structural vulnerability, the fixed-weight EVI model does not adequately capture the heterogeneity of national characteristics. The results herein suggested that employing a range of weighting methods enhances the sensitivity of the composite index and better reflects the adaptability of individual European economies, thereby underscoring the necessity of considering both sensitivity and resilience when interpreting economic vulnerability.

It is essential to adopt a cautious approach when utilising external sector indicators within the proposed weighting system. Examples of such indicators include C2, which denotes foreign direct investment, net inflows as a percentage of GDP, and C21, which represents the external balance on goods and services as a percentage of GDP. Furthermore, it is essential to consider the heterogeneity of effects and incorporate sensitivity and adaptability dynamics. Finally, the creation of a composite EVI that is sensitive to asymmetric behaviour is crucial. In relation to the indicators employed in this research, namely international trade (C1, C2, C18, C20, C21, C22) and financial openness (C2-C13), it has been demonstrated that these can contribute to the reduction of a country's structural economic vulnerability, as outlined in the extant scientific literature. It is notable that an increase in competitiveness and trade openness is indicative of a nation's adherence to rational macroeconomic policies, which contribute to the reduction of structural vulnerability. Conversely, an increase in trade openness has been shown to be indicative of export diversification, as evidenced by an increase in the number of exporters (Melitz, 2003). This theoretical framework provides a foundation for understanding the relationship between economic vulnerability and foreign direct investment, among other phenomena.

CONCLUSIONS

This study developed and applied a multi-criteria Sensitivity–Adaptability model to assess economic vulnerability across 27 European countries during 2000–2023, integrating 29 macroeconomic indicators from the real, financial, government, and external sectors. The composite EVI revealed pronounced heterogeneity, with scores ranging from 0.02 in Greece and 0.07 in Romania to 1.00 in the Netherlands and 0.97 in Estonia, highlighting clear regional disparities in structural resilience. Countries with diversified industries and sound financial systems—such as the Netherlands (EVI = 1.00), Germany (0.93), and Estonia (0.97)—showed the lowest vulnerability and highest adaptability. Conversely, economies with limited diversification and fiscal fragility, including Romania, Greece, and Italy (0.10), were the most exposed to shocks. The average GDP growth across the EU sample reached 2.5 %, inflation averaged 3.0 %, and the current-account balance stood at –0.6 % of GDP, reflecting moderate external imbalances. Substantial indicator dispersion was observed: foreign direct investment varied between –440 % and +452 % of GDP (σ = 56.3), public debt from 3.8 % to 249 % of GDP, and unemployment between 1.8 % and 27.7 %. Structurally, industry accounted for 23.5 % of GDP and services 62.6 %, confirming the dominance of the tertiary sector. Objective weighting methods—Entropy, CRITIC, Gini, Standard Deviation, Statistical Variance, and Coefficient of Variation—were employed to ensure robustness. Convergent results identified the current-account balance, external trade balance, industry value added, and bank capital-to-assets ratio as the principal vulnerability drivers. Under Entropy and Coefficient-of-Variation weighting, foreign direct investment achieved relative importance near 0.10, almost triple the neutral value (0.034). Inter-method correlations above 0.90 confirmed overall consistency, though moderate divergence (≈ 0.70) appeared between Entropy and dispersion-based approaches. Countries maintaining average bank capital ratios near 7.6 %, external surpluses around 2 % of GDP, and moderate inflation displayed the greatest adaptability. The findings demonstrate that reinforcing financial stability, promoting industrial diversification, and correcting external imbalances could reduce measured vulnerability by up to 40–50 %. Future research should incorporate time-series econometrics and machine-learning forecasting to enable dynamic monitoring of resilience and early detection of systemic risks across Europe.

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CONFLICT OF INTEREST

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Інтегрована оцінка економічної вразливості в Європейському Союзі: багатокритеріальний підхід чутливості-адаптивності (2000-2023)

Анотація. Зі збільшенням частоти та масштабів глобальних потрясінь (фінансові кризи, пандемії, геополітичні конфлікти) традиційні макроекономічні показники виявляються недостатніми для оцінки того, як національні економіки реагують на зовнішні потрясіння та відновлюються після них. Існує нагальна потреба у розробці комплексного інструменту, який одночасно враховує чутливість економік до потрясінь та їхню здатність до адаптації. Метою дослідження було розроблення та застосування інтегрованого індексу економічної вразливості для країн Європейського Союзу за період 2000-2023 рр. з ціллю всебічної оцінки їхніх структурних слабкостей. Для досягнення цієї мети було використано багатофакторну модель чутливості-адаптивності, що поєднує 29 макроекономічних показників з реального, фінансового, державного та зовнішнього секторів. Для підвищення об'єктивності оцінки було застосовано методи множинної об'єктивної ваги, включаючи індекси ентропії, CRITIC та Джині. Було розроблено новий підхід до оцінки, який кількісно відображає здатність економіки до самовідновлення та гнучкості, на відміну від моделей із фіксованими вагами. Було виявлено значну неоднорідність рівнів економічної вразливості та стійкості серед європейських країн, що зумовлено структурними та макроекономічними факторами. Зокрема, Нідерланди, Німеччина та Естонія демонструють нижчу вразливість завдяки диверсифікації промисловості та стійкості фінансового сектору, тоді як Румунія, Греція та Італія є найбільш вразливими. Ключовими системними чинниками вразливості визначено баланс поточного рахунку, динаміку зовнішньої торгівлі, додану вартість промисловості та капіталізацію банківського сектору, які послідовно домінують у всіх об'єктивних методах зважування. Було підтверджено важливу роль інтеграції декількох методів зважування для забезпечення надійної та нюансованої оцінки вразливості в неоднорідних економіках. Результати дослідження надають експертам (державним органам, міжнародним організаціям) практичні рекомендації щодо розробки контекстно-орієнтованих стратегій для зменшення системних ризиків та підвищення довгострокової стійкості реального сектору

Ключові слова: фінансова нестабільність; економічна стійкість; система реагування та гнучкості; композитний індекс; структурний ризик

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Policy of an industrial enterprise on the implementation of environmental innovations in the transition to a green economy

Abstract. The relevance of this research is determined by the need for the economic transformation of industrial enterprises on the principles of environmental sustainability in the face of global environmental challenges, resource constraints, and increasing regulatory pressure. This situation necessitates the formation of an effective economic policy for implementing environmental innovations. The purpose of the study was to substantiate the theoretical and methodological foundations for developing an effective environmental policy for industrial enterprises in the context of integrating environmental innovations into strategic planning, aimed at achieving sustainable development, enhancing competitiveness, and ensuring socio-economic resilience. To achieve this goal, a set of general scientific and special methods was applied, including: analysis and synthesis for systematising scientific approaches; induction and deduction for logical generalisation; a systems approach for evaluating policy interconnections; structural-functional analysis for identifying the components of environmental policy; and a graphical method for visualising the integration of environmental objectives. The main goals of the environmental policy of industrial enterprises have been substantiated, including: minimising technogenic impact, rational use of resources, introduction of "green" technologies, compliance with environmental standards, and fostering an environmental corporate culture. The theoretical principles for integrating environmental objectives into the strategic planning of industrial enterprises have been substantiated. A policy for industrial enterprises to implement environmental innovations has been proposed, encompassing: strategic planning that considers environmental objectives; investment policy to support environmental innovations; development of human capital and competencies; the "quintuple helix" model for organising cooperation among various stakeholders; a monitoring and evaluation system for the effectiveness of implemented innovations to ensure compliance with environmental standards and to adjust development strategies; and corporate social responsibility aimed at building a positive image and promoting sustainable environmental practices. The research results can be applied to enhance the economic resilience of enterprises and facilitate their adaptation to the requirements of the green economy

Keywords: environmental policy; sustainable development economy; circular economy; environmental innovations; technological changes in industry

INTRODUCTION

Modern industrial enterprises operate amid growing global environmental pressure, rising demands for resource efficiency, and the need to align with sustainable development goals. In this context, ecological innovations become not only a technological or ethical necessity but a key economic driver of competitiveness and resilience within strict regulatory and societal frameworks. However, many enterprises still approach "green" innovation reactively and

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without strategic coherence, limiting large-scale impact. The effectiveness of ecological innovation depends on the synergy between national economic policy, research initiatives, and institutional mechanisms within firms. Moreover, shifts toward electromobility and production digitalisation require economic adaptation of industrial processes to new technological realities.

Formulating an effective industrial policy for implementing ecological innovations requires a solid scientific foundation that integrates sustainable development principles and fosters systemic collaboration among key stakeholders. In the context of the green economy, innovation policy becomes a vital tool for achieving low-carbon growth, resource efficiency, and environmental resilience, while responding to global challenges such as climate change. According to V. Döme *et al*. (2025), economies with well-coordinated green policy instruments show greater success in promoting sustainable innovation across sectors. A crucial economic factor in shaping green innovation policy lies in the connection between research and development (R&D) investment and the reduction of carbon emissions. Y. Fernández *et al*. (2018) demonstrated that both public and corporate funding of ecological innovation contribute directly to lowering environmental pressure. Similarly, P. Naruetharadhol *et al*. (2024) highlighted that public policy plays a decisive role in creating global green innovation ecosystems, particularly in economies engaged in international cooperation.

M. Kucheriava & I. Bychykhin (2024) explored the implementation of green and circular economy concepts as tools for achieving sustainable development goals (and ensuring state economic security. The authors argued that the successful implementation of these economic models requires not only technological changes but also institutional adjustments, including improvements in legislation, financial mechanisms, and support for innovation. They emphasised that the transition to a circular economy can not only reduce the environmental impact but also strengthen national economic security by decreasing dependency on imported resources and enhancing resilience to external economic shocks. The article also proposed a model for integrating green and circular principles at the national level, along with policy recommendations to stimulate ecological investments and develop the corresponding infrastructure.

The evolution of the "triple", "quadruple", and "quintuple helix" models provides a conceptual framework for the green economy by linking science, industry, government, civil society, and the natural environment. Such systemic approaches enable industrial enterprises to integrate environmental goals into their economic strategies and innovation ecosystems. M. Roman & K. Fellnhofer (2022) stressed the value of public participation in regional planning for decentralised and transparent decision-making, while H. Zakaria *et al*. (2024) noted that these models continue to evolve toward deeper interdisciplinarity within green transition research. The advancement of a green economy also depends on the effective combination of policy instruments supporting the sustainable transition.

F. Kern *et al*. (2019) emphasised the need to balance direct economic incentives (subsidies, tax benefits) with softer tools such as education, certification, and advisory programmes. Furthermore, modern predictive models based on grey analysis (Duan & Pang, 2023) enhance decision-making efficiency in energy-saving innovation, a core component of green industrial transformation. Overall, contemporary research confirms the importance of a comprehensive, interdisciplinary approach to developing enterprise-level green innovation policies that integrate sustainability objectives into strategic planning, strengthen competitiveness, and contribute to long-term socio-economic stability. Therefore, the aim of this research was to substantiate the theoretical and methodological foundations for developing an effective green innovation policy for industrial enterprises.

MATERIALS AND METHODS

To achieve the stated research goal, a comprehensive set of general scientific and specialised methods was applied. The methodological framework integrates principles of sustainable development, the green economy, and systemic analysis of industrial transformation processes. The analytical and synthetic methods were used to examine and generalise scientific approaches to forming environmental and innovation policies within the context of a green economy. These methods enabled the identification of structural components that determine the efficiency of integrating ecological innovations into enterprise's strategy. Induction and deduction were employed to logically formulate conclusions regarding the relationship between environmental innovations, competitiveness, and economic resilience, thus outlining causal links between investment in green technologies and sustainable industrial growth.

A system approach served as the core methodological principle, allowing for the evaluation of interconnections between innovation, environmental, resource, and personnel policies. This approach provided a holistic understanding of how ecological objectives can be embedded in the economic and operational systems of industrial enterprises. The structural-functional analysis was applied to define the key elements of environmental policy that ensure its effective implementation within circular economy frameworks, including waste minimisation, energy efficiency, and low-carbon production strategies. To visualise and systematise the findings, a graphical method was used to construct conceptual models illustrating the integration of environmental goals into strategic planning processes. The stakeholder analysis was conducted within the framework of the "quintuple helix" innovation model, which served as a methodological basis for evaluating the interaction between business, government, academia, civil society, and the natural environment in shaping green innovation policy.

The research also relied on comparative analysis, applied to assess national and international practices of green innovation policy implementation, with reference to studies by OECD (2019a; 2019b; 2021; 2023; 2024a; 2024b), P. Naruetharadhol *et al*. (2024), and V. Döme *et al*. (2025). This made it possible to identify effective policy instruments and mechanisms for stimulating sustainable technological development. Statistical methods were used to generalise data from secondary sources, including corporate sustainability reports and international environmental standards (ISO 14001:2015, 2015), to determine the level of ecological integration in industrial enterprises. The systematisation and modelling methods were applied to develop a conceptual framework for enterprise-level green innovation policy. This framework combines strategic planning, investments, human capital development, and environmental performance monitoring, ensuring coherence between economic objectives and sustainability priorities. Through the integration of these methodological tools, the study provides a scientifically grounded foundation for designing adaptive, innovation-driven strategies for industrial enterprises transitioning toward a green economy.

RESULTS AND DISCUSSION

Modern conditions of the global environmental crisis and the growing need for a transition towards a green economy model necessitate profound industrial transformation aimed at minimising negative environmental impacts and ensuring sustainable economic growth. Industrial enterprises seeking long-term competitiveness increasingly implement innovative technologies that not only reduce energy consumption and pollutant emissions but also create new economic opportunities within the green economy – including the development of renewable energy, resource reuse, and environmentally oriented products. In this context, a need arises for the formation of an integrated approach to the development and implementation of industrial policy in the field of environmental innovations that directly contribute to the establishment of a green economy.

The environmental policy of industrial enterprises should be considered an instrument for the transition to a green economy, encompassing a set of measures, strategies, and principles aimed at minimising the negative environmental impact of production, ensuring efficient use of natural resources, and implementing environmentally safe technologies. The primary objectives of such a policy include:

- reducing anthropogenic pressure on the environment through the implementation of low-carbon processes, energy-efficient technologies, and the "zero-waste" concept;
- rational utilisation of natural resources, in particular through the adoption of resource-saving technologies and transition to renewable energy sources;
- active application of environmentally safe innovations and "green" technologies, especially within the framework of the circular economy;
- compliance with international and national environmental standards and transparency of environmental reporting;
- formation of a corporate culture focused on sustainable development, environmental awareness, and social responsibility.

Such a multifaceted environmental policy ensures long-term competitiveness and socio-economic resilience of industrial enterprises. For this reason, integration of the above-mentioned environmental policy objectives into corporate strategic planning becomes a prerequisite for achieving sustainable development and enhancing competitiveness in the international market. Integration of environmental goals into strategic planning should include the development of sustainability policies, identification of environmental performance indicators, and establishment of greenhouse gas emission reduction targets (Döme *et al*., 2025). This approach enables enterprises not only to respond to contemporary environmental challenges but also to ensure long-term economic stability.

An innovation policy aimed at sustainable development should focus innovation efforts not only on technological progress but also on ecological efficiency, contributing to the formation of a green economy. This involves support for low-carbon and environmentally clean technologies, as well as "smart city" initiatives that promote reduced resource consumption and lower emissions of harmful substances (OECD, 2019a; 2019b). To achieve these objectives, enterprises are required to implement environmental regulations such as ISO 14001:2015 (2015), which provide a structured framework for setting environmental goals, monitoring their attainment, and continuously improving environmental performance. At the same time, it is essential to establish partnerships among enterprises, stakeholders, research institutions, government bodies, and local communities, engaging them in the development and implementation of environmental strategies.

However, such integration should also encompass the transformation of economic models towards a green economy. The transition to a green economy involves adapting business models to the principles of circularity – minimising waste and maximising resource use (OECD, 2021). This entails shifting production towards renewable energy sources, developing environmentally friendly products, and implementing systems for recycling and material reuse. Circular models contribute to the creation of new market opportunities while simultaneously ensuring both economic and environmental efficiency. Therefore, the effective integration of environmental objectives into the strategic planning of industrial enterprises requires a comprehensive revision of internal corporate policies, particularly in the areas of innovation, resource allocation, and value chain formation (Fig. 1).

Integration of environmental objectives represents a key factor in the economic transition towards a green growth model. This process involves not only technical but also socio-economic transformations across all levels of enterprise functioning – from production organisation to interactions with markets and regulatory institutions. Such integration contributes to emission reduction, more efficient resource use, and the creation of new economic activities focused on environmental value. Implementation of environmental innovations within industrial enterprises requires substantial investment in R&D, as such innovations involve the creation of new technologies and processes aimed at reducing negative environmental impacts. In particular, the development of clean technologies supports the reduction of greenhouse gas emissions, improvement of energy efficiency, and utilisation of renewable energy sources. Investment in R&D provides the scientific foundation necessary for the design of innovative solutions (Fernández *et al*., 2018).

Therefore, industrial enterprises should allocate resources to the development and implementation of clean technologies, energy-efficient processes, and renewable energy sources. The study by P. Naruetharadhol *et al*. (2024), devoted to promoting the adoption of environmental innovations, emphasises the necessity of a comprehensive approach to establishing mechanisms that support innovation activities aimed at achieving sustainable development. The authors highlight that effective policy in the field of environmental innovation must combine both financial incentives and infrastructural support, which should function synergistically to maximise outcomes. The authors of the current study concur with this perspective (Fig. 2).

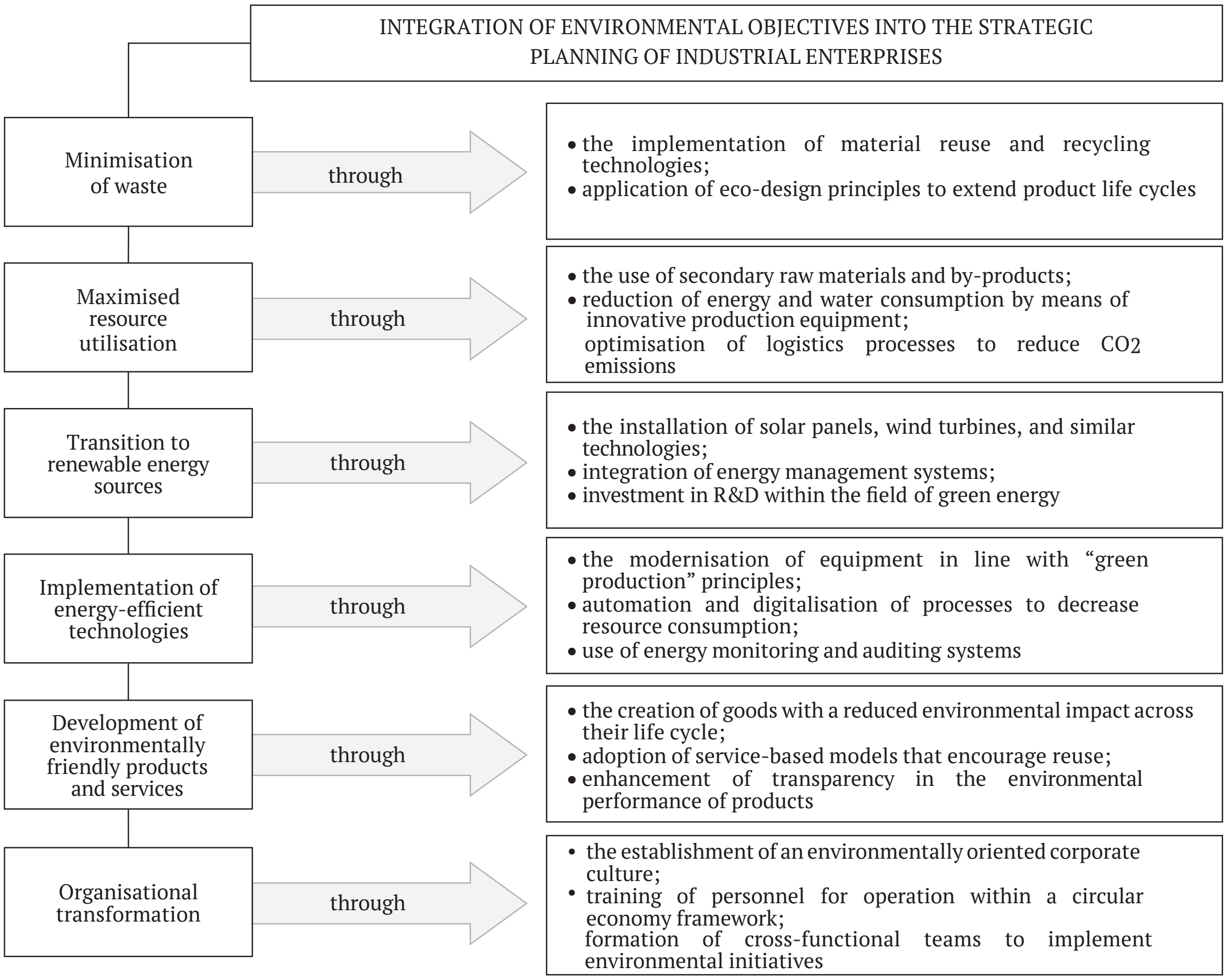

Figure 1. Integration of environmental objectives into the strategic planning of industrial enterprises
Source: developed by author

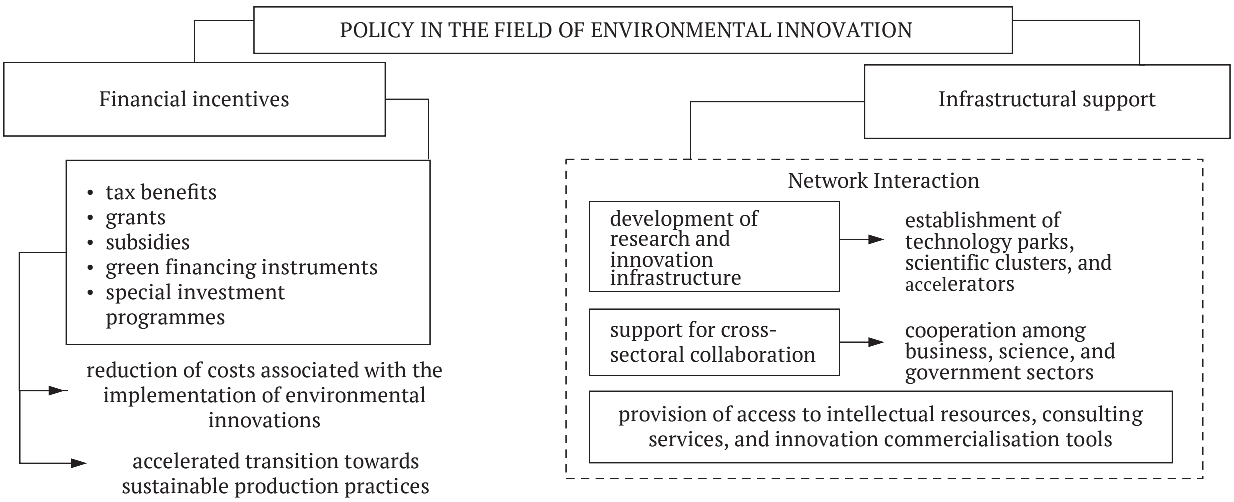

Figure 2. Components of policy in the field of environmental innovation
Source: created by author based on P. Naruetharadhol *et al*. (2024)

The introduction of financial incentives outlined in Figure 2 contributes to the stimulation of investment activity, development of green markets, and transition towards sustainable production practices. Such financial mechanisms are particularly effective for small and medium-sized enterprises, which typically possess limited resources for innovation but demonstrate high flexibility and capacity for rapid scaling of new solutions. It is also appropriate to emphasise the role of strategic planning at the national level, aimed at integrating environmental priorities into general innovation programmes. This approach fosters the creation of a supportive institutional environment in which environmental innovation is viewed not only as a tool for ecological modernisation but also as a driver of economic competitiveness amid global transformation towards a circular and green economy.

The transition of industrial enterprises towards a green economy requires the systematic implementation of environmental innovations, which serve as a key instrument of economic transformation, competitiveness enhancement, and the establishment of sustainable production practices. A crucial element of this process is the development of human capital, as investment in environmental education, awareness raising, and acquisition of green skills by employees fosters a culture of sustainable development and ensures the effective implementation of innovations. Research conducted by the OECD (2023) has demonstrated that the shift to a green economy is accompanied by changes in employment structure and professional competency requirements. In this context, industrial enterprises should prioritise the development of green skills, which include environmental awareness, understanding of sustainable development principles, and the ability to operate environmentally friendly technologies (OECD, 2024a; 2024b). Therefore, author agrees that such an approach not only enhances the efficiency of innovation implementation but also lays the foundation for structural economic transformation and the formation of a corporate culture oriented towards sustainable development.

Governments and industrial enterprises across various countries are actively investing in the development of environmental competencies. In the automotive industry of the United States and Europe, programmes for personnel retraining are being implemented to prepare workers for employment with electric vehicles and automated systems. In particular, the United States has invested USD 23.6 million in the "Battery Workforce Challenge" initiative, while Europe has established the "European Battery Academy" with the goal of training 800,000 workers by the end of 2025. Leading car manufacturers – including Jaguar, Land Rover, BMW, and Peugeot – are implementing extensive training programmes to develop new competencies among employees (Mehta, 2024).

Within the framework of the transition to a green economy, it is advisable for industrial enterprises to integrate training programmes on environmental awareness and sustainable development into internal professional development systems. Cooperation with educational institutions and governmental organisations is essential for the creation of specialised training programmes, ensuring employee access to modern learning resources and technologies, and establishing incentives for participation in education and skill development initiatives. The necessity of developing environmental competencies among personnel in forming an effective corporate policy for implementing environmental innovations is indisputable, as investment in employee training fosters a culture of sustainable development, enhances the efficiency of innovation implementation, and ensures enterprise competitiveness during the transition to a green economy.

Moreover, the successful implementation of environmental innovations in industrial enterprises requires active collaboration with various stakeholders, including enterprises themselves, governmental authorities, research institutions, and civil society organisations. Such cooperation facilitates knowledge exchange, supports the development of joint strategies, and ensures compliance with regulatory requirements. In the context of analysing stakeholders within the innovation process, particular relevance is attributed to the "triple helix" model, formulated by L. Leydesdorff & H. Etzkowitz (2000) and L. Leydesdorff (2013). This model serves as an effective theoretical foundation for innovation policy formation, based on close interaction among universities, industry, and government. Its practical implementation has demonstrated high effectiveness in technologically advanced countries, such as the United States, China, and others (Etzkowitz & Zhou, 2017).

Further development of this concept has led to the emergence of the "quadruple helix" model, which integrates civil society as a legitimate actor within the innovation system (Carayannis & Campbell, 2010; Roman & Fellnhofer, 2022). Subsequently, the "quintuple helix" model was introduced, incorporating the natural environment as a crucial element of sustainable development (Carayannis & Campbell, 2010; Carayannis *et al.*, 2012; Zakaria *et al.*, 2024). Practical implementation of the "quadruple" and "quintuple helix" models in Sweden and Germany has demonstrated significant achievements in the environmentalisation of the economy and the development of sustainable innovations (Wiesmeth, 2018; Kern *et al.*, 2019). These results confirm the relevance of a comprehensive approach to innovation policy formation that combines scientific progress, industrial application, governmental support, societal engagement, and environmental responsibility.

Accordingly, within the framework of developing an effective industrial policy for the implementation of environmental innovations, the "quintuple helix" model is considered the most appropriate. This model facilitates extended interaction among five key components and, unlike the "triple" and "quadruple" models, provides a systemic perspective on innovation activities under environmental challenges and economic transformation towards sustainable development. The application of this model offers a number of important advantages within the context of the current study. It enables the integration of the environmental dimension into enterprise activities by recognising the natural environment as a full-fledged element of the system. Such an approach helps align economic objectives with environmental priorities, ensuring their balanced and harmonious development.

The model also stimulates the implementation of environmental innovations through close collaboration among different sectors. Cooperation with research institutions provides access to cutting-edge "green" technologies; interaction with government ensures support through policy mechanisms and incentives; and partnerships with civil society enhance corporate reputation and strengthen public trust. Furthermore, the model contributes to the creation of an innovation ecosystem in which industrial enterprises become active participants in regional development, generating solutions that foster sustainable growth. Through broad stakeholder engagement, it also enhances enterprise resilience to external challenges, making operations more adaptive, accountable, and inclusive.

At the same time, to achieve the expected outcomes from environmental initiatives, industrial enterprises must integrate clear mechanisms for monitoring and evaluating the effectiveness of environmental measures. Monitoring and evaluation function as feedback instruments that allow for identifying gaps in policy implementation, adjusting decisions, and adapting approaches to a rapidly changing regulatory and technological environment. At this stage, strategic information obtained through stakeholder interaction is integrated into the decision-making system, thereby ensuring the comprehensiveness and dynamism of the environmental transformation of industrial enterprises.

Under current conditions of globalisation and increasing environmental requirements – particularly in the context of the European Green Deal – monitoring and evaluation have become key sources of institutional trust from governments, investors, and society. Monitoring of environmental innovations involves the systematic collection and analysis of quantitative and qualitative data related to the implementation of innovative technologies, changes in production processes, resource consumption, levels of energy efficiency, and emission volumes. Simultaneously, evaluation not only records the progress of policy implementation but also interprets its impact – economic, environmental, and social. Moreover, the monitoring process must be fully integrated into the enterprise's strategy and involve stakeholder participation, including governmental bodies, civil society institutions, and scientific organisations (OECD, 2024a; 2024b).

H. Duan & X. Pang (2023) indicated that effective assessment systems should be constructed on the basis of relevant indicators adapted to the industry-specific characteristics of an enterprise and its strategic objectives. Consequently, the use of integrated monitoring systems is essential, enabling enterprises to record outcomes while simultaneously facilitating strategic planning of subsequent actions, taking into account both internal resources and external challenges. The authors propose recommendations for monitoring the implementation of environmental innovations by industrial enterprises, which hold practical value and may be integrated into sustainable development strategies within the industrial sector.

Integration of environmental indicators into both strategic and operational planning enhances alignment between environmental and business objectives of a company. Involvement of stakeholders in the process of developing and evaluating environmental policy – including representatives of the public, the scientific community, governmental institutions, and suppliers – contributes to better adaptation of innovations to regional conditions and strengthens the social legitimacy of entrepreneurial activity. Application of digital tools for data collection and analysis, such as the Internet of Things, artificial intelligence-based systems, blockchain, and big data technologies, enables accurate and timely monitoring of environmental parameters. Regular review of performance indicators remains essential, as in a dynamic context of evolving regulatory frameworks and technological change, periodic updates of the system of environmental indicators ensure the continued relevance of monitoring while incorporating new scientific achievements and practical challenges. Development of human capital in the fields of environmental monitoring, digital tool utilisation, and interpretation of environmental data constitutes a prerequisite for the effective functioning of monitoring and evaluation systems, since a well-educated workforce significantly enhances the quality of reporting and strategic planning.

Within the context of implementing environmental innovations, the issue of social responsibility of industrial enterprises acquires particular significance. Environmental transformation cannot occur in isolation from the social environment, as any change in production processes, technologies, or corporate policies directly or indirectly affects all stakeholders. Consequently, social responsibility in the implementation of environmental policy by industrial enterprises serves as a critical factor in achieving sustainable economic development. Enterprises that actively introduce environmental initiatives gain not only economic benefits but also a positive public image, contributing to the creation of an environmentally conscious future. An effective policy of an industrial enterprise within the framework of the green economy should be based on an integrated approach that unites environmental objectives with strategic planning, investment decisions, human capital development, cross-sectoral cooperation, performance monitoring, and social responsibility. A substantiated model of such a policy must incorporate contemporary concepts of sustainable development, including the principles of the circular economy, inclusive growth, and ESG orientation (Fig. 3).

The principal advantage of the proposed policy lies in its systemic nature and adaptability, enabling industrial enterprises to respond promptly to external challenges, regulatory changes, and increasing stakeholder expectations. Through the integration of the "quintuple helix" model, enterprises gain enhanced opportunities for collaboration with the scientific community, governmental institutions, and the public. Implementation of environmental innovations within the framework of the green economy contributes to the creation of new markets, reduction of environmental risks, and alignment with ESG principles. Monitoring and evaluation systems ensure feedback and accountability, allowing timely adjustments and enhancing the effectiveness of implemented policies, while guaranteeing transparency and investor confidence.

Implementation of a well-grounded, comprehensive, and responsible environmental policy represents not merely a tool of ecological modernisation for industrial enterprises but a strategic condition for long-term economic viability and social responsibility amid the global transformation towards sustainable development. The conducted research confirmed the relevance and necessity of integrating environmental goals into the strategic planning of industrial enterprises, aligning with current trends in sustainable development and the growing environmental demands of society. The analysis revealed key vectors for the development of environmental policy, with a focus on the implementation of clean technologies, resource efficiency, circular economy, and raising environmental awareness among employees.

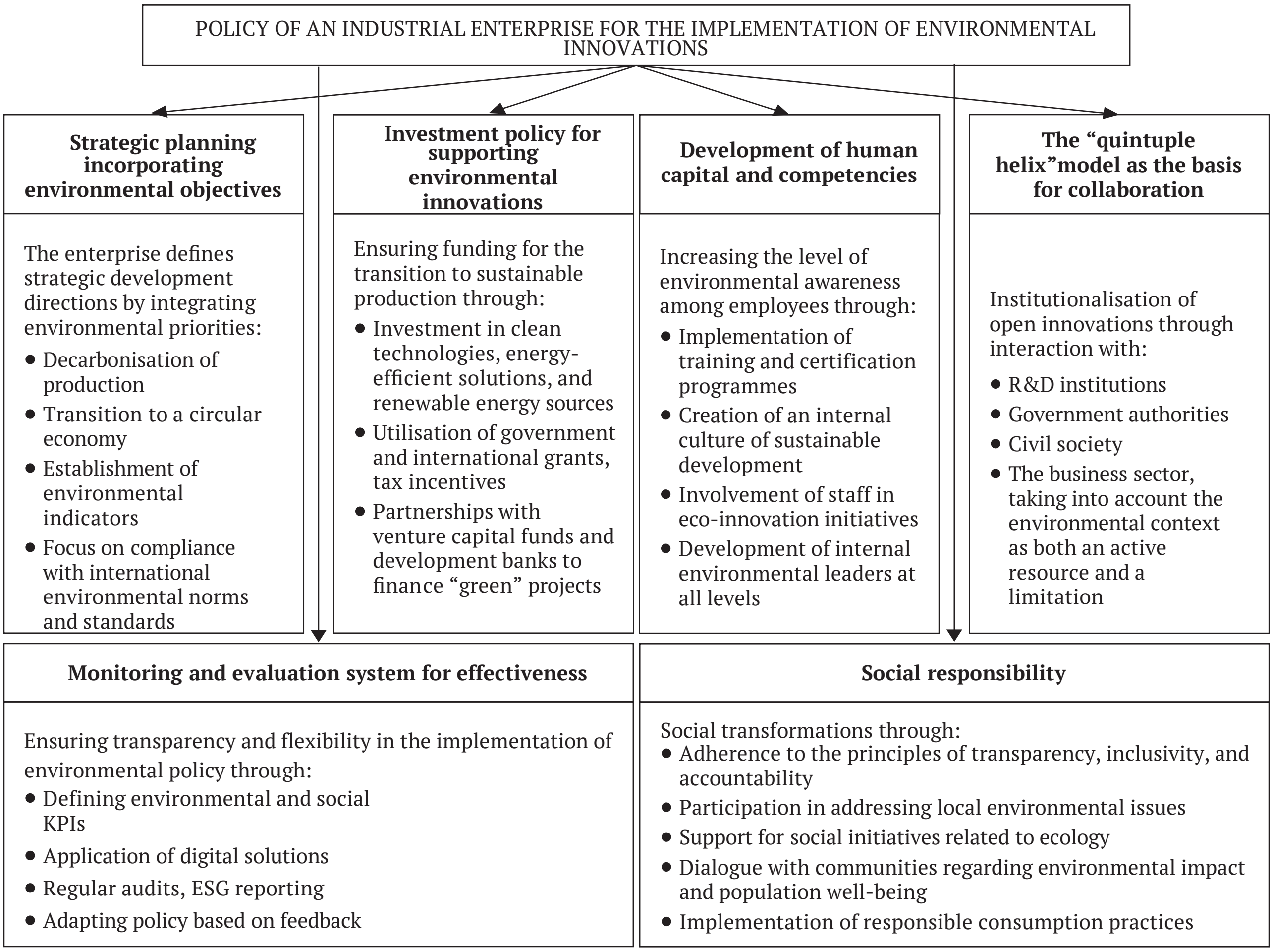

Figure 3. Policy of an industrial enterprise for the implementation of environmental innovations
Source: developed by the author

The results align with studies highlighting the importance of a strategic approach to forming environmentally-oriented business models. For instance, as shown in the work of Y. Li & F. Wang (2023), digital tools can significantly enhance the effectiveness of implementing green innovations, a trend also observed in the current research, where the role of digital technologies is emphasised as a key factor in the ecological transformation of enterprises. At the same time, unlike many theoretical concepts that focus solely on the regulatory aspect of environmental policy, the current study highlights the need for institutionalising environmental innovations as part of the overall competitiveness strategy. This is also emphasised in the work of Z. Zhu & Y. Tan (2022), which points to the importance of government incentives and green industrial policies in supporting green innovations within enterprises.

There is no consensus among scholars regarding which tools are most effective in driving the environmental transformations of enterprises. Specifically, some authors highlight the priority of technological innovations (Fernández *et al.*, 2018), while others emphasise the role of regulatory influence and the green finance market (Naruetharadhol *et al.*, 2024). The approach in the current study suggests a synergistic combination of both financial and infrastructural incentives, providing systemic support for environmental modernisation. A significant advantage of the proposed policy is its focus on the development of human capital, which, unlike most previous studies, plays a key role in driving environmental innovations. This is confirmed by the study of H. Sun *et al.* (2023), which stresses that investments in human capital are crucial for supporting environmental transformations in industry. The results of the current work show that environmental competencies among employees are critical for the successful implementation of environmental initiatives within enterprises.

At the same time, the issue of the balance between voluntary initiatives by enterprises and regulatory pressure remains debatable. As noted by H. Yu *et al.* (2025), digital transformation and investments in green technologies can be powerful catalysts for enterprises seeking "green" transformation. However, in the author's view, without a proper regulatory environment and government support, enterprises may remain at the stage of declarations rather than real changes. For instance, the study by H. Shao *et al*. (2024) confirms that environmental regulation, alongside green investments, has a significant impact on "green transformation" in developing countries. At the same time, current results indicate that this process can be considerably slowed down by weak legal norms and insufficient government support at the local level, as noted by B. Zhang & Y. Li (2025) in the context of cooperation between central and local authorities.

It is advisable to explore the application of quantitative models for assessing the effectiveness of green innovations, such as DEA models (Chen & Xu, 2024), to more precisely determine which environmental policy tools are most effective in the context of different economies and types of enterprises. Thus, the study outlines the need for a multi-level approach to the implementation of environmental innovations, which involves a combination of strategic planning, institutional support, financial incentives, human capital development, and technological base modernisation.

CONCLUSIONS

It has been proven that an effective environmental policy for enterprises must be multifaceted and should incorporate systematic measures aimed at reducing the negative environmental impact of production, enhancing the efficient use of natural resources, implementing "green" technologies, and ensuring compliance with environmental standards. The study underscores that the industrial innovation policy for the implementation of environmental innovations stands out for its high degree of systematisation and adaptability, allowing enterprises to respond promptly to dynamic challenges of the external environment, changes in the regulatory framework, and growing stakeholder expectations. Notably, the integration of the "quintuple helix" model will foster enhanced collaboration between enterprises, the scientific community, governmental institutions, and civil society, significantly boosting innovation potential and the legitimacy of environmental initiatives. This approach ensures a comprehensive strategy for environmental innovation that facilitates a sustainable, green transition.

Implementation of such policies will mitigate environmental risks, guarantee adherence to ESG principles, and create new market opportunities while reducing ecological impacts. Investment in human capital development, along with the promotion of environmental competencies, will cultivate an organisational culture focused on sustainable development. Furthermore, the introduction of monitoring and evaluation systems will ensure effective feedback mechanisms, accountability, and the capacity for timely adjustments. These mechanisms, integrated within the enterprise, will support the continuous alignment of business and environmental objectives, driving forward the transition to a green economy.

Thus, the proposed policy for implementing environmental innovations provides a robust framework for the sustainable development of industrial enterprises, aligning their activities with contemporary environmental priorities and the global shift towards sustainable, circular economic models. This holistic approach ensures long-term economic viability, compliance with environmental norms, and responsiveness to the evolving demands of stakeholders, thereby facilitating the achievement of both business and environmental objectives in the context of global transformation towards sustainability. The issue requires further research, particularly in terms of evaluating the effectiveness of implemented measures, developing monitoring indicators for environmental performance, and studying the impact of environmental policy on the competitiveness of enterprises.

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None.

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Політика промислового підприємства з впровадження екологічних інновацій в умовах переходу до зеленої економіки

Анотація. Актуальність дослідження зумовлена необхідністю економічної трансформації промислових підприємств на засадах екологічної сталості в умовах глобальних екологічних викликів, ресурсних обмежень і посилення регуляторного тиску, що потребує формування ефективної економічної політики впровадження екологічних інновацій. Мета дослідження полягала в обґрунтуванні теоретико-методичних засад щодо формування ефективної екологічної політики промислових підприємств у контексті впровадження екологічних інновацій в стратегічне планування з метою досягнення сталого розвитку, підвищення конкурентоспроможності та соціально-економічної стійкості. Для досягнення поставленої мети використано комплекс загальнонаукових і спеціальних методів, зокрема: аналіз і синтез для систематизації наукових підходів; індукцію та дедукцію для логічного узагальнення; системний підхід для оцінки взаємозв'язку політик; структурно-функціональний аналіз для визначення складових екологічної політики; графічний метод для візуалізації інтеграції екологічних цілей. Обґрунтовано основні цілі екологічної політики промислових підприємств, зокрема: мінімізація техногенного навантаження, раціональне використання ресурсів, впровадження «зелених» технологій, дотримання екологічних стандартів та формування екологічної корпоративної культури. Обґрунтовано теоретичні засади інтеграції екологічних цілей у стратегічне планування промислових підприємств. Запропоновано політику промислового підприємства з впровадження екологічних інновацій, що охоплює стратегічне планування з урахуванням екологічних цілей, інвестиційну політику для підтримки екологічних інновацій, розвиток людського капіталу та компетенцій, модель «п'ятірної спіралі» для організації співпраці між різними зацікавленими сторонами, систему моніторингу та оцінки ефективності впроваджених інновацій для контроля за дотриманням екологічних стандартів та коригування стратегій розвитку, соціальну відповідальність підприємства для формуванню позитивного іміджу та сталих екологічних практик. Результати дослідження можуть бути використані для підвищення економічної стійкості підприємств та їх адаптації до вимог зеленої економіки

Ключові слова: екологічна політика; економіка сталого розвитку; циркулярна економіка; екологічні інновації; технологічні зміни в промисловості

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