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ЗМІСТ / CONTENTS

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The inequality gap and the wartime shock: Income distribution in Ukraine

Abstract. Economic inequality has become a major global concern, and in Ukraine its assessment is complicated by methodological disagreements, post-Soviet institutional specificity, and the unprecedented distributional effects of the full-scale war that began in 2022. The study aimed to assess the dynamics of income inequality in Ukraine over 1990-2025 through systematic comparison of alternative data sources and international benchmarking against countries of similar institutional types. The methodological framework combined the analytical category of "inequality gap", one-way analysis of variance (ANOVA) with Tukey HSD post-hoc tests, pooled OLS, Fixed Effects, and Random Effects panel specifications, and the Hausman test for model selection. The analysis revealed a statistically significant intergroup typology of countries by inequality gap ($F = 51.59$; $p < 0.001$), within which Ukraine (0.163) belonged to the post-Soviet group alongside Georgia (0.211) and Moldova (0.185). Testing of the Kuznets hypothesis showed that the cross-country inverted U-curve (pooled OLS, peak at GDP ≈ 10,452 USD) did not hold when the panel structure was controlled for: the Random Effects specification, selected via the Hausman test, yielded a U-shaped (anti-Kuznets) relationship with a minimum at GDP ≈ 21,288 USD. The Gini coefficient in Ukraine rose from 0.25 (2020) to 0.50 (2025), and the decomposition identified the asymmetric collapse of labour incomes in the bottom quintile alongside rising incomes of the top deciles as the key channel of this shock. The findings allowed positioning the Ukrainian situation not as a methodological anomaly but as a manifestation of institutional features of the post-Soviet space, requiring systemic reforms of economic de-shadowing and progressive asset taxation within the post-war recovery agenda

Keywords: income inequality; Gini coefficient; hidden inequality; DINA; Kuznets hypothesis; shadow economy; labour share

INTRODUCTION

Economic inequality has become one of the defining challenges of the contemporary global economy. Over the past decade, inequality research has evolved from a relatively narrow academic field into a central issue of economic policy and international development debates. This transformation has been driven not only by rising distributive disparities but also by methodological advances in their measurement. The development of Distributional National Accounts (DINA), combining household surveys, tax statistics, and national accounts, substantially changed the understanding of global income concentration. According to recent international estimates, the top 10% of the world population receive approximately 52% of total global income, whereas the bottom 50% account for only 8.5%, indicating a historically high degree of concentration (Chancel *et al.*, 2022).

At the same time, empirical studies increasingly demonstrate that traditional survey-based methodologies systematically underestimate inequality, particularly in countries characterised by large shadow sectors, concentrated capital ownership, and weak institutional transparency. These methodological distortions are especially

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relevant for post-socialist and transition economies. Within this context, Ukraine represents a particularly important and methodologically challenging case. Official survey-based statistics have long recorded one of the lowest Gini coefficients in Europe – approximately 0.24-0.26 – formally placing Ukraine among the continent's most equal economies (World Bank, 2024). However, alternative DINA-based estimates produce substantially higher levels of inequality because they partially capture hidden capital concentration and shadow incomes. Considering that the shadow economy in Ukraine has been estimated at roughly 30-45% of GDP, the discrepancy between official and alternative measurements acquires structural significance rather than representing a purely technical statistical issue (Ministry of Economy, Environment and Agriculture of Ukraine, 2021).

Recent empirical literature increasingly interprets inequality as a phenomenon shaped by institutional quality, labour-market structures, and macroeconomic policy. S. Aleksić & R. Jovović (2025), examining Southeast European transition countries, identified institutional instability and uneven modernisation as key drivers of persistent inequality. Similar conclusions were reached by F. Martin-Mayoral & M. Plúa (2026), who demonstrated that governance quality and institutional capacity significantly influence inequality dynamics, while the classical Kuznets assumption of automatic inequality decline remains empirically unstable.

Another important direction of contemporary research concerns labour-market transformations and macroeconomic policy. E. Šoltés *et al*. (2023), using panel data for EU countries, identified an inverse relationship between the labour income share and inequality, concluding that declining labour income shares intensify income concentration in the upper deciles. P. Kerimov & Y. Shapoval (2024), focusing on Ukraine, demonstrated that social transfers only partially mitigate poverty risks under conditions of labour-market instability and wartime pressure. Y. Shapoval *et al*. (2024) further showed that rigid monetary policy regimes during crises may amplify distributive asymmetries by producing unequal effects on inflation exposure and employment. Similarly, A. Rabhi & B. Parsons (2025) found that inflationary shocks disproportionately affect lower-income groups in developing economies.

Despite the rapid expansion of contemporary inequality research, several important gaps remain unresolved. Existing studies rarely compare alternative estimates of inequality derived from official survey statistics and DINA-type methodologies. The post-Soviet region also remains insufficiently typologised according to the scale of hidden inequality associated with shadow economies and concentrated capital ownership. Finally, the distributive consequences of the full-scale war in Ukraine remain insufficiently quantified despite the unprecedented scale of the shock. According to international estimates, Ukraine's GDP declined by 29.1% in 2022 following the beginning of the full-scale invasion (World Bank, 2025). The economic collapse was accompanied by large-scale labour-market disruption, forced migration, destruction of productive assets, and asymmetric changes in household incomes. Existing studies, however, remain largely based on official household survey data and may therefore underestimate the actual scale of wartime inequality transformations.

The purpose of this article was to assess the dynamics of income inequality in Ukraine over the period 1990-2025 through a systematic comparison of alternative data sources and benchmarking against countries of similar institutional types. To achieve this aim, the article addresses the following tasks: to systematically compare alternative estimates of the Gini coefficient for Ukraine and to compute the inequality gap for a panel of 10 institutionally diverse countries, testing the statistical significance of intergroup differences and assess within-group heterogeneity in hidden inequality; to empirically test the Kuznets hypothesis on panel data using real GDP per capita, with formal selection between Pooled OLS, Fixed Effects, and Random Effects specifications; to assess the magnitude and structural drivers of the wartime inequality shock in Ukraine over 2022-2025.

MATERIALS AND METHODS

The empirical basis of the study comprises four independent data sources covering the period 1980-2025 for Ukraine and 1990-2024 for the nine comparator countries. The World Inequality Database (WID.world, n.d.) provides estimates of the Pre-tax National Income Gini coefficient and income shares (Top 10%, Middle 40%, Bottom 50%) under the DINA methodology. This database uses a combined approach: survey data as the base, with subsequent corrections based on national accounts (for sum totals) and tax statistics (for refining top-decile distributions). It should be noted that for Ukraine, WID data are genuinely updated only through 2019, while values for 2020-2024 are extrapolated (frozen series, Gini = 0.4292). It imposes an evident limitation: a full DINA analysis for the wartime period is impossible until new national accounts and tax data become available. The World Bank Poverty and Inequality Platform (PIP) provides a survey-based Gini index computed from official household surveys. For Ukraine, this series covers 24 observations over 1992-2020 with partial gaps in 1994, 1997-1998, and 2000-2001. The coefficient values range from 24.0% (2014) to 39.2% (1995). The latest update for Ukraine is 2020 (25.6%); the subsequent wartime period is not covered due to survey curtailment.

The third source is data from the State Statistics Service of Ukraine, drawn from the annual tables "Differentiation of the Living Standards of the Population" based on the Household Living Conditions Survey. The available observation points are the Gini coefficients for total income in 2019 (0.249), 2020 (0.247), and 2021 (0.244). These data effectively duplicate the World Bank PIP estimates, which is logical, since both sources are based on the same Household Living Conditions Survey with some methodological variations (cash income vs total income, different deflators, etc.). The fourth source – the World Bank's Listening to Ukraine (L2UKR) – is a series of wartime telephone surveys providing Gini estimates for 2023 (0.41) and 2025 (0.50). Separately, for testing the S. Kuznets (1955) hypothesis, the GDP per capita PPP (constant 2021 international $) indicator from World Development Indicators (WDI), series NY.GDP.PCAP.PP.KD is used. This indicator is available for all 10 countries in the sample over the full period 1990-2024, ensuring a balanced panel. The country sample for comparative analysis includes 10 states grouped into four institutional clusters: CEE/EU (Poland, Czech Republic,

Croatia, Romania), post-Soviet (Ukraine, Georgia, Moldova), Latin America (Brazil, Colombia), and post-conflict (Iraq). This selection allows positioning Ukraine in the context of both its immediate institutional analogs and countries with radically different distributional regimes. The total sample for panel model construction ranges from 218 to 246 observations, depending on the model specification.

To systematise the analysis, the 10 countries under study were divided into four institutional groups based on three interrelated criteria: historical trajectory of economic development; level of integration into the global economy and institutional architecture; type of macroeconomic environment (peacetime vs conflict). The CEE/EU group (Poland, the Czech Republic, Croatia, and Romania) comprises Central and Eastern European countries that underwent transformation in the 1990s and have since integrated into the European Union. Common features of the group include EU membership (institutional harmonisation with the acquis communautaire), well-developed social protection institutions, and moderate levels of shadow economy (10-20% of GDP) (Schneider *et al.*, 2010). Croatia is included in the group as it joined the EU in 2013 and adopted the corresponding institutional standards. The post-Soviet group (Ukraine, Georgia, Moldova) comprises former USSR countries that did not integrate into the EU and retained key institutional features inherited from the transition period: substantial shadow economies (30-45% of GDP), capital concentration among oligarchic groups, and limited effectiveness of formal rule-of-law institutions. All three countries are associated EU members through Association Agreements, but have no prospects of full membership in the short term (as of 2022 for Ukraine). Membership in this group is determined by institutional history (the transition from a planned economy without subsequent EU integration), not by empirically measured inequality gaps, which may vary considerably across these countries. The Latin American group (Brazil, Colombia) represents a region with traditionally high-income inequality (Gini > 0.5) and a structurally different type of economic development, based on commodity exports and substantial informal employment. The inclusion of this group allows Ukraine to be positioned in a broader global context and to test whether high hidden inequality is unique to post-Soviet economies.

The post-conflict group is represented by a single country – Iraq. Two considerations justify including only one country in this group. First, for most post-conflict countries (Syria, Afghanistan, Libya), WID or World Bank PIP data are unavailable or fragmentary. Second, Iraq demonstrates a unique combination of long-term armed conflict with a functioning state statistics system, making it the only reasonably reliable analogue for parts of Ukraine's wartime indicators. Given the small sample size (n = 3), the results for this group are interpreted with caution. Theoretical justification. The concept of the inequality gap (IG) as a measure of hidden inequality draws on the methodological literature on inequality measurement, notably the works of A.B. Atkinson (2015), T. Piketty *et al.* (2018), and F. Alvaredo *et al.* (2017). According to this literature, survey-based methodologies systematically understate the incomes of top deciles due to three structural limitations: low response rates of the wealthiest households in sample surveys; under-reporting of capital and entrepreneurial incomes; the fundamental impossibility of capturing incomes that flow through shadow and offshore structures. The DINA methodology compensates for these limitations by integrating survey data with tax statistics and national accounts, providing a more complete picture of income distribution. Consequently, a systematic positive difference between the DINA-Gini and survey-Gini can be interpreted as a measure of that portion of inequality which actually exists in the economy but is not captured by survey instruments. Operational definition. The inequality gap (IG) is computed as the arithmetic difference between the WID estimate and the World Bank PIP estimate of the Gini coefficient for a given year and country:

$$G_{\{i,t\}} = G_{\{i,t\}}^{\{WID\}} - G_{\{i,t\}}^{\{WB\}}, \quad (1)$$

where $G_{\{i,t\}}^{\{WB\}}$ – the Gini coefficient for country i in year t according to WID.world (DINA), and $G_{\{i,t\}}^{\{WID\}}$ – the same coefficient according to World Bank PIP (survey-based). This measure is interpreted as an indicator of "hidden inequality" not captured by traditional household surveys. Large IG values are associated with three interrelated mechanisms. First, in economies with a substantial shadow economy, a meaningful share of household and entrepreneurial incomes is not reported in surveys, which depresses the survey-based Gini relative to the actual distribution. Second, the top deciles tend to be systematically under-represented in survey samples – both through lower response rates and under-reporting of capital income – further compressing the upper tail of the survey distribution. Third, a substantial share of wealth in countries with concentrated ownership is held in the form of assets (real estate, corporate equity, offshore structures) that are poorly captured by income surveys but are reconciled through national accounts within the DINA framework, producing a higher Gini in the DINA-based estimate.

Theoretically expected IG levels. Based on the literature, one can outline the expected IG ranges for different economic types. For developed countries with low shadow economies (10-15% of GDP), the expected IG is 0.10-0.15. For countries with moderate shadow economies (15-25%), it is 0.15-0.20. For countries with substantial shadow sectors and concentrated oligarchic ownership (25%+), the expected IG exceeds 0.20. These theoretical expectations are used in the results section as a benchmark for interpreting the empirically observed typology. Distinguishing from statistical artifacts. The interpretation of IG as an indicator of hidden inequality assumes that the methodological difference between WID and World Bank PIP is structural, rather than random or driven by technical factors. To validate this assumption, three potential sources of 'spurious' discrepancies must be considered.

First, differences in the underlying indicators. WID uses the concept of pre-tax national income, while the World Bank PIP uses disposable income from surveys. It creates a systematic upward bias in the WID Gini, independent of the shadow economy. However, this bias is relatively stable over time (approximately 0.05-0.08), whereas the IG for post-Soviet countries exceeds 0.15. Therefore, part of the difference is explained by the underlying indicator methodology, but not all of it. Second, different equivalence scales and units of analysis. WID aggregates income per adult,

whereas the World Bank PIP often uses per capita or household-level measures. It creates a relatively small difference (0.01-0.03) that is constant over time. Third, potential sampling biases in the survey data. If World Bank PIP surveys in Ukraine have systematically lower response rates among wealthy households, part of the IG may be explained by this rather than by actual shadow income concentration.

Given these caveats, IG should be interpreted as an upper bound estimate of hidden inequality – not all of the observed difference necessarily reflects the shadow economy. Still, systematically high IG values (above 0.15) over extended periods are difficult to explain solely by statistical artefacts. It is precisely the comparison of IG across countries with different institutional environments that allows distinguishing the "structural" component of IG (related to the shadow economy and capital concentration) from the "methodological" component (related to differences in measurement). Analysis of variance for the country typology. To test the statistical significance of intergroup differences in the inequality gap, one-way analysis of variance (ANOVA) is applied. The dependent variable is IG; the independent variable is the categorical country group (CEE/EU, Post-Soviet, Latin America, Conflict). Ukraine is treated as a member of the Post-Soviet group in line with the institutional classification criteria. The null hypothesis is that the mean IG values are equal across groups. For pairwise comparisons, the Tukey HSD post hoc test is used to control the family-wise error rate. Testing the Kuznets hypothesis. The Kuznets hypothesis is tested via the classical quadratic specification:

$$C_{\{i,t\}}^{\{WB\}} = \beta^0 + \beta^1 \cdot \ln(GDP_{\{i,t\}}) + \beta^2 \cdot \ln(GDP_{\{i,t\}})^2 + \varepsilon_{\{i,t\}}, \quad (2)$$

where $C_{\{i,t\}}^{\{WB\}}$ – the survey-based Gini for country i in year t; $GDP_{\{i,t\}}$ – GDP per capita (PPP, constant 2021 international $). An inverted U-curve (confirming the Kuznets hypothesis) obtains when; In the case of opposite signs ($\beta_1 < 0 \wedge \beta_2 > 0$), the specification describes a U-shaped (anti-Kuznets) relationship $GDP^1_{\{i,t\}\beta} > 0 \wedge \beta^2 < GDP* = exp(-\beta_1/(2\beta_2)$ All computations are performed in R 4.3.3 using the packages tidyverse, plm, lmtest, strucchange, ineq, and corrplot. Graphical visualisation is implemented with ggplot2 and ggrepel. Data were preprocessed and combined into a single master dataset containing 451 observations from 10 countries over the period 1980-2025, covering 15 key indicators of inequality and macroeconomic context. Computation of the turning point. The extremum of the quadratic function (maximum for an inverted U or minimum for a U-shape) is found by analytical first-order differentiation:

$$\frac{\partial G}{\partial \ln(GDP)} = \beta^1 + 2 \cdot \beta^2 \cdot \ln(GDP) = 0, \quad (3)$$

from which the optimal value of $\ln(GDP)$ is:

$$\ln(GDP*) = -\frac{\beta^1}{(2 \cdot \beta^2)}, \quad (4)$$

and the turning point in GDP per capita units is:

$$GDP* = exp\left(-\frac{\beta^1}{(2 \cdot \beta^2)}\right). \quad (5)$$

Limitations of turning point interpretation. The computed turning point is valid only if both coefficients β_1 and β_2 are statistically significant; the computed GDP* value falls within the observed GDP range in the sample (in-sample); the specification matches the nature of the relationship (quadratic function adequately describes the data). Choice of panel model specification. The Kuznets model is estimated using three methods to ensure complete analysis: pooled OLS (which reveals the overall cross-country pattern without controlling for unobserved time-invariant country characteristics), Fixed Effects (which controls for unobserved time-invariant country characteristics through within-country estimation), and Random Effects (which assumes that individual effects are uncorrelated with regressors). For the formal choice between Fixed Effects and Random Effects, the Hausman test is applied. The null hypothesis of the test is that the difference between the FE and RE estimates is not systematic (i.e., the RE specification is valid). If the χ^2 statistic does not reject H0 ($p > 0.05$), Random Effects is the preferred choice due to estimator efficiency. If H0 is rejected, preference is given to Fixed Effects as a consistent specification in the presence of correlation between individual effects and regressors. Pooled OLS is not validated by the Hausman test and was used exclusively as a reference model for revealing the compositional effect of the sample.

RESULTS AND DISCUSSION

The first stage of the analysis consists of comparing four independent estimates of the Gini coefficient for Ukraine, presented in Figure 1. The most important empirical finding at this stage is a systematic and statistically stable discrepancy between methodologies that is not reducible to random sampling variation.

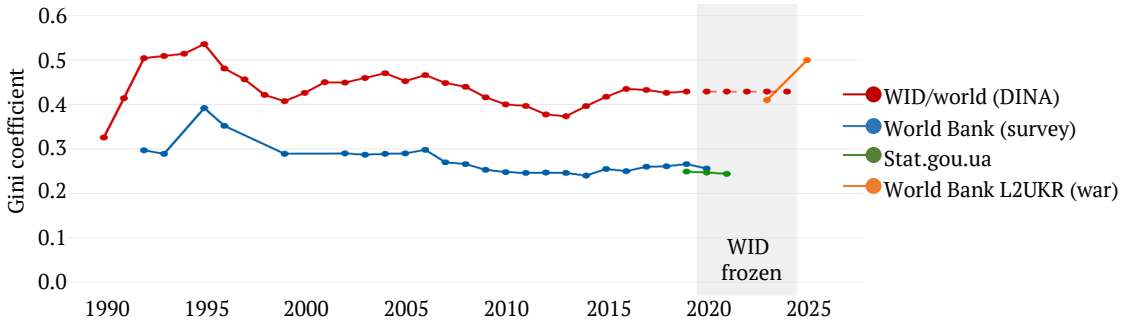

Figure 1. Dynamics of the Gini coefficient in Ukraine: alternative estimates (1990-2025)
Source: prepared by the author

The mean Gini coefficient estimated by WID.world is 0.437 (n = 35), within the range 0.375-0.536, indicating that Ukraine has moderately high inequality by international DINA standards. At the same time, survey-based estimates by the World Bank yield a mean of 0.277 (n = 24) within the range 0.240-0.392, corresponding to the level of low-inequality EU countries. State Statistics Service data for 2019-2021 (mean 0.247) fall within the same range, which is logical, since both survey-based sources are grounded in the same Household Living Conditions Survey. The divergence between approaches is not an artefact of specific years or sampling features. It has a fundamentally methodological nature and reflects a fundamental difference in the definition of "income": DINA includes all components of national income, including undistributed corporate profits, which are disproportionately concentrated in the top decile, whereas survey-based methodologies are restricted to the incomes households report in questionnaires. In countries with a developed shadow economy and concentrated capital, this difference assumes a structural character.

The wartime L2UKR data points (2023: 0.41; 2025: 0.50) deserve particular attention. They lie between WID estimates for the pre-war period and survey estimates, interpreted as the transformation of previously "hidden" inequality into "visible" inequality through two mechanisms. First, the collapse of specific economic sectors (notably those linked to frontline areas and destroyed infrastructure) reduced the incomes of lower deciles to such an extent that this became visible even in surveys. Second, budgetary payments to military personnel redistributed incomes in a way that is more readily captured in surveys, since these payments are formal and accounted through the banking system. The identified methodological discrepancies naturally raise the question: Is the Ukrainian gap between alternative Gini estimates a unique case, or does it reflect a broader pattern? Answering this requires cross-country comparison. Computation of the inequality gap for all 10 countries in the sample over 1990-2024 yielded 246 observations of paired estimates (Gini_WID – Gini_WB). Results are presented in Table 1.

Table 1. Country ranking by inequality gap and ANOVA results (1990-2024)

Rank	Country	Group	N	Mean	Median	SD	Min	Max
1	Iraq	Conflict	3	0.380	0.358	0.071	0.323	0.459
2	Georgia	Post-Soviet	29	0.211	0.202	0.024	0.179	0.258
3	Moldova	Post-Soviet	27	0.185	0.187	0.043	0.080	0.237
4	Romania	CEE/EU	30	0.184	0.182	0.027	0.128	0.243
5	Colombia	Latin America	27	0.177	0.175	0.020	0.140	0.230
6	**Ukraine**	**Post-Soviet**	**24**	**0.163**	**0.163**	**0.024**	**0.119**	**0.220**
7	Croatia	CEE/EU	21	0.159	0.152	0.018	0.134	0.200
8	Poland	CEE/EU	30	0.139	0.141	0.039	0.069	0.201
9	Brazil	Latin America	31	0.138	0.141	0.033	0.087	0.215
10	Czech Rep.	CEE/EU	24	0.125	0.126	0.011	0.103	0.146
	Group averages:							
	Conflict		3	0.380				
	Post-Soviet (incl. Ukraine)		80	0.186				
	Latin America		58	0.158				
	CEE/EU		105	0.141				

Note: Inequality gap = Gini_WID – Gini_WB. Data are sorted by mean gap value in descending order. Ukraine is shown in bold. ANOVA revealed a statistically significant difference between groups: $F(3, 242) = 51.59$; $p < 0.001$
Source: calculated by the author using based on World Bank (2024), WID.world (n.d.)

The Tukey HSD post-hoc test confirms the significance of pairwise differences between Conflict-CEE/EU, Post-Soviet-CEE/EU, Conflict-Latin America, Conflict-Post-Soviet, Post-Soviet-Latin America (all $p < 0.001$), except the comparison Latin America-CEE/EU ($p = 0.940$). The empirical ranking of countries by mean inequality gap reveals a more nuanced picture than a strict institutional ordering would suggest. While the four groups are statistically distinguishable in their means (see ANOVA results below), there is substantial within-group heterogeneity and partial overlap between groups. Iraq leads by a significant margin (0.380), reflecting the post-conflict context. Within the post-Soviet group, Georgia (0.211) and Moldova (0.185) show high IG values consistent with strong shadow-economy and oligarchic-concentration features. Ukraine (0.163), however, occupies an intermediate position: it is the lowest within its institutional group and is comparable to Romania (0.184, CEE/EU) and Colombia (0.177, Latin America). Croatia (0.159), Poland (0.139), Brazil (0.138), and the Czech Republic (0.125) close the ranking. This empirical heterogeneity within groups – and overlap between groups – is itself an important finding: it demonstrates that institutional inheritance shapes the average level of hidden inequality but does not deterministically predict the individual country position.

As reported in Table 1, the four institutional groups differ significantly in their mean IG values. The Tukey HSD post hoc test revealed significant pairwise differences in most comparisons. The largest gap is recorded between the Conflict and CEE/EU groups (0.227 points). The "Post-Soviet vs CEE/EU" gap is 0.035 points and also statistically significant ($p < 0.001$), documenting the structural persistence of the institutional divide between these two groups 30 years after the start of transition. An interesting incidental result is the absence of a significant difference between "Latin America" and "CEE/EU" (difference 0.003; $p = 0.940$), which warrants separate interpretation. The interpretation of the identified typology rests on two complementary

mechanisms. First, post-Soviet countries retain a substantial volume of shadow economy (estimated at 30-45% of GDP in Ukraine), which systematically "washes out" incomes from household surveys. The shadow economy has a multi-level structure: from the micro level (informal employment, untaxed earnings) to the macro level (offshore structures of large businesses, tax minimisation schemes). All these components are invisible to survey methodology. Second, the concentration of capital in the form of assets of oligarchic structures (financial-industrial groups, offshore structures) remains imperceptible to survey methodology but is fully accounted for under DINA through reconciliation with national accounts.

The opposite mechanism is observed in Latin American countries. Brazil and Colombia exhibit very high survey-based Gini coefficients (0.52-0.56), leaving little room for additional detection of hidden inequality – survey methodology already captures the bulk of stratification. It explains why, despite a formally lower inequality gap (0.138 for Brazil), the overall level of inequality is substantially higher than in post-Soviet countries. This counterintuitive feature underscores the importance of jointly analysing the absolute level of inequality and its "visibility" to statistical instruments – two indicators that do not always correlate. The institutional pattern of the inequality gap discussed above addresses the question of how concealed income concentration is from traditional surveys. No less important is the complementary question – how this concentration is distributed over time and across population groups within Ukraine. Answering it requires moving from aggregated Gini coefficients to the share-based distribution of national income across quantile groups.

The within-group heterogeneity deserves separate comment. Romania's relatively high IG (0.184) – above the CEE/EU average – reflects the country's specific transition path, with later EU accession (2007) and a persistent shadow economy estimated at 25-30% of GDP, which is closer to post-Soviet than to Western CEE patterns. Colombia (0.177), while located within Latin America, shares with post-Soviet countries a substantial concentration of wealth in informal and unmeasured channels, which inflates its IG above the Latin American average. Ukraine's position is the mirror image: the country belongs institutionally to the post-Soviet group but exhibits an IG closer to the CEE/EU range. Several explanations are plausible: Ukraine's shadow economy, although large in absolute terms, is partly captured by the State Statistics Service through its higher-quality household survey instruments compared with Georgia or Moldova; the WID data for Ukraine are frozen after 2019, which may underestimate the recent expansion of hidden inequality; Ukraine's pre-war income concentration, while substantial, may be lower in DINA terms than in countries with deeper oligarchic capture such as Georgia. These factors suggest that Ukraine's institutional belonging to the post-Soviet group is grounded in historical and economic structure rather than in the average level of its inequality gap alone.

Analysis of the share-based distribution of national income across quantile population groups (Fig. 2) reveals the dramatic transformation of 1990-1995, which became decisive for the subsequent trajectory of the Ukrainian economy. In 1990, the income distribution retained a Soviet egalitarian character: the top 10% share stood at 24.7%, the bottom 50% at 27.7%, and the middle 40% at 47.7%. It corresponded to a declaratively socialist distribution model and was close to Scandinavian indicators. This structure was consistent with administratively compressed wage differentials and limited capital income dispersion characteristic of centrally planned economies. By 1995, the structure had polarised sharply: the Top 10% share rose to 53.6% (a 28.9-percentage-point increase in 5 years), the bottom 50% fell to 16.5% (an 11.2-point decline), and the middle 40% to 29.9%. This transformation reflects the combined effects of price liberalisation, privatisation, and the emergence of concentrated capital ownership during the early transition recession. Importantly, this shift represents a discrete institutional shock rather than a gradual evolutionary adjustment, effectively redefining the baseline structure of income distribution for the post-transition period. The 1995 stabilisation crisis and the subsequent period of macroeconomic consolidation partially corrected the distribution; however, it did not return to Soviet proportions. As of 2019, the income structure looks as follows: Top 10-33.1%, Middle 40-44.3%, Bottom 50-22.6%. It implies a relatively stable top-to-bottom ratio of 1.46, which has remained broadly unchanged over the last decade. In comparative perspective, this places Ukraine close to countries such as the Czech Republic (1.14) and significantly below high-inequality economies such as Brazil (5.63) and Colombia (7.84). Such positioning suggests that, under consistent measurement approaches, Ukraine does not belong to the group of extreme-inequality economies, despite a relatively high inequality gap under alternative estimation frameworks. A notable feature of Ukrainian distributive dynamics is their relative stability over 2000-2019. Unlike several transition economies where inequality continued to rise after the initial liberalisation shock, Ukraine exhibited a prolonged plateau in the income share of the top decile at approximately 33-35%. This pattern suggests the emergence of a constrained distributive equilibrium shaped by incomplete institutional reforms and the coexistence of formal and informal economic structures. At the same time, this stability should not be interpreted as convergence toward equality, but rather as a locked-in configuration of post-transition distributional relations.

From a theoretical perspective, this empirical regularity raises a fundamental question regarding whether the long-run evolution of income distribution in Ukraine follows the canonical Kuznets mechanism, implying a systematic relationship between economic development and inequality, or whether it reflects a structurally different trajectory characteristic of transition economies. In other words, it remains to be determined whether the observed distributive stability is consistent with an inverted U-shaped relationship between inequality and income, or whether it indicates a deviation from the classical Kuznets hypothesis driven by institutional persistence. Addressing this question requires moving from descriptive analysis to formal econometric testing. If inequality dynamics are primarily governed by income level alone, Ukraine should converge toward the downward-sloping segment of the Kuznets curve as development progresses. However, if structural and institutional factors dominate, the

relationship may deviate significantly from this pattern. To empirically distinguish between these alternatives, the next section tests the Kuznets hypothesis using panel data across countries at different levels of economic development, thereby situating Ukraine within a broader comparative framework of inequality-development relationships.

Testing of the Kuznets hypothesis was conducted using panel data for 10 countries over 1990-2020 (218 observations), with real GDP per capita (PPP, constant 2021 prices) as the measure of economic development. The estimation results for the pooled OLS and fixed-effects models are presented in Table 2.

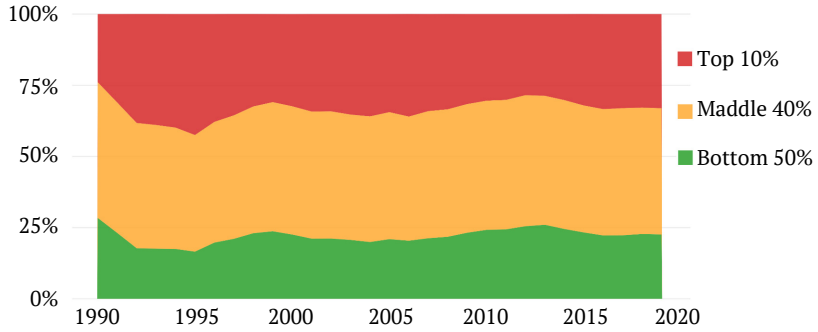

Figure 2. National income distribution by population groups in Ukraine (1990-2019)
Source: prepared by the author

Table 2. Estimation results of the Kuznets model: $\text{Gini} = \beta_0 + \beta_1 \cdot \ln(\text{GDP}) + \beta_2 \cdot \ln(\text{GDP})^2 + \varepsilon$

Variable	Pooled OLS		Fixed Effects		Random Effects	
	Coef. (SE)	p-value	Coef. (SE)	p-value	Coef. (SE)	p-value
(Intercept)	−6.251 (1.835)	0.001 ***	-	-	3.894 (0.677)	<0.001***
ln(GDP)	1.439 (0.379)	<0.001 ***	−0.726 (0.141)	<0.001***	−0.712 (0.141)	<0.001***
$\ln(\text{GDP})^2$	−0.078 (0.020)	<0.001 ***	0.037 (0.007)	<0.001***	0.036 (0.007)	<0.001***
Diagnostics:						
R^2	0.172		0.164 (within)		0.163 (overall)	
Adj. R^2	0.164		-		0.156	
N	218		218		218	
Turning point, $ PPP	10,452	(peak ∩)	20,964	(min ∪)	21,288	(min ∪)
Hausman test: χ^2			FE vs RE: 1.623	p = 0.444		
Specification conclusion					RE (preferred)	

Note: *** p < 0.001; ** p < 0.01; * p < 0.05. SE – standard error; within R^2 – share of within-country variation explained by the fixed effects model. Peak (∩) – maximum of the curve, interpreted as confirmation of the inverted U-shape of Kuznets; minimum (∪) – minimum of the U-shape (anti-Kuznets), characteristic of within-country dynamics. Period: 1990-2020. Number of countries: 10. Dependent variable: Gini coefficient (survey-based, World Bank); independent variable: natural logarithm of GDP per capita (PPP, constant 2021 international $; WDI, series NY.GDP.PCAP.PP.KD). The Hausman test results ($\chi^2 = 1.623$; $p = 0.444$) do not reject the null hypothesis of random effects, formally justifying the Random Effects specification as the basis for further interpretation. The RE model produced the following estimates: the coefficient on ln(GDP) equals −0.712 (SE = 0.141; $p < 0.001$), and the coefficient on $\ln(\text{GDP})^2$ equals +0.036 (SE = 0.007; $p < 0.001$), with a turning point at GDP ≈ 21,288 USD PPP. In form, this is a U-shaped (anti-Kuznets) relationship that virtually coincides with the results of the Fixed Effects model
Source: calculated by the author based on World Bank (2024), WID.world (n.d.)

This closeness of RE and FE estimates is an important analytical finding: it indicates that within-country variation dominates between-country variation in this sample. It means that the global Kuznets regularity (inverted U-curve) revealed by pooled OLS is not confirmed in Ukraine sample when the panel data structure is correctly controlled for. The pooled OLS result, in this light, should be interpreted with caution. It rather reflects a compositional effect – the fact that current sample simultaneously includes countries with low inequality and middle development (CEE/EU), countries with high inequality and middle development (Latin America), and countries with diverse development patterns. Averaging these heterogeneous cases creates the appearance of an inverted U-curve, which disappears when country effects are controlled for (Fig. 3).

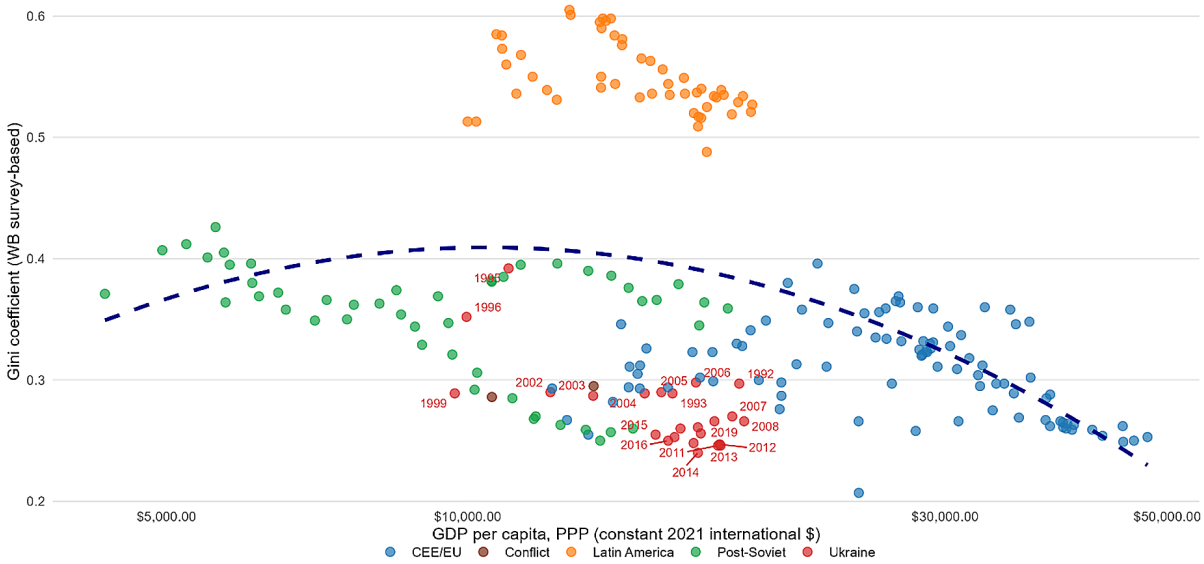

Figure 3. The Kuznets hypothesis: Gini vs GDP per capita (1990-2020)
Source: prepared by the author

Under the RE specification, Ukraine (GDP ≈ 17,000 USD) is positioned before the minimum of the U-curve (~21,300 USD), i.e., potentially in a zone where further GDP growth may be accompanied by rising inequality. This result does not contradict but rather confirms the article's central thesis: the automatic decline in inequality with GDP growth does not occur, and achieving inclusive development requires targeted institutional reforms. The wartime shock of 2022+ dramatically illustrates this conclusion – despite the relative stability of GDP per capita, inequality doubled due to institutional (not purely economic) factors. The classical Kuznets pattern emerged under conditions of peacetime and gradual structural change. The 2022 wartime shock created qualitatively different conditions in which traditional economic relationships may lose force. The most dramatic empirical finding of the study is the unprecedented rise in the Gini coefficient in Ukraine due to the full-scale war. According to World Bank Listening to Ukraine data, the coefficient rose from 0.256 (2020, State Statistics Service) to 0.41 (2023, L2UKR) and further to 0.50 (2025, L2UKR) – effectively doubling in five years. Such a pace of inequality growth has no analogues in the European region in recent history. For comparison, during the 2008-2009 global financial crisis, the largest Gini increase in Europe was recorded in Latvia (from 0.33 to 0.38) and Spain (from 0.31 to 0.35) – that is, 0.04-0.05 points. The Ukrainian wartime shock amounts to 0.24 points, which is 5-6 times larger.

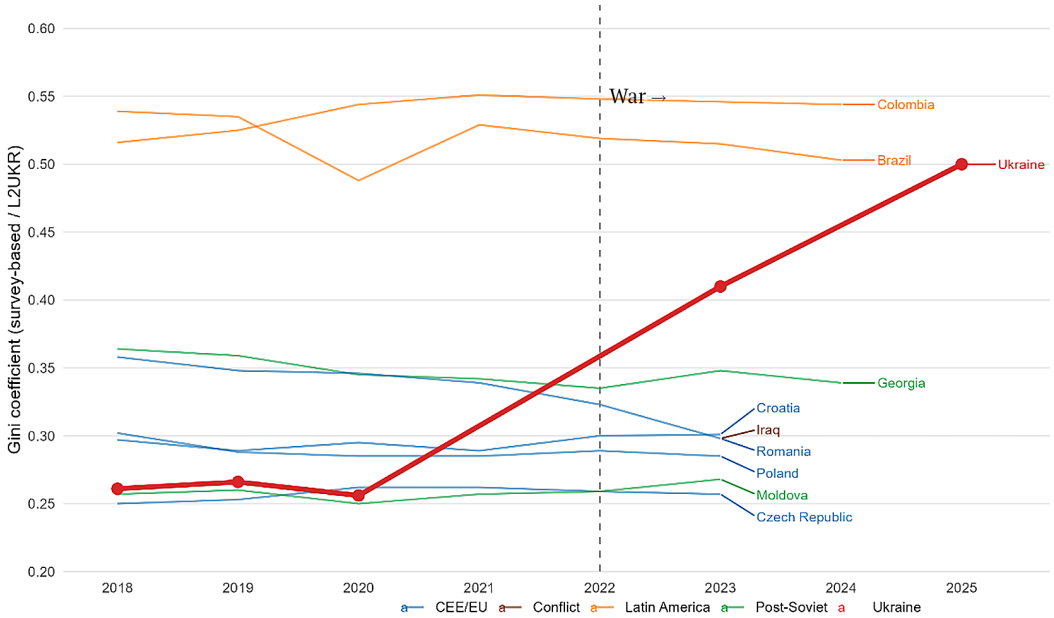

Figure 4. Wartime inequality shock in Ukraine in the context of 9 countries (2018-2025)
Source: prepared by the author

Comparing Ukraine's wartime trajectory with all countries in the sample (Fig. 4) demonstrates how exceptional this case is. No other country in the sample over the corresponding period exhibited Gini growth exceeding 0.02 points. Ukraine started at the level of CEE/EU countries (0.256 in 2020, close to the Czech Republic at 0.262 and Poland at 0.285) and, within five years, approached Latin American states, where Colombia has 0.544, and Brazil has 0.503. Should the 2023-2025 trend persist, in the next 2-3 years, Ukraine may surpass even Brazil in inequality, reaching levels of ultra-high inequality seen in countries such as Namibia (0.59) or South Africa (0.63). The structural drivers of the wartime shock are revealed through additional analysis of L2UKR data. First, real incomes of households at the bottom of the distribution (Q1-Q2) in 2024 declined relative to 2020, while incomes of the top quintile (Q5) grew the most rapidly (World Bank, 2025). This asymmetry alone is sufficient to explain the rise in the Gini coefficient from 0.25 to above 0.40.

Second, the share of households in the bottom quintile (B20) reporting labour income as a source of household earnings declined from 66% (2020) to less than 25% (2024). Three of every four poorest households thus lost access to the labour market during the wartime period and depend entirely on social transfers, humanitarian assistance, or non-monetary survival mechanisms (World Bank, 2025). In contrast, in the T20 group, employment rates remained high and stable throughout the observation period. The asymmetric character of the labour shock is the most important structural factor of wartime inequality, since it affects not only current incomes but also the capacity of lower deciles to restore their position after the war ends. Loss of labour activity over an extended period creates the well-known "scarring effects" – long-term negative consequences for human capital and employment opportunities. Third, sectoral wage differentiation in 2024 reached unprecedented levels. According to data from the State Statistics Service of Ukraine, in Q4 2024, the average wage in air transport was 54,600 UAH, in the IT sector 57,500 UAH, in education 14,300 UAH, in healthcare around 17,000 UAH, and in arts and culture 14,000-16,000 UAH. The gap reaches 3-4 times that amount. Agriculture, meanwhile, demonstrated one of the fastest growth rates – +33-43% year-over-year – but even with this growth, the sector's wage (around 20,000 UAH) remained substantially below the "new economy". This sectoral gap is closely correlated with the geographic one: "upper" sectors are concentrated in large cities and in the West, while "lower" sectors are in regions that suffered the greatest destruction (World Bank, 2025). The most concerning is the dynamics of education and healthcare. These sectors are critical for long-term human capital development but are funded on a residual basis under the wartime budget. In the future, this will create a serious challenge for the country's recovery and for maintaining the quality of education and healthcare amid low wages in those sectors.

The gender dimension of the wartime shock also deserves attention, although it cannot be fully analysed without microdata and has obvious empirical manifestations. The mobilisation of predominantly men changed the structure of households – a large proportion of families now have one adult (a woman) as the main earner and decision-maker. Payments to military personnel, which substantially exceed peacetime wages, redistributed part of family incomes, but simultaneously created a group of households without a primary male breadwinner and without substantial payments (families of mobilised persons from low-paid occupations). This phenomenon requires further research with microdata. Up to this point, the analysis of wartime shock has focused on the distribution of income across population groups. No less informative is the analysis of the functional distribution – the ratio between labour compensation and capital income – which is usually considered a more stable indicator of economic structure. Particular attention is warranted for the analysis of the functional distribution of income and the labour share in GDP. As shown in Figure 5, Ukraine exhibits a dynamic of this indicator that is unique within the studied group of countries, especially during the wartime period.

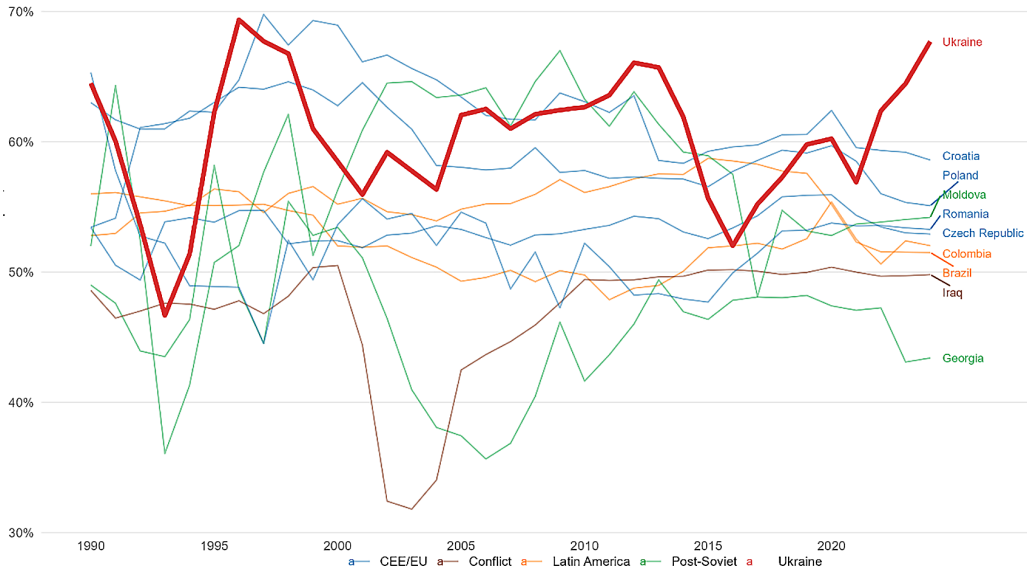

Figure 5. Labour share in GDP: Ukraine in the international context (1990-2024)
Source: prepared by the author

The overall mean labour share for Ukraine over 1990-2024 is 60.4%, with substantial variability (standard deviation 5.1 percentage points). The lowest value (46.7%) falls in 1993, the period of hyperinflation. Particularly noteworthy is the wartime period: following the trough in 2015-2016 (around 52-55%, linked to the Donbas crisis), the indicator rose sharply to 67.7% in 2024 – the highest value for Ukraine since 1998 and one of the highest in the entire country sample. It sharply contrasts with the global long-term trend of declining labour share observed in developed economies since the 1980s (Karabarbounis & Neiman, 2014). This result creates a paradox: formally, the labour share of GDP increased, which is traditionally associated with reduced functional inequality, while personal inequality (Gini) doubled. The resolution of the paradox lies in the structure of wartime redistribution: budget expenditures on defence and payments to military personnel constitute the main channel of increased labour share, alongside a collapse of business profits due to capital destruction and market losses. Within labour incomes, however, radical polarisation is observed: military pay raises the average wage, while civilian sectors (especially those affected by the war) remain low.

This phenomenon substantially distinguishes Ukraine from the "normal" long-term trend of declining labour share observed in Brazil, Colombia, and Georgia. It also calls into question the traditional interpretation of labour share as a measure of functional inequality – under wartime conditions, this indicator does not reflect the real balance between capital and labour, but rather serves as a proxy for budgetary transfers. This result has important methodological implications for further research. In countries undergoing major macroeconomic shocks, the labour share should be interpreted cautiously and considered alongside other distributional indicators. Summing up the analysis of the wartime shock, one can formulate the thesis of a "dual transformation" of the Ukrainian distributional situation. First, a dramatic rise in personal inequality has occurred, bringing Ukraine closer to Latin American standards. Second, an unusual (though possibly temporary) reversal of functional inequality has taken place toward an increased labour share. These two transformations simultaneously reflect the specifics of a wartime economy: large-scale budgetary transfers for defence create a substantial group of high-income recipients while asymmetrically affecting the civilian population. After the end of the war, this situation will inevitably change: the return of military personnel to civilian life, recovery of the private sector, and changes in the structure of budgetary expenditures – all these processes will shape a new distributional situation, which can be analysed only after some time has passed.

The findings of the present study can be situated within an expanding body of contemporary research on income inequality, labour markets, and the distributional consequences of war. Particularly informative for benchmarking are studies published in the last five years that directly address either the Ukrainian case or methodologically comparable contexts. Several recent contributions analysed the Ukrainian labour market under wartime conditions and provided important corroboration of these findings on the asymmetric distributional shock. V. Koziuk & A. Kremez (2023) examined the differentiation of income distribution in Ukraine during the war and post-war period. They concluded that the war has accelerated income polarisation through divergent sectoral trajectories – a conclusion fully consistent with current decomposition of the wartime shock by sector. Their analysis, however, was based on aggregated Derzhstat data and did not employ the alternative-source comparison developed in this study; consequently, the magnitude of the shock they document (a moderate widening of the income gap) is substantially smaller than DINA-informed estimate. This contrast reinforces central methodological argument: survey-based statistics alone tend to understate the true scale of wartime inequality.

A. Giacomo *et al*. (2026) provided a comprehensive analysis of the wartime Ukrainian labour market, documenting an unprecedented compression of formal employment alongside a sharp rise in informal and military-related earnings. Their findings complement current results on the collapse of the B20 labour-income share (from 66% in 2020 to under 25% in 2024) and lend external validity to the "scarring effects" mechanism that was identified. A. Tsapin & O. Zholud (2025) and A. Tsapin (2026) corroborated this picture from the firm-level perspective, showing that corporate employment and wage dynamics during the war exhibit pronounced sectoral and geographic heterogeneity. Their evidence on the divergence between "war-resilient" and "war-affected" sectors directly underpins observation of the 3-4 times wage gap between aviation/IT and education/healthcare/agriculture.

O. Cheromukhina & Y. Chaliuk (2022) provided an early assessment of the wartime labour market, focusing on internally displaced persons and the disruption of regional production networks. Current analysis confirms and extends their findings on the geographical concentration of labour market shocks by linking sectoral wage data with regional patterns of destruction. I. Tsymbaliuk *et al*. (2023) analysed migration trends and unemployment indicators during the war, identifying mass external migration as a structural driver of labour-market disequilibrium. While their study did not directly measure income inequality, their evidence on emigration-induced labour shortages helps explain why the labour share in GDP paradoxically rose during the wartime period – a finding central to this work.

A broader theoretical perspective is offered by T. de Vries & A. Toda (2022), who examined capital and labour income Pareto exponents across countries and over time. Their finding that capital income concentration is systematically higher than labour income concentration in transition economies is directly relevant to current interpretation of the inequality gap as a measure of "hidden" wealth concentration that escapes household surveys. Their cross-country evidence supports current claim that DINA-based estimates capture a structurally important component of inequality that survey methodology misses. S. Braun & J. Stuhler (2023) investigated the long-term labour market consequences of exposure to war, demonstrating that war-induced disruptions produce persistent negative effects on individuals' lifetime earnings – empirical support for the "scarring effects" interpretation that was applied to the Ukrainian B20 trajectory. While their study

examined Second World War cohorts in Germany, the parallels with the contemporary Ukrainian case are striking: an entire cohort of working-age individuals risks long-term marginalisation from the formal labour market, with consequences extending well beyond the war's conclusion.

The regional dimension of inequality in Ukraine was systematically studied by K. Huk & A. Zeynalov (2022), who documented substantial regional disparities and their relationship with economic growth. Their pre-war evidence on persistent regional gaps provides important baseline context for understanding the territorial dimension of the wartime distributional shock identified in this study. The wartime period evidently amplified the pre-existing regional disparities they documented, transforming them into a structural feature of the wartime economy. Beyond the Ukrainian context, the broader empirical literature on inequality measurement provides further validation. R. Steenbrink & A. Skali (2026), leveraging WID data on 165 countries between 1995 and 2019, found a statistically significant negative association between wealth inequality and economic growth (a one-standard-deviation increase in the wealth Gini coefficient corresponds to a 0.34 percentage-point decline in growth rates). This finding directly supports the policy implications drawn from Random Effects model: the U-shaped (anti-Kuznets) relationship identified suggests that, without targeted institutional reforms, the wartime increase in Ukrainian inequality may itself constrain post-war recovery – an argument consistent with the macroeconomic evidence in authors' contribution. Taken together, the contemporary literature supports the central empirical findings of this study: the wartime shock has produced a distributional disruption of unprecedented magnitude, driven by asymmetric labour-market effects, sectoral polarisation, and pre-existing structural vulnerabilities.

CONCLUSIONS

The study allowed the formulation of empirically grounded conclusions regarding income inequality dynamics in Ukraine over 1990-2025. Systematic comparison of four independent data sources revealed that the methodological gap between DINA-based (mean 0.437) and survey-based (mean 0.277) Gini estimates for Ukraine averaged 0.163 points. This gap reflects not a methodological error but the actual concealment of part of the inequality in traditional household surveys, driven by the shadow economy and asset concentration in the top decile. Analysis of variance on 246 observations confirmed a statistically significant ordering of countries across four institutional groups ($F = 51.59$; $p < 0.001$) in the hierarchy: Conflict (Iraq, 0.380) > Post-Soviet (0.186) > Latin America (0.158) > CEE/EU (0.141). Ukraine belonged institutionally to the post-Soviet group, although its empirical IG value (0.163) was lower than the group average, reflecting within-group heterogeneity. This positioning indicates that the Ukrainian case is not a methodological anomaly but reflects the broader pattern of post-Soviet institutional features, even though the magnitude of hidden inequality is somewhat smaller than in Georgia or Moldova.

Testing of the Kuznets hypothesis yielded mixed results. While the pooled OLS model formally confirmed the classical inverted U-curve ($\beta_1 = 1.439$; $\beta_2 = -0.078$; both $p < 0.001$) with a peak at GDP ≈ 10,452 USD PPP, the Random Effects specification – selected via the Hausman test ($\chi^2 = 1.623$; $p = 0.444$) – showed a U-shaped (anti-Kuznets) relationship with a minimum at GDP ≈ 21,288 USD, virtually identical to the Fixed Effects model. This positions Ukraine (GDP ≈ 17,000 USD) before the minimum, in a zone of potential inequality growth as GDP rises, underscoring that targeted institutional reforms – not merely economic growth – are necessary for inclusive development. The most dramatic finding was the wartime inequality shock: the Gini coefficient doubled from 0.256 (2020) to 0.50 (2025), an unprecedented phenomenon for the European region in recent history. The decomposition attributed this shock to the asymmetric collapse of labour incomes in the bottom quintile alongside rising top-decile incomes, a decline in the share of B20 households with labour earnings from 66% to under 25%, and unprecedented sectoral wage differentiation between the "new economy" and traditional sectors. These findings translate into clear policy implications: large-scale support for households that lost access to the labour market, de-shadowing of the economy combined with progressive asset taxation, and regional redistribution mechanisms within the post-war recovery program. Further research will benefit from integrating household microdata, extending panel specifications to include institutional indicators, and analysing the gender dimension of the wartime distributional shock.

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CONFLICT OF INTEREST

None.

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Розрив нерівності та воєнний шок: розподіл доходів в Україні

Анотація. Економічна нерівність є однією з ключових глобальних проблем, а в Україні її оцінювання ускладнюється методологічними розбіжностями, пострадянською інституційною специфікою та безпрецедентними перерозподільними наслідками повномасштабної війни, що розпочалася у 2022 році. Метою дослідження було оцінити динаміку нерівності доходів в Україні за 1990-2025 роки шляхом системного порівняння альтернативних джерел даних та міжнародного бенчмаркінгу щодо країн подібного інституційного типу. Методологічна рамка поєднувала аналітичну категорію «розрив нерівності», однофакторний дисперсійний аналіз (ANOVA) із пост-хок тестом Тьюкі HSD, моделі панельних даних Pooled OLS, Fixed Effects і Random Effects, а також тест Гаусмана для вибору моделі. Аналіз виявив статистично значущу міжгрупову типологію країн за розривом нерівності ($F = 51,59$; $p < 0,001$), у межах якої Україна (0,163) належала до пострадянської групи разом із Грузією (0,211) та Молдовою (0,185). Перевірка гіпотези Кузнеця показала, що крос-країнова інвертована U-крива (Pooled OLS, пік при ВВП ≈ 10 452 дол. США) не підтверджується при врахуванні панельної структури даних: модель Random Effects, обрана за тестом Гаусмана, виявила U-подібний (антикузнецівський) зв'язок із мінімумом при ВВП ≈ 21 288 дол. США. Коефіцієнт Джині в Україні зріс з 0,25 (2020) до 0,50 (2025), а декомпозиція показала асиметричне падіння трудових доходів у нижньому квінтилі разом зі зростанням доходів верхніх децилів як ключовий канал цього шоку. Отримані результати дозволили позиціонувати українську ситуацію не як методологічну аномалію, а як прояв інституційних особливостей пострадянського простору, що потребує системних реформ детінізації економіки та прогресивного оподаткування активів у межах повоєнного відновлення

Ключові слова: нерівність доходів; коефіцієнт Джині; прихована нерівність; DINA; гіпотеза Кузнеця; тіньова економіка; частка праці в доходах

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Digital transformation of port activities in the context of investment-driven development of water transport

Abstract. The global maritime sector shifted from traditional port modernisation to systemic digital integration, which required new economic frameworks to justify smart technology investments while ensuring financial security. The purpose of the study was to substantiate the methodological foundations of the digital transformation of port activities in the context of investment-driven development of water transport. The research employed a comprehensive methodological approach, including system analysis, comparative and structural analysis, and economic-statistical modelling to assess investment efficiency through cash flow indicators, profitability, and risk evaluation. The findings demonstrated that digitalisation functioned as a multidimensional economic driver, reducing administrative and documentation costs by 20-30%, vessel turnaround time by up to 25%, and cargo dwell time by approximately 40%. The study proposed an enhanced investment appraisal methodology integrating Real Options Valuation to account for strategic flexibility and introduced a digital premium that adjusted the discount rate based on increased operational transparency. A key innovation was the incorporation of a technological lag coefficient into payback period calculations, aligning capital recovery with the shorter cycle of digital obsolescence. The results indicated that digital investments generated non-linear returns through increasing returns to scale as more stakeholders joined the ecosystem, enabling shorter payback periods and self-financing cycles. Furthermore, the study conceptualised a mechanism for integrating digitalisation effects into the port's financial security architecture, proving that technological transparency and operational velocity serve as critical reserves for institutional resilience. The classification of digital risks into technological, financial, and cyber clusters allowed for a risk-oriented evaluation where investment projects were filtered through a security threshold to prevent systemic fragility. The practical value of the work lay in the developed tools for the economic justification of smart port projects, which enabled port operators and investors to accurately model incremental effects, optimise capital structure, and strengthen the financial security of water transport infrastructure in a digitalised global environment

Keywords: transport and logistics systems; port infrastructure development; investment efficiency; operational costs; cash flow management; risk assessment; financial and economic security

INTRODUCTION

The rapid transformation of global trade and logistics systems has significantly increased the strategic importance of port infrastructure as a critical node in international supply chains. Under conditions of growing uncertainty,

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geopolitical instability, and increasing requirements for efficiency and sustainability, traditional approaches to port development were becoming insufficient. The transition from physical infrastructure expansion to digital integration was no longer optional but represented a fundamental shift in the economic logic of port development. However, while digital technologies created new opportunities for improving operational performance, they simultaneously generated complex investment challenges related to risk, uncertainty, and the need to ensure financial and economic security. A key problem lay in the inconsistency between the dynamic nature of digital transformation and the inertia of traditional investment evaluation approaches. Existing methods for assessing infrastructure projects were primarily designed for long-term, capital-intensive assets with predictable life cycles, whereas digital technologies were characterised by rapid obsolescence, high uncertainty, and non-linear economic effects. This created a methodological gap in the economic justification of investments in port digitalisation, particularly in terms of integrating risk factors, evaluating financial performance, and ensuring system resilience.

Scientific literature extensively examined the impact of digital transformation on port performance and maritime logistics systems. E. Tijan *et al*. (2021) investigated the role of digital technologies in maritime transport and concluded that automation, artificial intelligence, and blockchain significantly transform operational processes and enable new models of value creation. S. Adabere *et al*. (2021) analysed the relationship between information technology adoption and port performance, demonstrating that digital tools contribute to increased efficiency through process optimisation and reduction of operational delays. G. Boakye *et al*. (2021) focused on data-driven approaches in port management and established that the use of analytical models enhances productivity and decision-making quality. M. Karlsson *et al*. (2023) explored the drivers and barriers of digitalisation in port environments and identified institutional, technological, and organisational constraints that limit the adoption of digital solutions, particularly insufficient investment and regulatory challenges. P.W. de Langen (2023) developed a conceptual framework of port development based on business ecosystems, highlighting the role of digital platforms in coordinating stakeholders and generating value. Z. Su (2026) examined the formation of digital ecosystems in port logistics and demonstrated that integration of digital technologies improves coordination and overall system performance. The investment dimension of digital transformation has also been addressed in recent studies. T. Notteboom *et al*. (2021) analysed the impact of global disruptions on port systems and emphasised the need for investments in digital technologies to enhance resilience and adaptability. M. Mollaoglu & M. Gul (2025) investigated the relationship between digital transformation strategies and investment decision-making, concluding that digitalisation significantly influences long-term competitiveness in maritime transport. O.-P. Brunila *et al*. (2021) studied the implementation of advanced technologies such as 5G in smart ports and identified both opportunities and infrastructural constraints affecting investment efficiency. T. Koritarov & D. Dimitrakiev (2025) substantiated that digitalisation is a key factor in improving the efficiency, sustainability, and competitiveness of modern ports.

In the context of increasing uncertainty and systemic risks, particular attention has been paid to the issues of resilience and security. A.K.Y. Ng *et al*. (2025) analysed the role of digital technologies in enhancing the resilience of maritime transport systems and demonstrated that digital solutions improve adaptability and risk assessment capabilities. G.V. Iefimova & O.V. Pashchenko (2025) examined the financial and economic security of port activities and concluded that digital transformation requires the integration of risk-adjusted approaches to investment evaluation and new criteria for ensuring financial and economic security. Despite the significant number of studies, the existing literature mainly focuses on either technological aspect of digitalisation or general issues of port development. At the same time, there is a lack of comprehensive methodological approaches that integrate digital transformation factors into the economic justification of investments, taking into account financial performance indicators, risks and security aspects. This determines the need for further research in this area. The purpose of the article was to substantiate the theoretical and methodological foundations of digital transformation of port activities in the context of investment-driven development of water transport and to develop a methodological approach to the economic justification of investments in port digitalisation, considering financial performance indicators, technological uncertainty, digital risks and security aspects.

MATERIALS AND METHODS

This study was based on a comprehensive methodological approach aimed at analysing the digital transformation of port activities in the context of investment-driven development of water transport. The research design combined theoretical generalisation, comparative analysis, and elements of economic modelling to ensure consistency and reproducibility of the results. The research process included several interconnected stages. At the initial stage, the problem was identified and global trends in the development of water transport and port infrastructure were analysed based on international analytical and statistical sources, including reports by the European Commission (n.d.), the World Bank (2025) and United Nations (2025) which provided a systematic overview of current challenges in maritime logistics and port digitalisation. To define the policy and institutional context of port digitalisation, the study also considered national and international strategic documents. In particular, the Danish Maritime Authority (n.d.) was used to identify how national maritime policy links digital technologies with efficiency improvement and sustainable development. The position of the International Maritime Organisation (2025) was analysed to determine the global priorities of maritime digitalisation, including safety, environmental performance and operational efficiency. In addition, OECD (2020) materials were used to place port digital transformation within broader digital economy trends, where data-driven technologies influence value creation, investment decisions and sectoral development. This stage allowed for the identification of key structural changes in maritime logistics, including increasing

digitalisation, supply chain disruptions, and the growing role of data-driven management.

The next stage involved the systematisation of methodological approaches relevant to the evaluation of port performance, investment efficiency, and digital transformation. In particular, multi-criteria approaches to port performance assessment were considered based on V. Lorenčič *et al*. (2022), which allowed for the identification of key performance dimensions beyond purely financial indicators. In addition, recent empirical studies on digital maturity and organisational performance, such as K.C. Shang *et al*. (2026), were used to incorporate the concept of dynamic capabilities and non-linear efficiency effects into the analytical framework. These approaches were selected because traditional models of investment evaluation do not sufficiently account for the complexity, uncertainty, and rapid technological change associated with digitalisation. Based on this, a methodological framework for the economic justification of investments in the digital transformation of port activities was developed. This framework integrates traditional investment appraisal tools with elements that reflect the specific characteristics of digital technologies, including shorter life cycles, higher uncertainty, and non-linear returns. The proposed approach combines traditional financial indicators, including net present value (NPV), internal rate of return (IRR), payback period (PP), and cash flow modelling, with additional digitalisation-specific parameters such as the digital premium, technological lag coefficient, and risk-adjusted discount rate. The assessment methodology also incorporates elements of real options valuation (ROV) to account for strategic flexibility and future technological expansion opportunities. The evaluation procedure was carried out using comparative analysis, economic-statistical modelling, scenario-based assessment, and risk analysis methods. Quantitative evaluation included the estimation of incremental revenues, operational cost savings, logistics efficiency indicators, and discounted cash flows, while qualitative assessment focused on operational transparency, resilience, interoperability, and cyber-security risks.

A set of general scientific and special methods was applied in the study. System analysis made it possible to consider port infrastructure as an integral element of transport and logistics systems and to identify the interrelations between digitalisation, investment processes and operational performance. Comparative and structural analysis were used to evaluate the impact of digital technologies on cost structure, port operations and efficiency indicators. Economic and statistical methods were applied to assess investment efficiency through indicators of cash flows, profitability and cost optimisation. In addition, methods of abstraction and generalisation were used to develop a unified methodological approach, while risk analysis methods allowed the identification and classification of key risks associated with digital transformation. The analytical assessment of the proposed methodological framework was carried out using a system of quantitative and qualitative criteria. Quantitative evaluation included the calculation and interpretation of standard financial indicators, such as net present value NPV, IRR, payback period, and changes in operating costs and revenue streams resulting from digitalisation. Qualitative assessment was based on criteria such as the level of operational transparency, improvement of coordination between stakeholders, service quality enhancement, and the ability to increase system resilience. In addition, risk-adjusted evaluation criteria were applied, taking into account uncertainty, variability of cash flows, and potential technological obsolescence. The empirical basis of the study relies on secondary data obtained from international analytical reports, statistical materials, and scientific publications in the field of maritime transport and logistics, including United Nations (2025), World Bank (2025), and recent peer-reviewed studies. This ensures the reliability, comparability, and relevance of the results. The use of generally accepted analytical tools and accessible data sources allows the proposed methodology to be replicated in different contexts, confirming its scientific validity and practical applicability.

RESULTS AND DISCUSSION

Impact of digitalisation on costs, port charges and logistics efficiency

Digital transformation of port activities represented a complex and multidimensional process that involves the integration of advanced information and communication technologies into operational, managerial and logistical processes. In the context of water transport development, digitalisation was defined as the systematic implementation of digital solutions aimed at increasing efficiency, reducing costs, enhancing transparency and improving the coordination of transport and logistics systems. Unlike traditional modernisation, digital transformation implied not only technological upgrades but also structural changes in business models, decision-making processes and interaction between stakeholders. Modern ports were increasingly evolving into so-called “smart ports”, where digital technologies ensured real-time data exchange, automation of operations and optimisation of resource use. As noted by E. Tijan *et al*. (2021), digital transformation significantly enhanced the efficiency of maritime transport systems by enabling data-driven management and integration of logistics chains. At the same time, Z. Su (2026) emphasised that digitalisation contributes to the formation of integrated digital ecosystems, where ports act as key nodes connecting various participants of global supply chains.

Among the key technologies that formed the basis of digital transformation in port activities, the Internet of Things (IoT) played a crucial role. IoT enabled the collection and transmission of real-time data from physical objects such as containers, cargo handling equipment and transport vehicles. For example, the implementation of sensor-based monitoring systems in ports allows tracking the location and condition of cargo, reducing delays and minimising losses. According to S. Adabere *et al*. (2021), the use of such technologies significantly improved operational efficiency and reduced idle time in seaports. Another important technological component was Big Data analytics, which allowed processing large volumes of structured and unstructured data generated by port operations. The use of Big Data enabled forecasting cargo flows, optimising port capacity utilisation and improving decision-making processes. For instance, ports that applied predictive analytics can better manage peak loads and reduce congestion, thereby lowering operational costs. The

importance of data-driven decision-making in port management is also highlighted by M. Karlsson *et al*. (2023), who identified data availability and analytical capabilities as key drivers of digitalisation.

AI further expanded the possibilities of digital transformation by enabling automation and intelligent optimisation of complex processes. AI technologies are used in ports for demand forecasting, automated scheduling of cargo handling operations and optimisation of logistics routes. In practice, AI-based systems can dynamically allocate resources depending on real-time conditions, increasing overall efficiency. As noted by K.C. Shang *et al*. (2026), the integration of AI into maritime transport systems was closely linked to the development of dynamic capabilities and improvement of organisational performance. Blockchain technology was another important element of digital transformation in port activities, particularly in ensuring transparency and security of transactions. Blockchain enabled the creation of decentralised and tamper-proof databases for recording transactions and tracking cargo movements. For example, the use of blockchain platforms in port logistics allowed reducing paperwork, accelerating customs procedures and minimising the risk of fraud. According to E. Tijan *et al*. (2021), blockchain significantly improved trust among supply chain participants and enhanced the efficiency of information exchange. In addition to individual technologies, the combined application of IoT, Big Data, AI and blockchain created a synergistic effect, transforming ports into integrated digital platforms. Such integration allowed not only improving operational performance but also creating new opportunities for investment and innovation. However, as highlighted by M. Karlsson *et al*. (2023), the implementation of these technologies required significant financial resources and faced barriers related to infrastructure, regulation and organisational readiness. The diversity and complexity of digital solutions in port environments were systematised in recent smart port studies, which highlighted the multidimensional nature of digital transformation and the interconnection between technological, organisational, and sustainability domains (Belmoukari *et al*., 2023). Thus, digitalisation in port activities was a key factor in increasing the efficiency and competitiveness of water transport systems. The use of advanced digital technologies not only transformed operational processes but also created a foundation for sustainable investment development and long-term growth of port infrastructure. The integration of digital technologies into port activities generated measurable economic effects, particularly in terms of cost reduction, optimisation of port charges and improvement of logistics efficiency. The obtained results confirmed that digital transformation acts as a key factor in increasing operational performance and investment attractiveness of port infrastructure.

Empirical evidence indicated that the implementation of digital solutions contributes to a significant reduction in operational costs. According to the World Bank (2025), the use of port community systems and automated data exchange platforms reduced administrative and documentation costs by approximately 20-30%. Similar results were reported by E. Tijan *et al*. (2021), who noted that automation of cargo handling processes and the use of digital tracking systems reduced vessel turnaround time by up to 25%, which directly affected port operating expenses. In addition, the application of IoT-based monitoring systems enabled predictive maintenance of equipment, reducing maintenance costs by around 10-15% (Adabere *et al*., 2021). The impact of digitalisation on port charges was primarily indirect and was manifested through increased transparency and optimisation of tariff structures. Digital platforms allowed for real-time calculation of port fees based on actual service usage, reducing inefficiencies and hidden costs. According to the European Commission (n.d.), the implementation of digital billing and integrated information systems contributed to a reduction in transaction costs by approximately 15-20%. At the same time, the standardisation of procedures and the reduction of administrative barriers led to a decrease in total logistics costs for port users.

The effect of digital transformation on logistics efficiency was particularly significant. The use of Big Data analytics and artificial intelligence allowed for optimisation of cargo flows, reduction of congestion and improvement of resource allocation. For example, ports implementing advanced data analytics systems demonstrated an increase in cargo throughput efficiency by 10-20% (Karlsson *et al*., 2023). This was also consistent with (Kotenko *et al*., 2022), who emphasised the role of transport infrastructure efficiency and transit potential in enhancing logistics performance under conditions of economic transformation. These findings were also consistent with studies demonstrating that improvements in port connectivity and logistics performance have a significant positive impact on trade efficiency and economic growth (Liang & Liu, 2020). Furthermore, blockchain technologies contributed to the acceleration of document processing and customs clearance procedures, reducing cargo dwell time by up to 40% (Tijan *et al*., 2021). The quantitative results of the impact of digitalisation on key performance indicators of port activities were summarised in Table 1.

Table 1. Impact of digitalisation on key economic indicators of port activities

Indicator	Effect of digitalisation	Average change, %
Operational costs	Decrease	20-30
Maintenance costs	Decrease	10-15
Transaction (administrative) costs	Decrease	15-20
Vessel turnaround time	Decrease	up to 25
Cargo dwell time	Decrease	up to 40
Logistics efficiency (throughput)	Increase	10-20

Source: compiled by the authors based on European Commission (n.d.), E. Tijan *et al*. (2021), S. Adabere *et al.* (2021), M. Karlsson *et al.* (2023), World Bank (2025)

The presented results demonstrated that the economic effects of digitalisation are multidimensional and mutually reinforcing. Cost reduction was achieved through automation and optimisation of processes, while improvements in logistics efficiency led to increase throughput and better utilisation of port infrastructure. At the same time, the reduction of transaction costs and increased transparency contributed to the optimisation of port charges and enhanced the overall investment attractiveness of ports. In comparison with existing studies, the obtained results were consistent with the findings of M. Mollaoglu & M. Gul (2025), who emphasised the role of digital transformation in improving operational efficiency and reducing costs in maritime transport. Similarly, T. Notteboom *et al*. (2021) underlined that digitalisation enhances the resilience and adaptability of port systems, particularly under conditions of global disruptions. However, unlike previous studies, the presented results provided a more integrated assessment of the economic effects of digitalisation by simultaneously considering costs, port charges and logistics efficiency within a unified analytical framework.

At the same time, the results raised several discussion issues. Despite the positive economic effects, the implementation of digital technologies required significant initial investments, which may limit their adoption, especially in developing port systems. In addition, the uneven level of digital maturity across ports created disparities in efficiency and competitiveness. As noted by O.-P. Brunila *et al*. (2021), infrastructural and technological barriers remained significant constraints for large-scale digital transformation. In addition, institutional and regulatory factors, including the role of state support in transport system development, remained critical, as noted by (Lutsenko, 2021). Thus, digitalisation had a substantial impact on the economic performance of port activities, contributing to cost reduction, optimisation of port charges and increased logistics efficiency. These findings confirmed the strategic importance of digital transformation as a key driver of investment development in water transport, while also highlighting the need for further research on balancing costs and benefits of digital investments.

Methodological approach to the economic justification of investments in port digitalisation

The development of a comprehensive methodological approach to the economic justification of investments in digital transformation was a critical step in ensuring the sustainable development of water transport. Unlike traditional infrastructure projects, digital investments were characterised by a high degree of intangible benefits and systemic effects that require a specific set of evaluation tools. The proposed approach was based on the integration of classical investment appraisal methods with the quantification of operational shifts derived from the implementation of smart technologies.

The central element of this methodology was the transition from simple cost accounting to the modeling of incremental effects. The system of indicators was structured to reflect the life cycle of digital solutions and their impact on the port's financial position. A key component of this approach was the modelling of cash flows, where the fundamental metric was the net cash flow generated specifically by the digitalisation project. In the context of port activities, the annual cash flow (CF_t) is defined as:

$$CF_t = (\Delta R_t + \Delta S_t) - (OC_t + M_t + T_t), \quad (1)$$

where ΔR_t – incremental revenue from increased throughput and new digital services; ΔS_t – cost savings (energy, labour, administrative expenses); OC_t – ongoing operational costs of the digital system; M_t – maintenance and software update costs; T_t – costs of personnel training and adaptation.

To justify the long-term viability of digital investments, particular attention was given to profitability indicators, including NPV and IRR, which must account for the specific "digital premium", defined as a reduction in the risk-adjusted discount rate due to increased operational transparency. This evaluation was further enhanced through the integration of Real Options logic, recognising that initial digital investments create a strategic foundation for future technological expansion without significant additional capital expenditures. Empirical evidence from global smart ports suggested that incorporating digitalisation effects into NPV calculations often reveals that projects appearing marginal in terms of direct revenue become highly attractive when considering total cost optimisation and reduced information asymmetry for stakeholders (Karlsson *et al*., 2023; World Bank, 2025). In this context, the recalculation of IRR reflected not only direct cost savings but also an increase in the asset turnover ratio, which served as an indicator of digital maturity and long-term financial resilience.

Given the rapid obsolescence of digital technologies, the PP becomes a critical constraint, requiring a transition from static models to a risk-adjusted approach. The proposed methodology demonstrated that digital transformation significantly shortens the payback period by accelerating cargo processing, as evidenced by the reduction of operational procedures from hours to seconds in Tianjin Port (Su, 2026). At the same time, the recovery process is characterised by non-linearity due to increasing returns to scale within digital ecosystems. To ensure financial resilience, a "technological lag coefficient" is incorporated into the payback period calculation, allowing investment recovery to be benchmarked against the shorter 3-5-year cycle of digital obsolescence rather than the long-term life cycle of physical infrastructure. This acceleration contributes to the formation of a liquidity cushion and enables self-financing cycles, where rapid capital recovery from initial digital modules, such as automated gate systems, generated internal resources for subsequent technological integration, thereby reducing dependence on external financing and strengthening the overall financial and economic security of the port.

To address the limitations of traditional investment appraisal, the methodological framework was expanded through the integration of several specialised conceptual components. The first component involved the incorporation of the real options valuation concept, aimed at overcoming the constraints of traditional net present value, which tends to underestimate digitalisation by treating investments as linear and fixed. In this study, digital transformation is conceptualised as the creation of a "digital foundation" for future innovations. Accordingly, the

classical NPV approach was supplemented with the ROV method, allowing for the consideration of strategic flexibility. Initial investments in digital platforms generated an "option to expand", enabling the subsequent implementation of advanced technologies, such as autonomous transport systems or blockchain-based smart contracts, without significant additional capital expenditures. This substantially increased the overall strategic value of investment projects compared to baseline scenarios.

Another important element of the framework was the adjustment of the discount rate through the concept of "data transparency". The digital premium was formalised by establishing a link between the quality of operational data and financial risk. The implementation of IoT technologies and real-time monitoring systems reduced information asymmetry for investors, thereby improving the transparency of operational processes. This allowed for the decomposition of the discount rate by isolating a digital transparency coefficient, which led to an increase in the project's internal rate of return not only due to higher cash inflows but also due to a reduction in the risk premium associated with operational opacity. A further component of the methodology was the integration of externalities into cash flow structures. Digitalisation often generates immediate financial benefits for port users, such as shipowners, through reduced vessel turnaround time and improved service efficiency. Although these effects were not directly reflected in the port's revenues, they were transformed into competitive advantages over time, contributing to increased customer loyalty and market share. Within the proposed approach, such indirect financial effects were incorporated into the NPV model, allowing ports to apply more flexible pricing strategies and attract technologically advanced carriers, thereby ensuring long-term stability and predictability of cash flows.

The final component concerned the introduction of dynamic payback thresholds and the mitigation of "technological lag". This element moved beyond the static calculation of the payback period toward a risk-adjusted model that accounts for the life cycle of digital assets. Given that digital software and hardware have a significantly shorter life cycle, typically ranging from 3 to 5 years, compared to physical infrastructure such as berths with a lifespan of 20 to 50 years, it is proposed to integrate a technological lag coefficient into the PP calculation ("digital obsolescence" buffer). This implies that the target payback period for digital investments should be strictly shorter than the expected cycle of the next technological upgrade. By accelerating throughput, for example reducing operational processes from hours to seconds as observed in Tianjin Port, digitalisation creates a "liquidity cushion" that enables the port to recover invested capital before the technology becomes obsolete.

At the same time, digital payback was characterised by cumulative efficiency rather than linear recovery. Unlike traditional infrastructure, which generated relatively constant marginal utility, digital systems demonstrated increasing returns to scale. As more stakeholders, including carriers, customs authorities, and terminal operators, became integrated into the digital ecosystem, the speed and efficiency of cargo processing increased exponentially, resulting in a compressed payback period at later stages of implementation. These transformations also corresponded to the shift toward customer-oriented and flexible logistics service models described by M. Hryhorak *et al*. (2020). Furthermore, the proposed approach considered the shortened payback period of digital projects as a mechanism for internal self-financing. Rapid capital recovery from initial digitalisation initiatives, such as automated gate systems, generated immediate liquidity that can be directed toward subsequent stages, including more advanced solutions like AI-driven berth planning. This created a "virtuous cycle" of investment, reducing dependence on costly long-term external financing and strengthening the overall financial and economic security of port operations.

The generalised results presented above can be further reinforced through an empirical illustration demonstrating the practical application of the proposed methodological framework. To this end, it was considered a stylised yet empirically grounded example of implementing a port community system (PCS) in a mediumsized seaport. This example provided a clear representation of how incremental effects, the "digital premium", and the logic of real options valuation collectively influence the economic assessment of digital investments. According to international studies referenced earlier, PCS implementation led to a 20-30% reduction in administrative and documentation costs, a decrease of up to 25% in vessel turnaround time, and a reduction of up to 40% in cargo dwell time, while predictive maintenance enabled by IoT technologies lowers equipmentrelated expenditures by 10-15% (European Commission, n.d.; Adabere *et al*., 2021; World Bank, 2025). Based on these empirically verified indicators, the modelled investment parameters included an initial capital expenditure of USD 4 million, annual operational cost savings of USD 0.9 million, additional revenue of USD 0.35 million attributable to increased throughput, and annual maintenance expenses of USD 0.25 million. Within our methodological framework, the annual incremental cash flow was thus calculated according to equation (1).

Incorporating the reduced risk profile associated with improved data transparency – reflected in a 1.5% "digital premium" applied to the discount rate – the effective discount rate is adjusted to 10.5%. The five-year discounted cash flow analysis yields a net present value of NPV = -0.262 million USD, which would traditionally position the project at the borderline of financial feasibility. However, as argued in the previous sections, digital transformation projects should not be evaluated as static, standalone investments but rather as foundational digital infrastructures that create strategic flexibility for future expansion. In the context of PCS deployment, this strategic flexibility was manifested in the ability to integrate additional modules such as AIbased berth scheduling, blockchainenabled documentation flows, and automated congestion forecasting systems. Empirical evidence from comparable port systems suggested that these extensions may generate approximately USD 0.4 million in additional annual benefits, modifying the cash flow to:

$$CF_t^{ROV} = 1.0 + 0.4 = 1.4 \text{ mln USD}.$$

Applying the real options valuation logic to incorporate this "option to expand" significantly altered the

project's financial profile. Under these revised conditions, the adjusted net present value became NPV_{ROV} = 1.233 mln USD, indicating a strongly positive investment outlook. This result empirically confirmed the non-linear nature of digital returns: performance gains raised not only from direct cost savings but also from cumulative ecosystem effects and the progressive expansion of digital functionality. The payback period further substantiated this conclusion. Given the rapid technological obsolescence typical of digital systems – estimated at 3-5 years – the payback period became a critical determinant of investment resilience. In the presented example, the adjusted payback period was:

$$PP = \frac{4}{1.4} \approx 2.9 \text{ years},$$

which falls well within the acceptable technological cycle. This accelerated recovery reflected the synergetic effects of increasing returns to scale: as more stakeholders adopt the digital platform, the marginal efficiency gains amplify, enabling internal reinvestment and reducing dependence on external financing. Overall, the empirical modelling results supported the core arguments advanced in this study. Digitalisation generated a multidimensional economic impact by simultaneously reducing costs, accelerating operational cycles, enhancing transparency, and creating strategic opportunities for innovation-driven growth. The proposed methodological framework made it possible to account for these complex and interdependent effects, thereby enabling more accurate and forward-looking investment decisions in the development of port infrastructure.

Comprehensive consideration of costs and digitalisation effects

A robust economic justification required a balanced view of the investment burden versus the efficiency gains. Within the proposed methodological approach, these factors were categorised into three interrelated components. The first component concerned investment expenditures (CAPEX) include not only tangible assets such as IoT sensors, 5G infrastructure, and servers, but also intangible elements, including digital platforms, data analytics systems, and cybersecurity protocols. The second component related to operational expenditures (OPEX) reflect a structural shift in cost composition, whereby labour costs decrease due to automation, reaching reductions of up to 60% in automated terminals, while costs related to system maintenance and data management increase moderately. Nevertheless, the overall effect remained positive due to the implementation of predictive maintenance and more efficient resource utilisation (Adabere *et al*., 2021). The third component represented the digitalisation effect represents the core "value driver" within the methodology. It is manifested through several interconnected outcomes, including cost reduction, such as decreased energy consumption of approximately 17% and lower administrative overhead; operational acceleration, reflected in faster vessel turnaround and reduced cargo dwell time; and logistics synergy, achieved through enhanced real-time monitoring, which minimises "hidden costs" associated with delays and operational errors.

The proposed methodological approach explicitly incorporated the "security-through-efficiency" principle. By improving the accuracy of cash flow forecasting and ensuring real-time control over port operations, digitalisation acted as a tool for strengthening the financial and economic security of the port enterprise. However, the transition to a digital model introduced a new layer of volatility. The acceleration of financial flows and the reliance on automated systems necessitated a specialised framework for risk assessment. The strategic shift towards a digital-centric port model necessitated a redefinition of the port's economic resilience. While digitalisation mitigated traditional operational risks (such as human error or data opacity), it simultaneously introduced systemic cyber-vulnerabilities and the risk of technological lock-in. In this context, financial security was no longer just about liquidity and profitability; it was about the port's capacity to maintain core economic functions during potential system failures or cyber-attacks. Consequently, the proposed methodological approach treated digital investments not merely as profit-generating assets, but as critical infrastructure components that require a dual-layer protection strategy: one aimed at capital recovery and another at safeguarding the integrity of the digital ecosystem. This methodological foundation served as the basis for the subsequent analysis of cyber-risks, technological dependencies, and the broader financial security architecture required to protect port infrastructure in an increasingly digitalised global environment. This transition to risk-oriented evaluation was crucial for ensuring that the economic benefits identified in this section were not undermined by emerging digital threats.

Risk assessment and financial-economic security of port digitalisation

The transition to a digitalised port model shifted the paradigm of economic security from physical asset protection to the integrity and availability of data flows. In this context, financial and economic security was defined as the port's ability to maintain stable operations and capital recovery cycles despite internal and external digital disruptions. This approach was consistent with general principles of risk assessment in large-scale transport infrastructure projects, where uncertainty and long-term investment exposure require systematic identification and mitigation of risks (Tzvetkova, 2020). To develop effective mitigation strategies, the risks associated with port digitalisation were classified into three primary clusters. Technological risks include the potential for "technological lock-in", reflecting dependency on a single vendor, interoperability failures between legacy infrastructure and newly implemented digital platforms, and the rapid obsolescence of hardware, which may outpace the expected payback period. Financial risks were characterised by the volatility of maintenance costs, the possible underestimation of the total cost of ownership (TCO), and the risk of "stranded assets" in cases where a selected digital standard became unsupported within the global maritime environment. Cyber risks represented the most critical category in the context of smart ports and encompass threats such as data breaches, ransomware attacks targeting terminal operating systems (TOS), and GPS/AIS spoofing, all of which may lead to disruptions in port operations, physical congestion, and significant financial losses. Digital transformation acts as both a disruptor and a stabiliser of the port's risk

environment. The proposed approach emphasised the "security-through-efficiency" mechanism, according to which improvements in operational performance directly contribute to risk reduction and overall system stability. Digitalisation reduced operational risks by automating manual processes and minimising the "human factor", which was responsible for a significant share of maritime accidents and documentation errors. The implementation of real-time IoT monitoring systems enabled early identification of potential equipment failures, reducing the probability of costly downtime and additional operating losses.

At the same time, digital transformation enhanced financial transparency using digital ledgers, including blockchain technologies, and integrated information platforms. These tools reduced the risks associated with corruption, shadow economic activities, and information asymmetry, thereby contributing to more stable and predictable cash flows. As a result, the financial position of the port was strengthened, which may improve its creditworthiness and reduce the cost of attracting external financing for future investment projects. To protect the investment-oriented development of water transport, a multi-level risk minimisation system was proposed, combining technological, organisational and financial measures. A key component of this system was the diversification of the digital architecture using open-source standards and modular cloud solutions, which reduced dependence on a single supplier and ensures the flexibility and scalability of digital systems. In parallel, the implementation of cyber resilience systems involved a transition from a passive protection model to an active resilience model, including regular stress testing of digital twins and the implementation of decentralised data storage protocols to increase the system's resilience to cyber threats.

At the economic level, this approach involved the formation of internal "digital reserve funds", as well as the use of specialised insurance instruments, such as cyber insurance, adapted to the specific risks of port logistics. Finally, constant adaptation of personnel remained a critical element of the system, since the changing risk landscape required support for the "man in the loop" principle. Ongoing training and development programs helped reduce the likelihood of internal security breaches and ensured effective management and oversight of increasingly automated systems. Thus, the assessment of risks and financial security was not a separate stage but an integral filter for the economic justification of investments. A project with a high IRR may be rejected if its "cyber-vulnerability score" exceeds the port's security threshold. This risk-adjusted evaluation ensured that digitalisation serves as a driver of sustainable and secure growth, rather than a source of systemic fragility in the maritime transport sector.

The proposed mechanism was based on the strategic conversion of operational advantages derived from digitalisation into multi-layered protective barriers for the port's financial and economic system. In this framework, digital transformation was viewed not merely as a tool for profit maximisation, but as the fundamental structural component of institutional resilience. By quantifying the impact of high-tech solutions on the stability of cash flows and the transparency of maritime operations, it was defined a clear transmission channel: from technological input to economic security output. This integration ensures that the "digital premium" acted as a buffer against market volatility and systemic disruptions. The structural relationship between specific digital effects and the resulting enhancements in the port's financial architecture was systematised in Table 2.

Table 2. Structural matrix of the digitalisation-security integration mechanism

Digitalisation effect	Impact on financial architecture	Security outcome (resilience benefit)
Real-time IoT data & Big Data analytics	Reduction of information asymmetry & operational opacity	Information security: mitigation of shadow economic activities and unauthorised data manipulation
Automation of cargo handling	Shift from variable to fixed costs; elimination of the "human factor"	Operational resilience: stabilisation of predictive cash flows and reduction in accident-related financial losses
Blockchain & smart contracts	Acceleration of transaction cycles and payment verifiability	Liquidity security: minimisation of accounts receivable risks and optimisation of working capital turnover
Predictive maintenance	Optimisation of the CAPEX/OPEX balance and asset life-cycle	Asset integrity: prevention of critical infrastructure failure and protection against "stranded asset" risks
Digital twins & AI simulation	Stress-testing of financial scenarios and risk modelling	Strategic security: data-driven justification of long-term investments and adaptive crisis management

Source: developed by the authors

The proposed mechanism of ensuring financial and economic security of port activities is based on a multi-level model that reflects the transformation of technological inputs into economic and security outcomes. The logic of the mechanism was grounded in the integration of digital technologies into port operations, which generate measurable financial effects and enhance the resilience of port systems under conditions of uncertainty. At the input level (technological impulse), the mechanism was driven by the implementation of advanced digital technologies, including the IoT, AI and 5G communication networks. These technologies enable the continuous generation and transmission of verified real-time data across port infrastructure. The availability of high-quality data significantly improved situational awareness and operational control, forming the basis for subsequent economic transformations.

At the transformation level (economic conversion), the generated data was converted into economic value through several key channels. First, increased transparency and data reliability contribute to the reduction of uncertainty, which allows for a lower discount rate in investment appraisal. This led to higher net present value of digital projects and improves their investment attractiveness. Next, the acceleration of operational processes, achieved through automation and real-time decision-making, reduced cargo handling time and shortened the payback

period of investments. Also, the automation of routine operations and optimisation of resource allocation result in cost savings, which form an additional financial buffer, defined as a "liquidity cushion". This reserved enhances the financial stability of port operators and increases their ability to withstand external shocks.

At the security level (result), the cumulative economic effects of digitalisation lead to the formation of an integrated architecture of financial and economic security. This architecture provides protection against three main types of threats. Financial risks were mitigated through the stabilisation of cash flows, supported by predictable revenue streams and reduced operational costs. Operational risks were minimised due to the reduction of human errors and the increased reliability of automated systems. Investment risks were addressed through the application of flexible decision-making tools, including real options, which allowed for the adaptation of investment strategies to changing market conditions. The functioning of the proposed mechanism is illustrated in Figure 1.

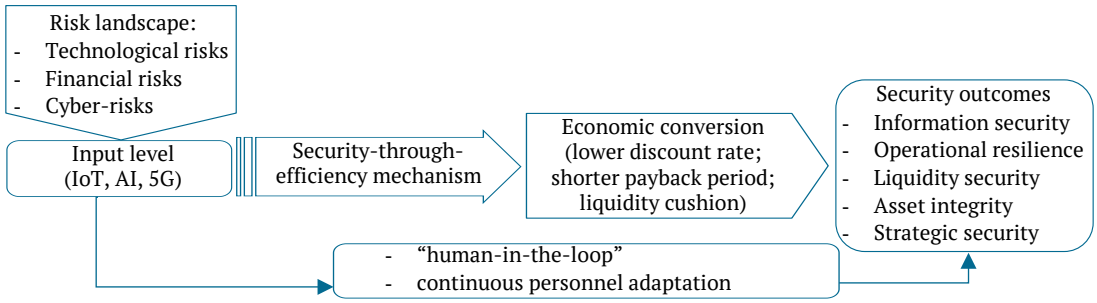

Figure 1. Mechanism of transformation of digital technologies into financial and economic security of port activities
Source: developed by the authors

The scientific significance of the proposed mechanism lay in the reinterpretation of the concept of financial and economic security in port activities. Unlike traditional approaches, which focused primarily on physical infrastructure protection and risk mitigation, the presented model considered data integrity and operational velocity as key strategic assets. This approach substantiated that the economic effects of digitalisation form not only an additional source of profitability but also a critical reserve that ensured the long-term sustainability of port systems in a volatile global environment. Thus, the mechanism demonstrated that digital transformation fundamentally changes the logic of investment evaluation and financial-economic security assessment in port infrastructure. The so-called "digital premium" should be interpreted not as an optional benefit, but as a necessary condition for maintaining competitiveness and ensuring financial and economic security in modern transport and logistics systems.

The obtained results confirmed that digital transformation in port activities generates a complex and multidimensional economic effect, which simultaneously affects cost structures, operational efficiency, and investment performance. Unlike prior studies that primarily focused on technological or organisational aspects, this research provided an integrated interpretation of digitalisation outcomes through financial and investment indicators. The empirical results demonstrating a 20-30% reduction in administrative and operational costs, as well as a decrease in vessel turnaround time and cargo dwell time, were consistent with existing findings. Similar cost reductions and efficiency gains were reported by World Bank (2025) and S. Adabere *et al*. (2021), who emphasised the role of digital platforms and automated data exchange in reducing transaction costs and operational delays.

At the same time, the present study extends these findings by quantifying their direct impact on cash flow generation and investment attractiveness, which is rarely addressed in previous research. The identified improvements in logistics efficiency and throughput capacity confirm the conclusions of M. Karlsson *et al*. (2023), who highlighted data availability and analytical capabilities as key drivers of performance in digitalised ports. However, while M. Karlsson *et al*. (2023) primarily analysed operational effects, this study demonstrated that these efficiency gains have a direct financial dimension, reflected in increased asset turnover and accelerated capital recovery. Thus, digitalisation should be interpreted not only as an operational improvement tool but also as a mechanism for enhancing investment efficiency. The results related to the optimisation of port charges and reduction of transaction costs align with the findings of the European Commission (n.d.), which emphasised the role of digital billing systems and integrated information platforms. In contrast to existing studies, the present research incorporated these effects into a broader financial model, showing that improved transparency and cost optimisation contribute to the formation of a "digital premium" through a reduction in the risk-adjusted discount rate.

The methodological contribution of this study was particularly evident in the development of an extended investment evaluation framework. The integration of dynamic capabilities and non-linear efficiency effects corresponded to the approach proposed by K.C. Shang *et al*. (2026), who demonstrated that digital maturity enhances organisational performance. However, this study advanced the discussion by applying these concepts at the infrastructure level and linking them to investment indicators such as NPV, *IRR*, and payback period. Similarly, the use of a multi-criteria perspective in evaluating port performance was consistent with V. Lorenčič *et al*. (2022), who underlined the importance of combining economic and operational indicators. Nevertheless, the present research expanded this approach by incorporating risk-adjusted financial metrics and by explicitly accounting for the effects of technological uncertainty and digital obsolescence. An important finding of this

study was the identification of non-linear returns to digital investments, driven by ecosystem effects and increasing returns to scale, which was consistent with the business ecosystem perspective in port development (de Langen, 2023). This result supported the conclusions of Z. Su (2026), who highlighted the role of digital ecosystems in improving coordination among port stakeholders. At the same time, the current research extended this perspective by demonstrating how these ecosystem effects translate into shorter payback periods and self-financing investment cycles.

The results also confirmed the growing importance of resilience in digitalised port systems. In line with A.K.Y. Ng *et al*. (2025), digital technologies enhance adaptability and risk mitigation capabilities. However, this study contributed to the literature by proposing a structured classification of risks (technological, financial, and cyber) and by introducing a risk-adjusted investment filter, where financial indicators were evaluated in conjunction with cyber-vulnerability thresholds. Furthermore, the proposed "security-through-efficiency" mechanism provided a novel interpretation of financial and economic security in port activities. While previous studies (Ng *et al*., 2025) emphasised resilience, the present research demonstrated that operational efficiency itself became a source of financial stability by improving predictability of cash flows and reducing uncertainty.

The results highlighted that traditional investment evaluation approaches were insufficient for digital projects due to their shorter life cycles and higher uncertainty. The introduction of a technological lag coefficient and the application of Real Options Valuation addressed this limitation by aligning capital recovery with the dynamics of digital obsolescence. This finding complemented the existing literature on digital transformation and investment strategies (Mollaoglu & Gul, 2025), while providing a more detailed and operationalised methodological framework. Overall, the discussion confirmed that digital transformation fundamentally changes the economic logic of port development. The key contribution of this study lay in integrating operational, financial, and risk-related effects of digitalisation into a unified investment evaluation framework, thereby offering a more comprehensive basis for decision-making in the development of modern port infrastructure.

CONCLUSIONS

The conducted research demonstrated that the digital transformation of port operations, in the context of investment-driven development of water transport, was not merely a localised technological upgrade but represented a systemic structural evolution of the entire sector. The synthesis of empirical and analytical results confirmed that digitalisation generates substantial and quantifiable economic effects, including significant reductions in costs and operational time. Collectively, these outcomes significantly enhanced the overall investment attractiveness of port infrastructure assets. The main scientific contribution of the research lied in the development of an extended investment evaluation framework adapted to the specific characteristics of digital assets. This framework integrated financial performance indicators with risk-adjusted approaches and accounts for technological uncertainty, non-linear returns, and the shortened life cycle of digital solutions. In particular, the study introduced the concept of a "digital premium" associated with increased transparency, as well as a technological lag coefficient that aligned capital recovery with the dynamics of digital obsolescence.

Another key scientific contribution of the study was the conceptualisation of the "Security-through-Efficiency" mechanism, which demonstrated how digitalisation reinforces the financial and economic security of seaports by stabilising cash flows and transforming technological advantages into protective barriers within the financial architecture. At the same time, it was shown that high profitability indicators must be assessed through an integrated filter of digital-specific risks, including technological dependency and cyber threats. The proposed approach provided a comprehensive basis for more accurate and forward-looking investment decision-making in port development under conditions of increasing digitalisation and risk. Future research should focus on the development of quantitative metrics for assessing the cyber-vulnerability of digital projects and on investigating the role of artificial intelligence in ensuring the long-term resilience of Ukrainian port systems during post-war reconstruction and integration into the global digital ecosystem of maritime transport.

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Цифрова трансформація портової діяльності в контексті інвестиційно зумовленого розвитку водного транспорту

Анотація. Глобальний морський сектор перейшов від традиційної модернізації портів до системної цифрової інтеграції, що зумовило потребу в нових економічних підходах для обґрунтування інвестицій у смарт-технології із одночасним забезпеченням фінансової безпеки. Метою дослідження було обґрунтування методологічних засад цифрової трансформації портової діяльності в контексті інвестиційно зумовленого розвитку водного транспорту. У дослідженні застосовано комплексний методологічний підхід, що охоплює системний аналіз, порівняльний і структурний аналіз, а також економіко-статистичне моделювання для оцінювання інвестиційної ефективності за показниками грошових потоків, прибутковості та оцінювання ризиків. Отримані результати засвідчили, що цифровізація функціонувала як багатовимірний економічний драйвер, знижуючи адміністративні та документаційні витрати на 20-30 %, час оброблення суден у порту – до 25 %, а час перебування вантажів – приблизно на 40 %. У дослідженні запропоновано удосконалену методику оцінювання інвестицій, яка інтегрує оцінювання реальних опціонів для врахування стратегічної гнучкості, а також введено цифрову премію, що коригує ставку дисконтування на основі підвищення операційної прозорості. Ключовою інновацією стало включення коефіцієнта технологічного відставання до розрахунків строку окупності, що узгоджує відновлення капіталу з коротшим циклом цифрового застарівання. Результати засвідчили, що цифрові інвестиції генерують нелінійну віддачу через зростаючу віддачу від масштабу в міру приєднання більшої кількості стейкхолдерів до екосистеми, забезпечуючи коротші строки окупності та цикли самофінансування. Крім того, у дослідженні концептуалізовано механізм інтеграції ефектів цифровізації в архітектуру фінансової безпеки порту, доведено, що технологічна прозорість і операційна швидкість виступають критичними резервами інституційної стійкості. Класифікація цифрових ризиків на технологічний, фінансовий і кібернетичний кластери дала змогу здійснювати ризик-орієнтоване оцінювання, за якого інвестиційні проєкти фільтруються через поріг безпеки для запобігання системній вразливості. Практична цінність роботи полягає в розроблених інструментах економічного обґрунтування проєктів смарт-портів, які дають змогу портовим операторам та інвесторам точно моделювати інкрементальні ефекти, оптимізувати структуру капіталу та зміцнювати фінансову безпеку інфраструктури водного транспорту в цифровізованому глобальному середовищі

Ключові слова: транспортно-логістичні системи; розвиток портової інфраструктури; інвестиційна ефективність; операційні витрати; управління грошовими потоками; оцінювання ризиків; фінансово-економічна безпека

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Formation of consumer value of a product under conditions of digitalisation and sustainable development

Abstract. The relevance of this study was driven by the transformation of consumer value formation under the influence of economic digitalisation and the growing importance of sustainable development principles. The aim of the research was to identify the key determinants of consumer value and to develop an integrated model of their interaction. The study was based on a survey of 210 respondents aged 18-45 who regularly made online purchases. The results showed high average evaluations of key variables: digital experience (4.25), perceived consumer value (4.18), personalisation (4.12), brand trust (4.05), and environmental sustainability (3.89). Correlation analysis revealed the strongest relationship between brand trust and consumer value ($r = 0.72$), followed by personalisation ($r = 0.68$) and digital experience ($r = 0.65$), confirming the critical role of intangible factors. The regression model demonstrated strong explanatory power ($R^2 = 0.62$). Brand trust had the greatest impact on consumer value ($\beta = 0.36$, $p < 0.01$), followed by personalisation ($\beta = 0.31$, $p < 0.01$), digital experience ($\beta = 0.28$, $p < 0.01$), and environmental sustainability ($\beta = 0.19$, $p < 0.05$). Additionally, the combined effect of personalisation and environmental sustainability increased perceived value by 18% compared to their individual effects, indicating a significant synergistic effect. The findings provided empirical evidence that consumer value was a multidimensional construct shaped by the interaction of digital and sustainable factors, with trust acting as a key mediating variable. The proposed model could be applied to improve product policy, enhance competitiveness, and strengthen long-term consumer relationships

Keywords: consumer behaviour; product policy; customer experience; brand trust; environmental responsibility; personalisation strategies; marketing analytics

INTRODUCTION

In contemporary market conditions, firms faced increasing challenges in creating and delivering value that corresponds to rapidly evolving consumer expectations. The rapid development of digital technologies, the expansion of online platforms, and the growing importance of environmental and social responsibility have fundamentally transformed the mechanisms of consumer decision-making. As a result, traditional approaches to consumer value formation, primarily based on functional characteristics such as price and quality, are becoming insufficient. Instead, consumer value is increasingly shaped by a combination of digital experience, personalisation, emotional engagement, and sustainability-related attributes.

At the global level, digitalisation has been recognised as a key driver of transformation in marketing theory and practice. Y.K. Dwivedi *et al*. (2021; 2023) analysed the evolution of digital and social media marketing, focusing on changes in consumer-firm interactions. These studies demonstrate that technological progress leads to more interactive and data-driven marketing models. However, the authors primarily concentrated on communication processes and did not sufficiently examine how digital product attributes contributed to consumer value formation. S. Verma *et al*. (2021) emphasised the growing role of artificial intelligence and data-driven technologies in marketing, highlighting their impact on personalisation and consumer decision-making.

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Recent studies indicate that digital environments significantly enhance customer participation and value co-creation through interactive and personalised experiences. In particular, influencer-driven and digitally mediated interactions stimulate consumers' active engagement and contribution to value creation processes (Bu *et al.*, 2022). Furthermore, the growing integration of artificial intelligence into service systems enables more adaptive and responsive interactions, thereby strengthening customer engagement and perceived value (Huang & Rust, 2021). As a result, digital technologies not only facilitate communication between firms and consumers but also transform consumers into active participants in value co-creation.

At the same time, sustainability has become an increasingly important determinant of consumer behaviour. Recent research demonstrates that sustainability attributes significantly influence purchasing decisions, although potential trade-offs with functionality may still occur (Qalati *et al.*, 2024). The influence of sustainability on consumer behaviour has also been actively explored in recent studies. F. Riva *et al.* (2024) demonstrated that sustainability-related brand positioning and green brand associations play an important role in shaping green brand trust, particularly under conditions of sustainability skepticism. This study supports these conclusions but further demonstrates that sustainability has both direct and indirect effects on perceived value, particularly through trust formation. This highlights the importance of integrating sustainability into broader value creation strategies rather than treating it as an isolated attribute.

Sustainability attributes significantly influence consumer behaviour and purchasing decisions, particularly depending on how consumers perceive and accept sustainable innovations (Giacalone & Jaeger, 2023). However, existing research predominantly examines digitalisation and sustainability as separate domains. Recent studies emphasise the need to integrate these perspectives, as digital transformation plays a crucial role in enabling sustainability while also revealing significant research gaps (Feroz *et al.*, 2021; Guandalini, 2022).

Despite the significant body of research, the existing literature revealed an important gap. Most studies analysed digitalisation and sustainable development as separate directions, without sufficiently exploring their interaction and combined impact on consumer value formation. In particular, the mediating role of trust and the synergistic effect of combining digital and sustainability-related product attributes remain insufficiently investigated. The relevance of this study is therefore determined by the need to develop an integrated approach to consumer value formation that reflects the interaction between digital and sustainable factors. Addressing this issue is essential for improving product competitiveness and ensuring long-term consumer relationships in the context of digital transformation.

The aim of the article was to identify the key determinants of consumer value formation in the context of digitalisation and sustainable development and to substantiate their integration into firms' product policy. To achieve this aim, the following objectives were defined: to analyse contemporary approaches to consumer value formation and to identify key digital and sustainable factors influencing consumer value; to empirically assess the relationships between these factors; to develop an integrated model of consumer value formation. The scientific novelty of the study lies in the development of a comprehensive model that integrates digital and sustainable determinants of consumer value while incorporating brand trust as a mediating variable and accounting for their synergistic effect.

MATERIALS AND METHODS

This study was based on a combination of theoretical and empirical research methods aimed at ensuring the validity, transparency, and reproducibility of the results. The research design included several stages, namely the conceptualisation of variables, data collection through an online survey, and statistical analysis of the obtained data. The methodological approach was grounded in contemporary frameworks of quantitative marketing research and data analysis (Sarstedt & Mooi, 2019; Hair *et al.*, 2022; Enholm *et al.*, 2022). The empirical study was conducted using a structured online survey administered via Google Forms. Data collection took place between March and April 2025. Respondents were recruited using a non-probability convenience sampling method through social media platforms and online communities. The inclusion criteria required participants to be between 18 and 45 years old and to have prior experience with online shopping, ensuring the relevance of responses to digital consumption contexts. A total of 210 valid responses were collected. Participation was voluntary and anonymous.

The study adhered to established ethical standards for social research, including informed consent, confidentiality, and the right to withdraw at any stage. Ethical considerations were guided by established principles for research involving human participants (American Psychological Association, 2020; The Declaration of Helsinki, 2024). In addition, broader ethical principles related to digital technologies and data use were considered (European Commission, 2019). All respondents were informed about the purpose of the study and provided consent prior to participation. The questionnaire consisted of several blocks designed to measure key constructs: personalisation, digital experience (UX), environmental sustainability, brand trust, and perceived consumer value. All variables were operationalised using multi-item scales adapted from recent empirical studies in digital marketing and consumer behaviour (Bleier *et al.*, 2019; Huang & Rust, 2021) and measured on a five-point Likert scale (1 = strongly disagree; 5 = strongly agree).

Personalisation was assessed through items reflecting the degree to which products and services met individual preferences. For example, respondents evaluated statements such as: "The products I purchase online are tailored to my personal preferences" and "Online platforms provide recommendations that match my needs". Digital experience (UX) was measured based on usability, interactivity, and ease of navigation, including items such as: "The website or application is easy to use" and "I can quickly find the information I need". Environmental sustainability included perceptions of ecological product characteristics and responsible production practices, with statements such as: "I prefer products that are environmentally friendly" and "I consider the environmental impact of products when

making a purchase". Brand trust was operationalised as the level of consumer confidence in the brand's reliability and integrity, for example: "I trust the brands I purchase from online" and "These brands keep their promises". Perceived consumer value was defined as the overall assessment of product usefulness and benefits, measured through items such as: "The products I purchase provide good value for money" and "Overall, I am satisfied with the benefits I receive from these products".

The dependent variable in the study was perceived consumer value. Independent variables included personalisation, digital experience, and environmental sustainability. Brand trust was treated as a mediating variable, as it explained the mechanism through which product attributes influenced perceived value. This approach was theoretically grounded in relationship marketing and supported by recent studies emphasising the role of trust in digital environments (Bleier *et al.*, 2019). Data analysis was performed using standard statistical techniques. Descriptive statistics (mean values and standard deviations) were used to summarise the characteristics of the sample and the main variables. To ensure the internal consistency of measurement scales, reliability analysis was conducted using Cronbach's alpha coefficient, with all constructs exceeding the recommended threshold of 0.7, indicating satisfactory reliability (Hair *et al.*, 2022).

Correlation analysis was applied to examine the relationships between variables and identify the strength and direction of associations. Multiple regression analysis was used to assess the impact of independent variables on perceived consumer value and to determine the relative importance of each factor. In addition, subgroup analysis was conducted to examine differences between age groups (18-25, 26-35, and 36-45), allowing for the identification of variations in consumer perceptions across segments. To evaluate the presence of interaction effects, an additional analysis of the combined influence of personalisation and environmental sustainability was performed. The results enabled the identification of a synergistic effect, reflected in a higher level of perceived value compared to the individual contribution of each factor. Despite the robustness of the applied methods, the study had certain limitations. The use of convenience sampling might have affected the generalisability of the results, while self-reported data could be subject to response bias. However, these limitations were partially mitigated by the consistency of the results and the application of validated measurement scales.

RESULTS AND DISCUSSION

The empirical analysis aimed to identify the key determinants of perceived consumer value and to assess the strength and nature of relationships between digital, sustainable, and relational factors. To ensure a structured interpretation of the findings, the analysis was conducted in several stages, including descriptive statistics, correlation analysis, and regression modelling. At the first stage, the descriptive statistics of the main variables were analysed (Table 1).

Table 1. Descriptive statistics of variables

Variable	Mean value	Standard deviation
Personalisation	4.12	0.78
Digital experience (UX)	4.25	0.71
Product environmental sustainability	3.89	0.85
Brand trust	4.05	0.74
Perceived consumer value	4.18	0.69

Source: developed by the author based on survey data

The results presented in Table 1 indicate generally high evaluations across all variables, suggesting that respondents perceive digital and relational attributes as important components of consumer value. The highest mean value was observed for digital experience (M = 4.25), reflecting the critical role of usability, convenience, and interface quality in shaping consumer perceptions in digital environments. Perceived consumer value (M = 4.18) and personalisation (M = 4.12) also received high evaluations, indicating that consumers place significant importance on tailored offerings and relevant interactions. In contrast, environmental sustainability demonstrated a relatively lower mean value (M = 3.89), suggesting that although sustainability is recognised as important, it remains a secondary factor compared to immediate functional and experiential benefits. However, mean values alone do not fully reflect the structure of responses. Therefore, at the second stage, a distribution analysis was conducted to examine the proportion of respondents selecting different response categories (Table 2).

Table 2. Distribution of respondents' evaluations, %

Variable	High (4-5)	Medium (3)	Low (1-2)
Personalisation	72	18	10
Digital experience (UX)	78	9	13
Product environmental sustainability	61	24	15
Brand trust	74	11	15
Consumer value	76	14	10

Source: developed by the author based on survey data

As can be seen from Table 2, more than 70% of respondents provided high evaluations for digital experience, personalisation, and consumer value, confirming the consistency of positive perceptions across these dimensions. In contrast, environmental sustainability shows the greatest variability, with a relatively high proportion of neutral responses (24%), indicating that its importance varies among consumer segments. This variability can be explained by differences in consumer awareness, income levels, and the perceived trade-off between price and environmental responsibility. These findings suggest that digital and experiential factors dominate immediate consumer decision-making, whereas sustainability plays a more differentiated and context-dependent role.

Based on the distribution results presented in Table 2, it can be concluded that each factor contributes to consumer value formation through distinct behavioural mechanisms. In practical terms, digital experience directly influences purchase completion rates, as users are more likely to abandon transactions in poorly designed interfaces. Personalisation increases engagement and repeat purchases, while trust reduces perceived risk and strengthens long-term relationships. Environmental sustainability, although less immediate, enhances brand image and contributes to long-term loyalty. To further examine the relationships between variables identified in the previous stage, a correlation analysis was conducted (Table 3).

Table 3. Correlation matrix

Indicators	1	2	3	4	5
1. Personalisation	1				
2. UX	0.62	1			
3. Sustainability	0.41	0.38	1		
4. Trust	0.57	0.52	0.60	1	
5. Value	0.68	0.65	0.54	0.72	1

Source: developed by the author based on survey data

The correlation analysis demonstrates strong and statistically significant positive relationships between all variables. The strongest relationship was identified between brand trust and perceived consumer value ($r = 0.72$), indicating that trust plays a central role in shaping consumer evaluations. This relationship can be explained by the characteristics of digital consumption, where uncertainty is higher due to the intangible nature of products and services. In such conditions, trust acts as a mechanism for reducing perceived risk, increasing confidence in the brand, and enhancing overall value perception. This finding has important managerial implications, suggesting that investments in trust-building mechanisms, such as transparency, data security, and consistent brand communication, can yield substantial returns in terms of consumer value.

Personalisation ($r = 0.68$) and digital experience ($r = 0.65$) also demonstrated strong relationships with perceived value. These results indicate that consumers respond positively to tailored and user-friendly interactions, which enhance both functional and emotional aspects of value. From a strategic perspective, this suggests that firms should prioritise customer-centric design and data-driven personalisation to improve competitiveness. Environmental sustainability showed a moderate but meaningful relationship with perceived value ($r = 0.54$). This indicates that sustainability contributes to value perception, although its effect is less immediate and may operate through indirect mechanisms such as trust and emotional engagement. To assess the relative importance of each factor, multiple regression analysis was conducted, the results of which are presented in Table 4.

Table 4. Results of the regression analysis

Variable	β coefficient	p-value
Personalisation	0.31	<0.01
UX	0.28	<0.01
Environmental sustainability	0.19	<0.05
Brand trust	0.36	<0.01

Note: $R^2 = 0.62$
Source: developed by the author based on survey data

The regression model demonstrates strong explanatory power ($R^2 = 0.62$), indicating that the selected variables explain 62% of the variance in perceived consumer value. This confirms the adequacy of the proposed model and its practical relevance. Among the predictors, brand trust has the strongest effect ($\beta = 0.36$), highlighting its central role in value formation. From an economic standpoint, this implies that trust functions as a key intangible asset that amplifies the perceived benefits of product attributes. Firms that successfully build trust can achieve higher consumer value without necessarily increasing functional product characteristics.

Personalisation ($\beta = 0.31$) also demonstrates a substantial effect, confirming that tailored offerings significantly enhance perceived relevance and customer satisfaction. This suggests that investments in data analytics and customer profiling can directly improve value perception and strengthen competitive positioning. Digital experience ($\beta = 0.28$) contributes through usability and convenience, reducing cognitive effort and improving interaction

efficiency. This indicates that user interface design and platform optimisation are critical components of value creation in digital markets. Environmental sustainability has a weaker but statistically significant effect (β = 0.19), suggesting that its influence is more indirect. Sustainability primarily enhances value through emotional and ethical dimensions and contributes to trust formation rather than immediate functional utility.

An important finding of the study is the presence of a synergistic effect between personalisation and environmental sustainability. When both factors are highly developed, perceived consumer value increases by approximately 18% compared to their individual effects. This result indicates that consumers respond more positively to integrated value propositions that combine functional, emotional, and ethical attributes. From a managerial perspective, this implies that firms should not implement sustainability initiatives in isolation but should integrate them with personalised offerings to maximise their impact. From an economic perspective, these findings indicate that investments in digital experience and trust-building mechanisms can generate higher returns compared to traditional product improvements. Improving UX reduces transaction costs and decision-making time, while trust increases conversion rates, customer retention, and lifetime value, thereby enhancing overall marketing efficiency.

The analysis of age groups revealed significant differences in consumer behaviour. Younger consumers (18-25) demonstrated higher sensitivity to digital factors, particularly usability and personalisation, which can be explained by their greater familiarity with digital technologies and higher expectations regarding user experience. In contrast, older consumers (36-45) placed greater emphasis on trust and reliability, reflecting higher risk perception and a stronger need for security in digital environments. These findings suggest that marketing strategies should be differentiated based on demographic characteristics, with a stronger focus on innovation and personalisation for younger segments and trust-building for older consumers. To complement the previous findings and explore potential heterogeneity in consumer behaviour, a comparative analysis across age groups was conducted (Table 5).

Table 5. Share of respondents with high evaluations (4-5), %

Factor	18-25	26-35	36-45
Personalisation	80	73	64
UX	85	78	69
Environmental sustainability	58	63	66
Brand trust	68	74	79

Source: developed by the author based on survey data

These differences can be explained by variations in risk perception and digital literacy. Younger consumers tend to prioritise convenience and speed due to their higher familiarity with digital technologies, while older consumers focus more on trust and reliability due to greater sensitivity to potential risks and financial losses. As indicated in Table 5, younger consumers demonstrate a higher sensitivity to digital experience and personalisation, whereas older consumers place greater emphasis on trust. This pattern confirms that the importance of specific value drivers varies across segments, which has important implications for marketing strategy. This result further confirmed that the interaction between digital and sustainability-related factors amplifies perceived consumer value beyond their individual effects. This finding suggests that the highest level of value is achieved not through isolated improvements, but through the integration of multiple factors. Therefore, the combined interpretation of results from Tables 1-5 indicates that firms should adopt an integrated approach to value creation, focusing on the simultaneous development of digital experience, personalisation, sustainability, and trust-building mechanisms.

Based on the obtained results, several practical recommendations can be formulated. Firms should prioritise the development of integrated value propositions that combine digital experience, personalisation, and sustainability. For example, companies can implement AI-based recommendation systems to enhance personalisation, optimise website navigation and interface design to improve digital experience (UX), and integrate sustainability labels into personalised offers to increase their effectiveness. Such measures not only improve customer satisfaction but also contribute to higher conversion rates and long-term customer retention. Particular attention should be paid to building brand trust, as it has the strongest impact on perceived value. In addition, segmentation strategies should be applied to tailor marketing approaches to different consumer groups. The conceptual model of consumer value formation (Fig. 1) summarises the key findings of the study and illustrates the interaction between digital, sustainable, and relational factors. Consumer value is formed through the interaction of digital factors (personalisation and UX), sustainable factors (environmental and social responsibility), and relational mechanisms, with brand trust acting as a mediating variable linking product attributes to perceived value and purchase intention. The proposed model can serve as a practical framework for designing product strategies, enhancing customer experience, and supporting managerial decision-making in digital environments. It highlights the importance of integrating digital capabilities, trust-building mechanisms, and sustainability initiatives to maximise perceived consumer value and long-term competitiveness. The findings of this study were compared with existing literature to provide a deeper understanding of consumer value formation in digital environments. In contrast to a fragmented view in prior research, this study enabled a more systematic interpretation of how digital, sustainable, and relational factors interact in shaping perceived value.

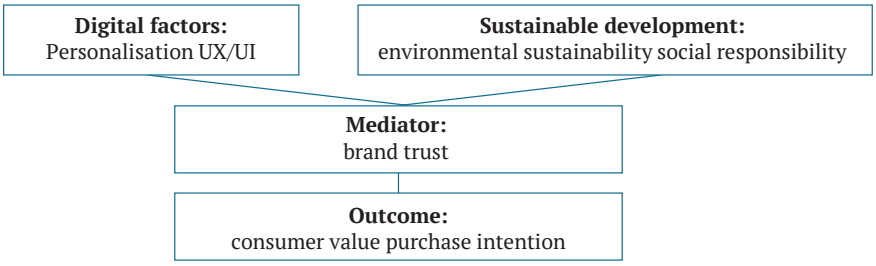

Figure 1. Consumer value formation model

Source: developed by the author

Recent studies in digital marketing emphasise the growing importance of customer experience and value co-creation in digital environments. F. Ahmad *et al*. (2022) demonstrated that online customer experience enhances customer engagement and loyalty, while value co-creation strengthens the relationship between digital experience and consumer responses. These findings are consistent with the results of this study, where digital experience showed a strong positive effect on consumer value. However, while prior research primarily focused on engagement and loyalty outcomes, the present study extends this perspective by empirically confirming the direct impact of digital experience as an independent determinant of perceived consumer value.

Recent research further supports the central role of digital experience in shaping consumer behaviour. For instance, S. Molinillo *et al*. (2022) demonstrated that retail app experience significantly influences customer loyalty through cognitive, affective, relational, and sensorial dimensions of digital customer experience. A.L. Roggeveen & R. Sethuraman (2020) emphasised that seamless omnichannel experiences enhance perceived value by reducing friction in the customer journey. These findings reinforce the results of this study and highlight the importance of continuous investment in digital capabilities.

The role of trust in digital environments has been widely discussed. M. Harrigan *et al*. (2021) demonstrated that trust plays a central role in shaping online purchase intention, particularly through perceived usefulness and peer communication in digital environments. The present study not only supports these conclusions but also demonstrates that trust has the strongest direct effect on perceived value ($\beta = 0.36$), thereby positioning trust not merely as a supporting factor but as a central mechanism in consumer value formation. Their findings suggested that trust reduces perceived risk and enhances customer engagement. The present study not only supported these conclusions but also demonstrated that trust had the strongest direct effect on perceived value ($\beta = 0.36$), thereby positioning trust not merely as a supporting factor but as a central mechanism in consumer value formation.

This interpretation is further supported by recent studies on digital trust. For example, S.A. Qalati *et al*. (2021) demonstrated that trust in online environments significantly influences purchase intention and plays a mediating role between perceived quality factors and consumer behaviour, particularly under conditions of uncertainty and information asymmetry. This aligns with the findings of this study and confirms the mediating role of trust in transforming product attributes into perceived value. M.-H. Huang & R.T. Rust (2021) developed a framework explaining how artificial intelligence can support customer engagement in service contexts, including standardisation, personalisation, and relationalisation. The authors demonstrated that data-driven personalisation significantly improves customer engagement and perceived value. These findings are consistent with the results of this study, which confirm the strong positive effect of personalisation on consumer value. At the same time, this research extends prior work by identifying a synergistic effect between personalisation and environmental sustainability.

The influence of sustainability on consumer behaviour has also been actively explored in recent studies. Recent studies (e.g., S.A. Qalati *et al*. (2024)) demonstrate that sustainability-related attributes significantly influence consumer trust and purchasing decisions in both online and offline environments. This study supported their conclusions but further demonstrates that sustainability has both direct and indirect effects on perceived value, particularly through trust formation. This highlights the importance of integrating sustainability into broader value creation strategies rather than treating it as an isolated attribute. Recent contributions also highlighted the strategic importance of sustainability integration. Recent studies emphasise that sustainability initiatives are most effective when they are integrated into broader marketing strategies and value creation processes rather than communicated as isolated attributes (Qalati *et al*., 2024; Riva *et al*., 2024). This supports the findings of this study regarding the synergistic effect between sustainability and personalisation.

The integration of digital and sustainable strategies has been increasingly addressed in recent research. I. Guandalini (2022) emphasised that digital transformation can support sustainability-oriented business development, while A.K. Feroz *et al*. (2021) identified digital technologies as important enablers of environmental sustainability. The present study strongly supported this view and provided empirical evidence of a synergistic effect between digital and sustainable factors, demonstrating that their combined implementation led to a significantly higher level of perceived consumer value.

In contrast to studies that focus primarily on global markets, Ukrainian research has also contributed to understanding digital transformation in marketing. S. Illiashenko *et al*. (2022) analysed the impact of digital transformation on enterprise development in the digital economy and emphasised the importance of integrating digital technologies into business and marketing processes. These findings

are consistent with the results of Ukrainian researchers, who emphasise the importance of digital marketing transformation in shaping customer-oriented strategies and enhancing value creation (Oklander *et al.*, 2024). While these studies supported the general direction of this research, they primarily considered digitalisation separately from sustainability, whereas the present study demonstrated the necessity of their integration.

An important contribution of this study was the identification of the mediating role of trust. While many previous studies acknowledged trust as an important factor, it was often conceptualised as an outcome of customer experience. In contrast, this research demonstrated that trust functioned as a mechanism through which digital and sustainability-related attributes influenced perceived value. This interpretation provided a more nuanced understanding of value formation, particularly in digital environments characterised by uncertainty and information asymmetry. Furthermore, the findings revealed that consumer responses to value drivers were not uniform across segments. Younger consumers were more sensitive to digital attributes such as usability and personalisation, whereas older consumers placed greater emphasis on trust and reliability. This result expanded existing literature by demonstrating the importance of demographic segmentation in value formation and suggested that marketing strategies should be adapted accordingly.

From a managerial perspective, the results indicated that firms should adopt an integrated approach to value creation. Investments in digital experience and personalisation should be combined with sustainability initiatives and supported by trust-building mechanisms. The findings suggested that isolated improvements in individual attributes were less effective than their coordinated implementation, as the highest level of perceived value was achieved through their interaction. Overall, the study not only confirmed key assumptions of recent research but also extended them by providing empirical evidence of the interdependence between digital, sustainable, and relational factors. By integrating these dimensions into a unified model, this research contributed to a deeper understanding of consumer value formation and provided a foundation for future theoretical and empirical developments. This integrated perspective provides a comprehensive framework for understanding how digital transformation and sustainability jointly shape consumer value in modern markets.

CONCLUSIONS

The results of this study confirmed that consumer value formation in contemporary market conditions was a complex and multidimensional process determined by the interaction of digital, sustainable, and relational factors. The empirical findings demonstrated that digital experience, personalisation, and brand trust played a dominant role in shaping perceived consumer value. The proposed model showed strong explanatory power ($R^2 = 0.62$), confirming its ability to capture the key determinants of consumer value. Among the examined factors, brand trust had the strongest influence ($\beta = 0.36$), highlighting its role as a central mechanism that transforms product attributes into perceived value, particularly in digital environments characterised by higher uncertainty. The study also confirmed the significant contribution of personalisation and digital experience, reflecting the growing importance of user-centred and data-driven approaches in marketing. At the same time, environmental sustainability, although less influential in direct terms, contributed to value formation through emotional and ethical dimensions and reinforced trust.

An important contribution of the study was the identification of a synergistic effect between personalisation and environmental sustainability, which increased perceived consumer value by approximately 18% compared to their individual effects. This finding emphasised the importance of integrated value propositions. The results also revealed differences across consumer segments, indicating that younger consumers were more sensitive to digital attributes, while older consumers placed greater emphasis on trust and reliability. This highlighted the need for differentiated marketing strategies. From a managerial perspective, the findings suggest that firms should adopt an integrated approach to value creation. In particular, companies should prioritise investments in digital experience (UX) to reduce transaction costs and improve usability, implement data-driven personalisation to enhance relevance and customer engagement, and develop trust-building mechanisms such as transparency, data protection, and consistent communication. In addition, sustainability initiatives should be integrated into personalised offerings rather than implemented as isolated attributes, as this significantly increases their effectiveness. The results indicate that the highest level of consumer value is achieved through the coordinated interaction of these factors rather than their separate implementation.

The theoretical contribution of the study lies in the development of an integrated model of consumer value formation that incorporates trust as a mediating variable and demonstrates the interdependence and synergistic effects of digital and sustainability-related determinants. This contributes to a more comprehensive understanding of value formation in digital environments and extends existing research by combining previously fragmented perspectives. Despite its contributions, the study has several limitations that open avenues for future research. First, the use of a convenience sample may limit the generalisability of the findings. Future studies could apply probabilistic sampling methods and include a larger and more diverse sample. Second, further research could explore cross-country differences in consumer value formation to identify cultural and institutional influences. Third, longitudinal studies would allow for the analysis of how consumer value evolves over time in response to digital transformation. Finally, future research could examine the role of emerging technologies, such as artificial intelligence and big data analytics, in enhancing personalisation and trust, as well as their interaction with sustainability initiatives.

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Формування споживчої цінності продукту в умовах цифровізації та сталого розвитку

Анотація. Актуальність цього дослідження зумовлена трансформацією формування споживчої цінності під впливом цифровізації економіки та зростанням значущості принципів сталого розвитку. Метою дослідження було визначення ключових детермінантів споживчої цінності та розроблення інтегрованої моделі їхньої взаємодії. Дослідження ґрунтувалося на опитуванні 210 респондентів віком 18-45 років, які регулярно здійснювали онлайн-покупки. Результати показали високі середні оцінки ключових змінних: цифровий досвід (4,25), сприймана споживча цінність (4,18), персоналізація (4,12), довіра до бренду (4,05) та екологічна сталість (3,89). Кореляційний аналіз виявив найсильніший зв'язок між довірою до бренду та споживчою цінністю ($r = 0,72$), далі – персоналізація ($r = 0,68$) і цифровий досвід ($r = 0,65$), що підтверджує критичну роль нематеріальних чинників. Регресійна модель продемонструвала високу пояснювальну здатність ($R^2 = 0,62$). Найбільший вплив на споживчу цінність мала довіра до бренду ($\beta = 0,36$, $p < 0,01$), за нею – персоналізація ($\beta = 0,31$, $p < 0,01$), цифровий досвід ($\beta = 0,28$, $p < 0,01$) та екологічна сталість ($\beta = 0,19$, $p < 0,05$). Крім того, комбінований ефект персоналізації та екологічної сталості підвищував сприйману цінність на 18 % порівняно з їхнім окремим впливом, що свідчить про значний синергійний ефект. Отримані результати надали емпіричні докази того, що споживча цінність є багатовимірною конструкцією, сформованою взаємодією цифрових і сталих чинників, де довіра виступає ключовою медіуючою змінною. Запропонована модель може бути використана для вдосконалення товарної політики, підвищення конкурентоспроможності та зміцнення довгострокових відносин із споживачами

Ключові слова: поведінка споживачів; товарна політика; клієнтський досвід; довіра до бренду; екологічна відповідальність; стратегії персоналізації; маркетингова аналітика

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The experience of Poland in the development of agri-food clusters

Abstract. The purpose of the study was to identify the features of the functioning of agri-food clusters in Poland through an analysis of their organisational structure, mechanisms of interaction between participants in the value chain, financial support, and performance results. The methodological framework combined document analysis, structural-functional and case-based approaches, comparative-analytical methods, descriptive interpretation of quantitative indicators, systematisation, and scientific generalisation. The study established that agri-food clusters in Poland function as multilevel networks combining raw-material producers, processing enterprises, logistics structures, sales channels, research institutions, and support bodies. As of 30 June 2025, 83 cluster organisations were registered for Poland on the European Cluster Collaboration Platform; in the 2024 benchmarking sample of 42 clusters, the total number of participants was 4,942, and the average was 117.7 participants per cluster. The key mechanisms were short supply chains, direct links between producers and buyers, shared logistics and packaging solutions, and cooperation in food quality systems. Financial support from the European Union forms the resource basis for development: the budget of the Common Agricultural Policy Strategic Plan of Poland for 2023-2027 is EUR 25.243 billion, with EUR 7.778 billion allocated to rural development. The study generalised that the performance of Polish agri-food clusters is determined by the completeness of value-chain coverage, the coordinating role of the cluster core, the participation of research and advisory structures, and the ability to combine local sales forms with broader market channels. The practical value of the findings lies in their possible use by agricultural and regional policy bodies, cluster coordinators, farmers' associations, processing enterprises, and research institutions for improving cross-sectoral cooperation, planning funding, developing short supply chains, and strengthening the organisational resilience of the agri-food sector

Keywords: financial support; logistics structures; processing enterprises; self-government; market

INTRODUCTION

The cluster approach in the agri-food sector of Poland retains practical significance as an instrument for coordinating production, processing, logistics, sales, knowledge services, and institutional support. The relevance of the subject is strengthened by the fact that in 2023-2027, Poland is implementing the Common Agricultural Policy Strategic Plan with a total budget of EUR 25.243 billion, of which EUR 7.778 billion is allocated to rural development (European Commission, 2025). For this reason, the experience of Poland is illustrative: the country has a substantial agricultural base, developed regional food specialisations, and one of the largest networks of cluster organisations in Central and Eastern Europe. As of 30 June 2025, the European Cluster Collaboration Platform (2025) recorded 83 Polish cluster organisations, which provides grounds for considering Poland a relevant example of institutionally

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supported agri-food clustering. D. Kuberska & M. Mackiewicz (2022) examined the evolution of cluster policy in Poland, the factors of its performance, and implementation problems. The researchers stressed the significance of government recognition of the cluster approach, coherence between national and regional strategies, continuity of state support, and consideration of the development stage of cluster organisations, in particular, their internationalisation. I. Lipińska (2022) considered the agri-food supply chain through the prism of legal solutions and indicated that cluster forms of coordination contribute to stabilising economic activity at the level of EU (European Union) law and national regulation. A.M. Lis & M. Mackiewicz (2023) analysed the role of clusters in the green transformation and distinguished integrative, resource, and educational actions through which Polish clusters move towards green, low-carbon, and circular economies. Z. Nasalski (2023) investigated the conditions for farm coopetition in the agri-food sector using the example of the Warmińsko-Mazurskie Voivodeship. The study emphasised that the constraining factors include low awareness among parts of the business environment, the unwillingness of entities to cooperate, and the absence of tested coopetition models, while in the institutional dimension, advisory structures, economic self-government bodies, sectoral associations, and research institutions play an important role. N. Drejerska & W. Sobczak-Malitka (2023) focused on the role of short supply chains in the transformation of food systems in Poland and linked this issue with sustainable development, healthy nutrition, and food policy. The study outlined spatial differences in the development of local food systems and demonstrated that short supply chains contribute to increasing the accessibility of local products and are linked to support for local producers and regional development.

M. Raftowicz *et al.* (2024) considered short food supply chains as a practical manifestation of sustainable development ideas. The study addressed the capacity of short chains to ensure sustainable rural development and indicated that their assessment requires simultaneous consideration of economic, social, and environmental dimensions, together with critical comparison with longer supply chains. S.T. Ozougwu & O.M. Grabowska-Chenczke (2025) examined management practices in agri-food companies of the Wielkopolskie Voivodeship as a factor in agribusiness growth. The researchers determined that a considerable share of companies had no established talent-management practices, which was combined with insufficient attention to team-building and unclear communication of shared business goals and vision by management. L. Ossowska *et al*. (2025) analysed the digital presence and e-commerce maturity of regional food producers in Poland. The study noted that the use of e-commerce remains limited, although online sellers are more often characterised by a larger scale of activity, a wider sales radius, more active use of regional raw materials and external funding sources, and the need for infrastructure and training support for the further expansion of the digital sales channel. I. Zdráhal & J.M. Fannin (2025) examined the place of food-processing industries of the Visegrad Group countries in global value chains during 1995-2018. The researchers identified differences between the V4 countries in the forms and intensity of integration, and recorded for this area increasing participation in global chains before the Great Recession, a subsequent slowdown, and stronger attachment to European value chains, with a noticeable role for value added originating from service sectors. Y. Deroche-Leydier (2025) analysed the perceived resilience of Polish farms during the COVID-19 pandemic and the post-pandemic crisis depending on participation in short supply chains. The study demonstrated that farms included in short chains reported a higher overall level of perceived resilience, while the most visible differences concerned adaptability and transformative capacity, especially for farms that combined short and longer sales channels.

The analysis of sources indicated that the academic field consistently addresses several interconnected problem areas: cluster policy and the legal support for cluster functioning; cooperation and coopetition among agri-food sector entities; short supply chains as a mechanism for the structural transformation of the food system; digital and human-resource aspects of agri-food business development; and the inclusion of the food-processing sector in broader regional and global value chains. However, the material in these studies focused on separate levels of analysis, so the purpose of this study was to determine the specific features of the functioning of agri-food clusters in Poland by analysing their organisational structure, mechanisms of interaction between participants in the value chain, sources of financial support, and main performance results. The objectives were to characterise the structure, principles of functioning, and typical models of agri-food clusters in Poland; clarify the mechanisms of interaction between farmers, processing enterprises, and sales links, along with the role of funding in the development of cluster formations; and generalise success factors and the main results of the activities of Polish agri-food clusters.

MATERIALS AND METHODS

The study used a qualitative documentary-analytical design combining case-based, comparative, and descriptive approaches to quantitative indicators. The object of the research was the institutional and organisational environment for agri-food cluster development in Poland. The subject included the structure, coordination mechanisms, functional models, and performance factors of Polish agri-food clusters and related cooperation initiatives. To characterise the institutional, financial, and organisational environment, the study applied document analysis to official and analytical materials. The European Commission (2025) provided the basis for determining the total funding, support structure for rural areas, and the role of the Common Agricultural Policy (CAP) Strategic Plan, LEADER, and EIP-AGRI. The European CAP Network (n.d.b) clarified the role of network structures and advisory services in the Polish national CAP network. The OECD (2025) specified the relationship between agricultural policy, funding for food chains, and rural development support. To analyse the organisational structure and functional roles within Polish clusters, the study used the structural-functional method. M. Piotrowska *et al.* (2024) supplied quantitative parameters of the cluster environment, including average cluster size, innovation profile, internationalisation level, and examples of agri-food and bioeconomic clusters. The European Cluster Collaboration Platform (2023a)

characterised general cluster policy, support instruments, and the connection between clusters and innovation ecosystems in Poland. The European Cluster Collaboration Platform (2025) integrated regional innovation networks, using the Podkarpackie Voivodeship as an example. AgroBioCluster (n.d.) supported the analysis of a model combining business, local government, and research institutions. The European Agri-food Cluster (2023) characterised direct interaction between producers, buyers, and logistics partners in cereal, pulse, meat, and related markets.

To examine specific practices of short supply chains, logistics-sales cooperation, and technological modernisation, the study applied case analysis. The first case (Zamojska Farma operational group for food potatoes) demonstrated the mechanism for strengthening farmers' positions and reducing intermediaries (European CAP Network, 2024a). The second case (automation of sorting and packaging in Polish vegetable value chains) illustrated technological modernisation affecting product quality and reducing losses in short supply chains (European CAP Network, 2024b). The third case (AgroBRIDGES project materials) systematised barriers and solutions related to transport, packaging, demand, marketing, and stakeholder participation in short food chain models European CAP Network (n.d.a). To distinguish alternative models of agri-food clustering, the study used the comparative-analytical method based on AgroBioCluster (n.d.) and the European Agri-food Cluster (2023). This comparison identified market-sales, logistics-cooperative, innovation-bioeconomic, and regional-ecosystem models. To interpret the statistical and financial characteristics of the Polish cluster environment, the study employed descriptive analysis of quantitative indicators. The European Cluster Collaboration Platform (2025) determined the number of registered cluster organisations in Poland. At the final stage, systematisation and scientific generalisation, based on all previous analytical steps, identified key performance factors of Polish agri-food clusters: coordinating role of the cluster core, completeness of value-chain coverage, combination of production, processing, logistics and sales, involvement of research and advisory structures, development of short supply chains, use of quality systems, access to EU funding, and inclusion of clusters in regional innovation ecosystems.

RESULTS AND DISCUSSION

The study establishes that agri-food clusters in Poland develop in a context where the agri-food sector has high structural significance for the national economy. Rural areas occupy 85% of the country, agricultural land accounts for 52%, approximately 15 million people live in rural areas, and the number of identified farms is approximately 1.4 million. Dairy, grain, pig, poultry, and horticultural production occupy leading positions in the structure of Polish agricultural production, which creates preconditions for cluster models with pronounced territorial-sectoral specialisation (European Commission, 2025). At the national level, the cluster landscape of Poland is characterised by a developed but heterogeneous structure. According to the European Cluster Collaboration Platform, as of 30 June 2025, Poland had 83 registered cluster organisations, with the agri-food area present in the national cluster field, although it was represented by fewer organisations than the digital and energy segments. The PARP benchmarking results for 2024 indicated that, in a sample of 42 clusters, the total number of members reached 4,942, and the average number of participants per cluster increased to 117.7 at the end of 2023. In 41 clusters for which complete employment data were available, the total number of employees in member companies reached 1,060.4 thousand people. Thus, the Polish experience reflects the presence of institutionally formed interorganisational structures with a noticeable critical mass of participants, rather than fragmented local initiatives European Cluster Collaboration Platform (2023a) and M. Piotrowska *et al.* (2024).

The results are consistent with the conclusions of J. Abrham (2014), who demonstrated, using the material of the Visegrad Group countries, that the development of clusters in tourism, agriculture, and the food industry was linked to regional concentration, structural diversity, and support from national programmes and EU funds. The comparative context confirms the relatively developed character of the Polish cluster environment: as of 2025, 83 cluster organisations from Poland were registered on the ECCP (European Cluster Collaboration Platform), whereas in Czechia, according to 2023 ECCP data, 35 cluster organisations were recorded, and in Hungary, 28 were recorded (European Cluster Collaboration Platform, 2023b; European Cluster Collaboration Platform, 2023c). Thus, by the number of registered cluster organisations, Poland considerably outpaced some Central and Eastern European countries, which provides grounds for considering it not peripheral but one of the more visible examples of institutionally formed clustering in this macroregion. However, the average indicator of 117.7 participants per cluster in the Polish sample was not exceptionally high on the European scale, since the average size of EU cluster organisations on the ECCP was approximately 170 participants, and 22% of EU cluster organisations had between 101 and 200 participants (Piotrowska *et al.*, 2024). This means that Polish clusters belong to the medium-size segment by the number of participants, but their significance is determined by both the breadth of value-chain coverage, the presence of coordinators, links with EU funding, and inclusion in regional innovation ecosystems. The organisational architecture of Polish clusters is built around a coordinator who ensures communication between participants and integrates different levels of the value chain. In the Polish cluster policy, the representation of different levels of a common value chain, including infrastructure, human resource management, technologies, research and development, procurement, logistics, production, marketing, and sales, is regarded as a feature of a fully developed cluster. This means that an agri-food cluster in the Polish context functions not as an association of homogeneous producers but as a coordination platform for vertically and horizontally connected entities (European Cluster Collaboration Platform, 2023a). This conclusion correlates with the study by P. Garbade *et al.* (2013), in which the functions of a cluster organisation were considered a key condition for coordination between different groups of participants. For Polish agri-food clusters, this means that the coordinator performs an administrative role while also linking production, knowledge, innovation, marketing, and market promotion into a single service system.

Polish practice includes several models of agri-food cluster formation. Some clusters are built according to the logic of a direct market connection between producer and buyer, while others follow the logic of innovation-bioeconomic integration, in which research institutions, local self-government bodies, advisory centres, and laboratory infrastructure are added to producers and processors. NUTRIBIOMED Cluster is illustrative in this respect, as its multilevel support model combines agricultural, biotechnological, research, and medical communities, and covers infrastructural, research, technological, and educational levels. AgroBioCluster represents another type, bringing together 46 companies, representatives of local self-government, and research institutions. A separate format is represented by the European Agri-food Cluster (2023), focused on direct links between producers and buyers in the markets for cereals, pulses, meat, and related logistics (Piotrowska *et al.*, 2024; AgroBioCluster, n.d.). Similar logic appears in the work of J. Wiśniewska-Paluszak *et al*. (2020), where the example of a Polish agri-food cluster showed the significance of cooperation with universities for the development of modern distribution channels, joint investment, and innovative solutions. This confirms that the success of Polish clusters depends on both the number of business participants and stable links with research institutions and educational-research infrastructure. In the regional dimension, agri-food clusters function as an element of broader innovation ecosystems. The example of the Podkarpackie Voivodeship illustrates this pattern: of the seven ECCP-registered cluster organisations in the region, one was directly assigned to the agri-food ecosystem, while regional cluster structures generally had compact staff, a limited number of coordinators, and a network-based membership model. Most of these organisations were characterised by international orientation, project partnerships, and participation in training activities (Table 1).

Table 1. Representative models of agri-food clusters in Poland

Cluster/model	Structural composition	Functional principle	Recorded performance profile
NUTRIBIOMED Cluster	agricultural producers, processors, companies in food innovation, universities, laboratory and medical structures	multilevel integration of infrastructure, R&D, technologies, education, and food safety control	strengthening of local supply chains, knowledge transfer, and support for functional food products
AgroBioCluster	46 companies, local self-government, and research institutions	combination of agri-food production and bioeconomic solutions	network association of business, research, and the public sector
European Agri-food Cluster	producers of plant and animal products, buyers, and logistics and transport partners	direct links between producers and buyers, and coordination of sales and logistics	reduction of distance between producer and market, and commodity specialisation by segment
Regional agri-food clusters of Podkarpacie	small coordination teams, a compact member network, and cross-sectoral partners	project cooperation, training, and international links	inclusion of the agri-food area in the regional innovation ecosystem

Source: developed by the author based on M. Piotrowska *et al.* (2024), European Cluster Collaboration Platform (2025), AgroBioCluster (n.d.), European Agri-food Cluster (n.d.)

This indicates that Polish agri-food clusters develop not in isolation but in constant intersection with mechanisms of smart specialisation, interregional cooperation, and European innovation integration. In the structure of Polish agri-food clusters, cooperation between farmers, processors, and sales links is formed mainly around three interconnected mechanisms: coordination of short supply chains, joint modernisation of production-packaging processes, and collective promotion of products within quality systems. At the strategic planning level, the CAP Strategic Plan of Poland supports stronger cooperation between farmers and the processing sector, in addition to the development of short supply chains, especially for small farms and higher-quality products. This means that the logic of cooperation in Poland is built around production, processing, the local market, and channels for delivering products to final consumers (European Commission, 2025). This result is consistent with the conclusions of O. Bareja-Wawryszuk (2020), who, using the material of Poland, considered direct sales, agricultural retail sales, and small-scale, localised, and restricted activity as organisational forms of local food systems. In the context of Polish clusters, this confirms that short supply chains are not a secondary sales channel but a separate organisational model of spatial concentration of local food production.

According to European CAP Network (2024a) materials, the Zamojska Farma operational group aimed to create a short supply chain for the distribution and sale of fresh vegetable products, primarily potatoes, along with sweetcorn and cauliflower. Five local farms were involved in the project, combining the shortening of the supply chain with automation of product sorting, washing, weighing, and packaging. Quantitative results indicated a 40% increase in the selling price of potatoes, a 15% increase in labour productivity due to the automation of packaging and sorting, a 20% reduction in operating costs through reduced dependence on intermediaries, and an increase in the number of online-store customers from 50 to 800. In addition, shortening the sales chain ensured direct sales on the farm or delivery of products to the consumer in approximately two working days. Thus, this case confirms that Polish short supply chains may have both organisational and measurable economic effects for producers: higher selling prices, lower costs, expansion of the customer base, and stronger control over added value within the local food chain. Similar logic is demonstrated by the study of M. Sylla *et al*. (2017), in which the model of community-supported agriculture in Poland was analysed as an example of a short food chain with direct involvement of producers and consumers. This allows the Polish experience to be interpreted more broadly: reducing intermediaries in cluster and quasi-cluster models is associated not only with economic benefits for farmers but also with the formation of new social links between the producer and the local market. In

the structure of Polish agri-food practices, the mechanism of joint technological modernisation of post-production operations plays a distinct role. Polish examples indicate that automation of vegetable sorting and packaging is an instrument for simultaneously increasing the speed of product circulation, reducing losses, and stabilising the quality of fresh products for the consumer. In the relevant EU case, it was directly stressed that short vegetable supply chains strengthen customer loyalty and have environmental benefits, while automation of the logistics-packaging stage contributes to a better supply of fresh products to the market. Thus, the interaction between the farmer, the sorting-packaging link, and the trade channel in Polish practices has a technologically organised character (European CAP Network, 2024b). Conclusions on logistics and packaging are consistent with the study by T. Bosona & G. Gebresenbet (2011), in which integration of logistics networks in local food chains was considered a means of increasing efficiency, reducing environmental impact, expanding the market for local producers, and improving traceability of food origin. Thus, Polish cases of post-harvest automation confirm the broader conclusion that cluster cooperation becomes effective only when institutional cooperation is complemented by real logistics integration.

Existing Polish clusters also show a format of direct coordination between producers and buyers without excessive branching of intermediary structures. The European Agri-food Cluster (n.d.) directly declared its focus on establishing direct relations between producers and buyers, concentrating on cereals, pulses, meat, and related goods, including oils, pasta products, and meat products. Notably, alongside commodity areas, the cluster website presented a logistics-transport function, meaning that sales cooperation is understood as part of a single process, not as a service added after the fact. This aspect can be compared with the study of N. Drejerska *et al*. (2019), in which small-scale, localised, and restricted activity in Poland was considered a business model for creating value for local food products. In Polish agri-food clusters, direct links between producers, buyers, and trade channels perform a similar function: they help both sell products and retain a larger share of added value within the local system. Inter-subject coordination in the Polish agri-food sector is also supported through instruments of food quality systems. Under Plan Strategiczny WPR 2023-2027, Poland presents separate interventions 13.3 and 13.4, aimed respectively at the promotion, information, and marketing of products made within quality systems, and at the development of producer cooperation within these systems. The plan indicates that such interventions are intended to increase product recognition, strengthen cooperation, and ensure the presence of such goods on the market. This means that, for Polish cluster and cooperation models, qualitative product differentiation is combined with organisational strengthening of producer groups (Ryć, 2023). This conclusion is supported by the study of A. Barska & J. Wojciechowska-Solis (2018), in which conventional and regional products in Poland were considered through consumer perception, purchase motives, and development prospects for this segment. For agri-food clusters, this means that quality systems and collective marketing are significant both for producers and for building trust, recognition, and consumer value for local products. However, Polish examples emphasise that the effectiveness of cooperation depends on the capacity to resolve infrastructure and market bottlenecks. Within the AgroBRIDGES initiative for Poland, 10 key barriers were analysed, and 15 solutions for the development of short supply chains were proposed. Transport and packaging were identified as key barriers and critical success factors; the significance of demand and social trends related to the consumption of sustainably produced goods was also stressed separately (Table 2).

Table 2. Main mechanisms of cooperation in Polish agri-food clusters

Mechanism	Content of interaction	Participants	Recorded effect
Short supply chains	direct or shortened channel between producer and buyer	farmers, producer groups, local buyers, and trade partners	strengthening of farmers' positions, reduction of the role of intermediaries, and growth of market share
Joint sorting, packaging, and preparation for sale	automation of post-harvest processes and standardisation of quality	producers, processing/packaging links, and logistics operators	reduction of losses, acceleration of circulation, and stabilisation of fresh product quality
Direct production-sales links	coordination of contracting and commodity flows	producers, buyers, logistics, and transport	reduction of market distance and specialisation of sales channels
Cooperation in quality systems	joint promotion, marketing, and development of cooperation	farmers, processors, quality organisations, and advisory structures	increased recognition, strengthened cooperation, and better market accessibility
Multi-actor solutions for SFSC	removal of barriers in packaging, transport, and demand	farmers, agri-food enterprises, digital partners, and regional stakeholders	development of solutions for more resilient local sales models

Source: developed by the author based on I. Ryć (2023); European CAP Network (2024a; 2024b; n.d.a); European Agri-food Cluster (2023); European Commission (2025)

Thus, cluster interaction in the Polish agri-food sector is not limited to institutional cooperation between entities but requires appropriate logistics and marketing adjustment. Further explanation is provided by the study of I. Navarro-del Aguila & J. de Burgos-Jiménez (2022), in which the development of hybrid agri-food chains in South-Eastern Spain showed the possibility of combining conventional export channels with short supply channels. In the Polish case, this allows short chains to be considered not as an alternative to the entire market system but as a flexible element of a hybrid model combining local sales, retail, logistics, and broader commodity flows. The results highlight that EU funding in the Polish case does not act as a separate external resource but is embedded in the development system of the agricultural, processing, and cluster environment through a set of CAP instruments, rural

development, network structures, and EIP-AGRI innovation groups. Under the CAP Strategic Plan for 2023-2027, the agricultural and rural development of Poland is organised through a funding system combining EAFRD, EAGF, and national contributions. The Polish PRN+ network was created to support the use of European agricultural and rural funding and, together with specialised services of the Polish innovation network and demonstration farms, covers 35 entities across the country. This organisation means that European funding functions both as a financial flow and as an instrument for the institutional deployment of cooperation networks (European CAP Network, n.d.b). The results are consistent with the conclusions of J. Jorge-Vázquez *et al*. (2021), who stressed the strategic importance of digitalising the European agri-food cooperative sector for increasing competitiveness, efficiency, and the ability to respond to economic and environmental challenges. In the Polish case, this means that EU funding should be considered both a source of investment and an instrument for technological, digital, and knowledge-based modernisation of agri-food networks. According to European Commission (2025) data, under the CAP Strategic Plan of Poland for 2023-2027, the total budget is EUR 25.243 billion, of which EUR 17.327 billion is allocated to direct payments, EUR 7.778 billion to rural development, and EUR 138.5 million to sectoral support. Within the allocation structure, EUR 2.076 billion is reserved for environmental and climate objectives within rural development, EUR 4.334 billion for eco-schemes, EUR 407.9 million for LEADER, and EUR 493.2 million for generational renewal in agriculture. Although these funds are not intended exclusively for clusters, they form the material field in which clusters obtain access to investment, advisory services, cooperation, and local development (European Commission, 2025).

CAP support is directly oriented towards cooperation models that influence cluster development. The Polish plan supports stronger cooperation between farmers and the processing sector, short supply chains, investments in high-quality food production, and strengthening the market orientation of farms. More than 127 thousand people are expected to receive advisory, training, or another form of knowledge support, or to participate in EIP-AGRI Operational Groups; more than 25 thousand people are also expected to be covered by measures related to environmental and climate performance. This confirms that the Polish model for developing agri-food clusters is based on both capital investment and the large-scale expansion of knowledge-cooperation infrastructure (European Commission, 2025). The analysis further indicates that cluster policy instruments in Poland combine EU-wide funding with the national and regional framework of cluster support. According to the materials of the European Cluster Collaboration Platform (2023a), the instruments include funding for joint initiatives, support for research and development projects, support for small and medium-sized enterprises joining clusters, funding for cluster infrastructure and networking events, concept testing and demonstration projects, innovation vouchers, support for hiring specialists with academic degrees, development of professional and communication skills, market analytics, export consultancy, and marketing activities. Thus, Polish agri-food clusters develop within a complex financial-organisational package in which European funds strengthen production investment, managerial capacity, innovation capacity, and export capacity. This corresponds to the study of E. Giuliani & M. Bell (2005), which established, using the example of a Chilean wine cluster, that knowledge within a cluster does not spread automatically but concentrates around firms with higher absorptive capacity and around technological intermediaries. For Polish agri-food clusters, this means that instruments for supporting research and development, innovation vouchers, and concept testing have the greatest effect when the cluster includes entities capable of receiving, adapting, and disseminating new knowledge among other participants.

A characteristic feature of the Polish experience is the increase in funding in related areas directly connected with food-chain resilience. After the revision of the National Recovery and Resilience Plan of Poland in July 2024, funding for four investment measures related to food-chain resilience, research capacity, and sustainable water use increased from EUR 1.9 billion to EUR 2.6 billion. Alongside this, under the Polish CSP, the total rural development budget is EUR 7.778 billion, with an EU funding share of 60% and 46 interventions. This means that cluster and quasi-cluster forms of cooperation in the agri-food sector are provided with a relatively broad resource field for modernisation, logistics adaptation, and greening (OECD, 2025). A separate segment of European funding is linked to support for producers in quality systems and cooperation formats. Interventions 13.3 and 13.4 in the Polish WPR plan are aimed at marketing food products in quality systems and developing producer cooperation within these systems (Table 3).

Table 3. Main areas of the influence of EU funding on the development of agri-food clusters in Poland

Instrument/programme	Recorded resource	Functional significance for clusters
EU Common Agricultural Policy Strategic Plan for 2023-2027	EUR 25.243 billion of total budget	formation of the general investment and cooperation framework for the agricultural sector, processing, and rural development
Rural development	EUR 7.778 billion	support for modernisation, cooperation, local development, and advisory services
LEADER programme	EUR 407.9 million	strengthening of local networks, territorial initiatives, and local partnership
Knowledge exchange and the European Innovation Partnership for Agriculture	more than 127 thousand participants; more than 25 thousand participants in climate- and environment-related measures	deployment of knowledge and innovation infrastructure
National Recovery and Resilience Plan package on the resilience of food chains	increase in funding from EUR 1.9 billion to EUR 2.6 billion	strengthening of food-chain resilience, research capacity, and water management

Table 3. Continued

Instrument/programme	Recorded resource	Functional significance for clusters
Cluster policy instruments	research and development, networking events, concept testing, innovation vouchers, export consultancy, and marketing support	increase in the organisational, innovation, and external-market capacity of clusters
Interventions 13.3 and 13.4 within quality systems	promotion and development of producer cooperation	support for collective marketing, recognition, and the connectivity of quality systems

Source: developed by the author based on I. Ryć (2023), European Cluster Collaboration Platform (2023a), European Commission (2025), OECD (2025), European CAP Network (n.d.b)

Through such instruments, European funding effectively strengthens market communication, collective promotion, and the organisational density of production networks, which is one of the basic features of a mature cluster model in the agri-food sector. The generalisation of the Polish experience indicates several factors that systematically accompany the positive dynamics of agri-food clusters. Above all, this concerns the presence of a coordinator capable of ensuring administrative coordination and building practical services for participants, from project management to training, promotion, R&D, and internationalisation. This logic is visible in Polish instruments supporting key national clusters, where funding is linked to the development of the cluster offer for companies, networking events, knowledge transfer, market analytics, export consultancy, and partnership with research and innovation actors (European Cluster Collaboration Platform, 2023a). The second factor is the completeness of value-chain coverage. The Polish experience shows that more resilient formats are those in which primary production, processing, logistics, marketing, quality systems, and innovation-advisory support are combined. In this context, NUTRIBIOMED Cluster represents a model in which cooperation covers agricultural advisory centres, farms, local producers, universities, technological solutions for monitoring food safety, packaging, HACCP, GHP, and GMP standards, and the promotion of functional food products. As a result, the integration of different links in the chain enables movement from a simple association of participants towards the development of new products and new commercialisation channels (Piotrowska *et al.*, 2024). Comparison with the study of M. Schoonhoven-Speijer & S. Vellema (2020) demonstrates that the resilience of an agri-food cluster depends on the ability to institutionally consolidate the role of intermediary links that provide access to food, trade, and the market. In the Polish case, this confirms the significance of producers, processors, logistics, trade, advisory, and coordination participants, which form the "middle" infrastructure of food provision.

The third factor is the ability of clusters to connect knowledge, innovation, and the market. In the general Polish benchmarking, almost all clusters provided pro-innovation services, although the average number of such services remained limited at approximately 3-4, and cooperation with technology-transfer institutions covered fewer than half of the clusters. This demonstrates the uneven maturity of the innovation component. However, where the innovation component was institutionally formalised, results were recorded in the form of SME access to expertise, testing, commercialisation, and development of new food products (Piotrowska *et al.*, 2024). The fourth factor is internationalisation, although its level in Polish clusters remains uneven. On average, Polish clusters were characterised by a relatively low level of internationalisation: the average composite indicator in this area was 0.29, while the internationalisation potential indicator was 0.30. The most common internationalisation instruments were trade missions, participation in international fairs, joint exhibitions, and promotion of brands and products in external markets. The average number of internationalisation services decreased from 6.4 to 5.1, but the number of members actually using these services increased to 1,085. This indicates a shift from a broad but not always demanded offer towards more targeted use of external-market instruments (Piotrowska *et al.*, 2024). The results can be compared with the study of P. Bertolini & E. Giovannetti (2006), in which internationalisation of the agri-food district of Modena was considered a factor in structural change in the conventional food industry. For Polish clusters, this means that entering external markets has export significance and changes the internal organisation of production, logistics, marketing, and interaction between participants. A similar emphasis appears in the study by F. Musso & B. Francioni (2015), where the example of Italian wine-producing SMEs emphasised that network relations may support internationalisation, although their effect depends on the type of ties and the real ability of firms to use local and external contacts. In the Polish case, this explains the unevenness of internationalisation: participation in a cluster does not guarantee entry into external markets if local networks are not supplemented by targeted services for export, branding, and international promotion. The fifth factor is the connection of clusters with broader regional innovation ecosystems. The material of Polish regional cluster networks recorded a positive relationship between the presence of cluster organisations and indicators such as business R&D investment, patent activity, employment in information and communication technologies (ICT), labour productivity, and GDP per capita. These results were formulated as correlations, not causal relationships, but they indicate that clusters in the Polish environment function as institutional intermediaries through which knowledge, technologies, and entrepreneurial activity are translated into regional economic results (Table 4).

Table 4. Success factors and key results of Polish agri-food clusters

Factor	Documented manifestation	Key result
Critical mass of participants	4,942 participants in 42 clusters; 117.7 participants per cluster	an organisational base for cross-sectoral cooperation is present

Table 4. Continued

Factor	Documented manifestation	Key result
Coordination core	project-management, training, marketing, R&D, and internationalisation services	the cluster coordinator combines production, knowledge, innovation, and sales
Complete value chain	combination of production, processing, logistics, quality control, and sales	NUTRIBIOMED integrates safety, packaging, HACCP/GHP/GMP standards, and functional food products
Innovation services	on average, 3-4 pro-innovation services per cluster; cooperation with technology transfer institutions covers fewer than half of clusters	innovation maturity is uneven and requires strengthening
Internationalisation	index of 0.29; potential of 0.30; 1,085 members use internationalisation services	demand for export services is growing despite a decrease in the average number of such services from 6.4 to 5.1
Short supply chains	3 analysed cases; AgroBRIDGES identified 10 barriers and 15 solutions	performance depends on logistics, packaging, transport, demand, and collective marketing
EU financial framework	EUR 25.243 billion under the CAP; EUR 7.778 billion for rural development; EUR 407.9 million under LEADER	funding supports investment, cooperation, knowledge, and local development
Regional integration	7 cluster organisations in Podkarpacie; positive relationship with R&D, patents, ICT employment, labour productivity, and GDP per capita	clusters act as institutional intermediaries in regional innovation ecosystems

Source: developed by the author based on I. Ryć (2023), M. Piotrowska *et al*. (2024), European Cluster Collaboration Platform (2023a; 2025), European CAP Network (2024a; 2024b), European Commission (2025)

For agri-food clusters, this means inclusion in broader structures of smart specialisation, digitalisation, and green transformation, rather than confinement to the food market alone. The study by P. Galaso & A. Rodríguez-Miranda (2022) on a dairy agro-industrial cluster in Uruguay confirms that strategic cooperation in agro-industrial clusters depends on the territorial structure of networks and interaction between subgroups of firms. This allows a deeper interpretation of the Polish experience: regional agri-food clusters are effective when they operate as territorial networks, not merely as formal associations of enterprises. In the area of market results, Polish agri-food cluster practices primarily show strengthening of producers' positions in supply chains, a reduced role of intermediaries, increased controllability of quality, and reduced logistics and packaging losses. The potato short supply chain case demonstrated a measurable economic effect for farmers: expansion of the customer base, a higher selling price, lower operating costs, and stronger control over the sales circuit. In the case of vegetable packaging operations, optimisation of fresh product handling, lower losses, and better capacity to respond to market demand were recorded. In the case of NUTRIBIOMED, strengthening of local supply chains, reduced dependence on imports, and easier access for SMEs to testing facilities and commercialisation pathways were recorded (European CAP Network, 2024a; European CAP Network, 2024b; Piotrowska *et al*., 2024). At the systemic level, the key result of the Polish experience is the institutional consolidation of the cluster environment. Compared with previous monitoring waves, the number of cluster members increased consistently, and the average cluster size in 2024 exceeded the 2018 level. This dynamic means that Polish clusters, including those operating in the agri-food sphere and related bioeconomic areas, are established as stable forms of cross-sectoral cooperation. However, unevenness in the level of innovation and international activity remains, which indicates the existence in Poland not of a single universal model but of several types of agri-food clustering, from market-logistics to R&D-integrated models.

CONCLUSIONS

The study established that agri-food clusters in Poland operate as multilevel organisational structures that combine raw-material production, processing, logistics, sales, research and advisory support, and institutional coordination. Their functioning is not limited to the territorial concentration of enterprises but depends on stable horizontal and vertical links between farmers, processors, market intermediaries, trade channels, and support institutions. The Polish model combines cluster organisation with short supply chains, quality systems, local sales channels, and broader interregional market links. Quantitative indicators confirmed the institutional scale of the Polish cluster environment. As of 2025, 83 registered cluster organisations were recorded in Poland. According to the 2024 PARP benchmarking, the sample of 42 clusters included 4,942 participants at the end of 2023, averaging 117.7 participants per cluster. Such concentration creates conditions for stable network interaction, while cluster effectiveness depends largely on the completeness of value-chain coverage. The key outcomes of Polish agri-food clusters include stronger positions of producers in sales channels, reduced dependence on intermediaries, lower logistics and packaging losses, and expanded opportunities for collective marketing, innovation cooperation, and use of research infrastructure. The study also showed that EU financial support plays an important role in cluster development. Poland's CAP Strategic Plan amounted to EUR 25.243 billion, including EUR 7.778 billion for rural development, supporting production modernisation, cooperation, advisory mechanisms, and market promotion. The practical recommendations follow from these findings. Given the average cluster size in the PARP sample, priority should be given to expanding membership and strengthening the coordinator's service role in marketing, R&D, export support, and project cooperation. The Zamojska Farma case demonstrated the value of short supply chains; therefore,

local logistics, packaging, sorting, and digital sales channels should be further developed. Financial support should prioritise cluster models that integrate producers, processors, logistics partners, research institutions, and quality systems. Further research should compare Polish clusters by specialisation, examine digital tools in sales coordination, and assess the long-term impact of financial support on the competitiveness of agri-food chain participants.

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Досвід Польщі у розвитку агропродовольчих кластерів

Анотація. Метою дослідження було визначити особливості функціонування агропродовольчих кластерів у Польщі через аналіз їхньої організаційної структури, механізмів взаємодії між учасниками ланцюга створення вартості, фінансової підтримки та результативності діяльності. Методологічну основу дослідження становили поєднання документального аналізу, структурно-функціонального та кейсового підходів, порівняльно-аналітичних методів, описового тлумачення кількісних показників, систематизація та наукове узагальнення. Дослідження встановило, що агропродовольчі кластери в Польщі функціонують як багаторівневі мережеві структури, які об'єднують виробників сировини, переробні підприємства, логістичні структури, канали збуту, науково-дослідні установи та дорадчі органи. Станом на 30 червня 2025 року на Європейській платформі кластерної співпраці для Польщі було зареєстровано 83 кластерні організації; у вибірці бенчмаркінгу 2024 року з 42 кластерів загальна кількість учасників становила 4 942, а середня кількість – 117,7 учасника на один кластер. Ключовими механізмами виявилися короткі ланцюги постачання, прямі зв'язки між виробниками та покупцями, спільні логістичні й пакувальні рішення, а також співпраця в системах якості харчових продуктів. Фінансова підтримка з боку Європейського Союзу формує ресурсну основу для розвитку: бюджет Стратегічного плану Спільної аграрної політики Польщі на 2023-2027 роки становить 25,243 млрд євро, з яких 7,778 млрд євро спрямовано на розвиток сільських територій. Узагальнення, отримані в дослідженні, свідчать про те, що результативність польських агропродовольчих кластерів визначається повнотою охоплення ланцюга створення вартості, координувальною роллю кластерного ядра, участю науково-дослідних і дорадчих структур, а також здатністю поєднувати локальні форми збуту з ширшими ринковими каналами. Практична цінність отриманих результатів полягає в можливості їх використання органами аграрної та регіональної політики, координаторами кластерів, асоціаціями фермерів, переробними підприємствами та науково-дослідними установами для вдосконалення міжгалузевої співпраці, планування фінансування, розвитку коротких ланцюгів постачання та зміцнення організаційної стійкості агропродовольчого сектору

Ключові слова: фінансова підтримка; логістичні структури; переробні підприємства; самоврядування; ринок

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The transformation of the financial and economic security of economic systems: European experience and the challenges of the digital economy

Abstract. The relevance of this study stems from the need to rethink approaches to ensuring the financial security of economic systems in the context of digital transformation, increasing geopolitical instability and growing systemic risks. The aim of this article was to examine the transformation of the financial security of economic systems in the context of the digital economy, based on the integration of institutional, risk-oriented and digital approaches, as well as to summarise European experience in countering financial risks and threats to financial security, and to identify opportunities for its adaptation to the Ukrainian context. To achieve this aim, methods of theoretical generalisation, content analysis of academic and analytical sources, and systematic and comparative analysis were employed. The application of these methods made it possible to examine the evolution of academic approaches to the interpretation of financial security, to identify the characteristics of its transformation under the influence of digitalisation, and to carry out a comparative analysis of threats to financial security in the countries of the European Union and Ukraine. As a result of the research, an original interpretation of financial security as an integrated property of the economic system is proposed; a mechanism for the interaction between the macro- and micro-levels of financial security has been developed; and an integrated conceptual model of its transformation in the context of the digital economy has been formulated. It has been established that the digitalisation of the financial sector is significantly altering the structure of threats to financial security due to the intensification of cyber risks, technological dependence and the impact of digital infrastructure on the resilience of economic systems. Differences have been identified in the structure of threats to financial security in the EU and Ukraine. It has been determined that the modern European model for ensuring financial security is based on the principles of digital resilience, institutional coordination and proactive risk management. The practical significance of the findings lies in the potential to utilise the proposed approaches when formulating state policy in the field of financial security, developing strategies for the digital transformation of the financial sector, enhancing digital resilience, and adapting European experience to the conditions of Ukraine's post-war economic recovery

Keywords: diagnosis; resilience; financial stability; financial engineering; credit burden; digital technologies; European integration

INTRODUCTION

In the current climate of digital transformation, geopolitical instability and rising systemic risks, the financial security of economic systems is becoming particularly relevant. The traditional understanding of this concept

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through the prism of macro-financial stability no longer fully addresses contemporary challenges, as the digitalisation of the financial sector amplifies the role of cyber risks, technological dependence, data protection and the resilience of digital infrastructure. In these circumstances, financial security should be viewed not merely as the financial system's ability to maintain equilibrium, but as a multi-level characteristic of the economic system, reflecting its capacity to adapt to financial, digital, institutional and geopolitical threats. This issue is of particular significance for the countries of the European Union and Ukraine. The European model for ensuring financial security is gradually shifting towards a combination of macroprudential regulation, digital operational resilience and proactive risk management. For Ukraine, the relevance of this research is heightened by the impact of the war, macroeconomic instability, the destruction of critical infrastructure and the need to adapt European experience to the conditions of post-war recovery. This necessitates the development of an integrated approach to studying the financial security of economic systems in the context of the digital economy.

The study by G. Gorton & G. Ordoñez (2020) focuses on the mechanisms underlying the formation of financial cycles and systemic crises. The authors concluded that periods of financial growth can have both positive and negative effects on the economy, depending on the nature of the accumulation of credit imbalances and the quality of information in financial markets. Particular attention is paid to the mechanisms by which systemic risks spread among financial institutions. The study's findings confirm the need to take systemic risks into account as a key component of modern financial security. B. Walker (2020) examined the nature of resilience as a property of complex systems. As a result of the study, the author concluded that resilience lies not only in a system's ability to withstand shocks, but also in the preservation of its key functions and its adaptation to changes in the external environment. This approach allows for a broader interpretation of financial security beyond the traditional understanding of financial stability.

N. Nosan & S. Nazarenko (2022) investigated methodological issues in the management of financial security within economic security systems at various levels of governance. The authors justified the need to consider financial security as a component of a broader economic security system and concluded that it is important to coordinate financial security management mechanisms across different levels of the economic system. These findings confirm the validity of a systematic approach to the study of financial security in economic systems. J. Haldon *et al.* (2021) analysed the historical experience of societies functioning under conditions of crisis and prolonged stress. Based on the results of their study, the authors found that the resilience of systems is determined not only by their ability to adapt to change, but also by their capacity to undergo structural transformation in response to new challenges. The findings indicate the need to view financial security not only as a mechanism for protection against risks, but also as the economic system's capacity for adaptation and transformation in the face of long-term crisis impacts.

The relationship between resilience and sustainable development in a war economy was investigated by O. Semenenko *et al*. (2025). The authors concluded that modern resilience should be viewed as the ability of economic systems not only to recover from crisis events, but also to develop new mechanisms for growth in conditions of prolonged uncertainty and military risks. The findings of the study confirm the need to take security and military factors into account when assessing the financial stability of economic systems. Alongside the development of concepts of systemic risk and resilience, a separate strand of contemporary research focuses on the impact of digital transformation on financial security. The BIS (2023) report analyses the consequences of the proliferation of financial technologies, digital platforms and the activities of large technology companies in the financial sector. The report concludes that digitalisation creates new opportunities to improve the efficiency of financial services, but at the same time gives rise to additional risks related to cybersecurity, data concentration and the technological dependence of financial infrastructure. These findings highlight the need to incorporate a digital component into contemporary approaches to ensuring financial security.

Thus, the results of recent research demonstrate the evolution of approaches to interpreting financial security from ensuring macro-financial stability to understanding it as a multi-level characteristic of the economic system, combining risk-based, resilience-based and digital approaches. At the same time, the digital transformation of the financial sector is creating new challenges that require the further development of the theoretical and methodological foundations for ensuring financial security. Despite the significant contribution of the studies cited to the development of financial security theory, a number of aspects remain insufficiently explored. In particular, most studies focus on issues of financial stability and systemic risks, as well as on the resilience of economic systems, whilst the interrelationship between institutional, digital, geopolitical and financial factors in the transformation of financial security has been studied only in a fragmented manner. However, aspects relating to the integration of risk-based, institutional and digital approaches to ensuring financial security, as well as the adaptation of European experience in ensuring financial stability to the conditions of Ukraine's economy during a period of digital transformation and military challenges, remain under-researched. The aim of this article was to examine the transformation of financial security in economic systems within the context of the digital economy, based on the integration of institutional, risk-oriented and digital approaches, as well as to summarise European experience in countering financial risks and threats to financial security, and to identify opportunities for its adaptation to the Ukrainian context.

MATERIALS AND METHODS

The methodological basis of the study was an interdisciplinary approach to the analysis of the financial security of economic systems, which combined institutional, systemic, comparative and risk-oriented approaches. The application of this approach was dictated by the multi-level nature of financial security, which is shaped by macroeconomic, institutional, geopolitical and digital factors and is undergoing transformation in the context of the digitalisation of the economy. The study utilised the methods

of theoretical generalisation, scientific abstraction and content analysis of academic and analytical sources – to systematise approaches to interpreting the categories of "economic system" and "financial security", as well as to identify the evolution of scholarly approaches to understanding financial security within the Anglo-American and European traditions. The institutional approach was applied to examine the role of the regulatory environment, the architecture of the financial system and the mechanisms for coordinating economic policy in shaping the financial security of economic systems, particularly in the context of European practice in ensuring macro-financial and digital stability. The systems approach was used to justify financial security as an integrative characteristic of the economic system, shaped through the interaction of macro- and micro-levels, and to construct a conceptual model of the transformation of financial security in the context of the digital economy. Attention was paid to the mechanisms linking a state's financial stability, the functioning of the financial system and the financial security of economic entities against a backdrop of growing digital, geopolitical and macroeconomic risks.

A comparative analysis was used to contrast Anglo-American and European academic traditions in the interpretation of financial security, as well as to identify differences in the structure of threats to financial security in the European Union and Ukraine, and the potential for adapting European experience to Ukrainian conditions (Adrian & Brunnermeier, 2016; Gorton & Ordoñez, 2020; European Central Bank, 2024). To conduct a comparative analysis of threats to financial security, a targeted selection of academic publications and analytical reports from international organisations and specialist institutions was carried out (International Monetary Fund, 2024; European Union Agency for Cybersecurity, 2024a; European Central Bank, 2024), published predominantly between 2022 and 2025. The criteria for including sources were: relevance to the issue of financial security in the context of digital transformation; the presence of an analysis of contemporary financial, cyber, geopolitical and institutional risks; and the possibility of using the results to compare the operating conditions of the economic systems of the EU and Ukraine.

Methods of analysis and synthesis were used to summarise the findings of contemporary scientific and analytical studies on digital, financial, geopolitical and institutional risks, as well as to develop an integrated approach to ensuring the financial security of economic systems in the context of digital transformation. The analysis includes human resources and social factors, as contemporary research on financial security and digital resilience considers the shortage of skilled personnel, migration processes and the level of digital competences to be important factors in the formation of financial and cyber risks. To summarise European experience in ensuring economic and financial security, the "Promote – Protect – Partner" analytical framework, proposed by the European Commission as part of the EU Economic Security Strategy initiative package (European Commission, 2024a), was used; this enabled the systematisation of instruments for enhancing resilience, protection and international partnership in the field of economic security.

RESULTS AND DISCUSSION

Against a backdrop of high uncertainty, digital transformation and geopolitical challenges, the issue of financial security becomes rather complex. It is difficult to consider it in isolation, without taking into account the broader environment in which the economy operates. Thus, to gain a thorough understanding of financial security, it is advisable to analyse it through the prism of the economic system, which is the primary subject of study. In international economics, the economic system is viewed as an organised structure comprising rules – both formal and informal – and mechanisms for regulating economic activity. The quality of resource allocation, the development of the banking sector and the economy's capacity for stable growth depend on the quality of its institutional framework (Rodrik, 2021). In this context, the financial subsystem, as an integral part of this structure, plays a vital role in the reallocation of resources, risk management and ensuring overall macroeconomic stability.

In the works of Ukrainian researchers, the economic system is defined as a complex, unified and multifaceted socio-economic structure capable of adapting to external changes (Kanova, 2023). A study of Ukraine's banking sector during times of war and crisis has shown that the resilience of the economic system is largely determined by the ability of the financial subsystem to function effectively, the flexibility of its regulatory framework, and the ability of financial institutions to maintain the continuity of financial flows (Tymoshyk *et al.*, 2022; Arzhevityn *et al.*, 2023). This is corroborated by data from the Financial Stability Report (National Bank of Ukraine, 2024), according to which the high liquidity and operational resilience of the banking infrastructure have served as key buffers against systemic shocks. In this sense, the economic system emerges as an integrated complex of production, financial and regulatory mechanisms operating within a single institutional architecture. As noted in the World Bank (2026) report, it is the quality of institutional design that determines the ability of national economies to recover in the face of global fragmentation. Its stability is based on the financial subsystem's capacity to offset internal and external disruptions, thereby ensuring a high level of confidence in financial institutions.

Thus, the economic system constitutes a coherent structure that integrates production, financial and regulatory instruments. It operates within a defined institutional framework and ensures the continuity of economic processes. Its stability depends on the financial subsystem's ability to adapt to changes in the risk environment, to maintain confidence in the institutions of the financial system, and to preserve the balance and continuity of financial flows. Based on an analysis of international and Ukrainian academic sources, the author proposes the following definition: an economic system is a multi-level, institutionally organised model of economic activity that integrates mechanisms for the production, distribution and redistribution of resources and ensures the coordination of interaction between economic agents and risk management. The stability of such a system depends on the quality of its institutional structure, its ability to regulate processes, and the adaptability of the financial subsystem to changes in the internal and external risk environment.

From this perspective, financial security is an integral component of the economic system, as it ensures the continuity of financial flows, the efficient reallocation of resources and the support of economic agents' operations in conditions of risk. A high level of financial security helps to preserve macroeconomic stability, enhance investment attractiveness, maintain the financial resilience of businesses and households, and strengthen confidence in financial institutions. In this context, financial security is one of the key factors in ensuring the resilience and adaptability of the economic system in the face of digital transformation and growing uncertainty. Thus, the institutional organisation of the economic system plays a key role in developing mechanisms to ensure financial security and adapting them to the conditions of the digital economy. Within this framework, financial security is regarded as a comprehensive characteristic of the economic system, reflecting the financial subsystem's ability to ensure the uninterrupted flow of financial resources, their optimal reallocation and resilience to exogenous and endogenous risks.

Financial systems are being transformed by digital technologies, which are changing the ways in which financial resources are moved, risks are assessed and financial flows are managed. They use algorithms and artificial intelligence to assess risks and manage the assets of their clients and other financial institutions, creating a new way in which the financial sector is interconnected and interdependent (BIS, 2023). The BIS (2023) report notes that digitalisation accelerates the processing of financial information, improves access to financial services and reduces transaction costs, but at the same time increases financial institutions' technological dependence. Institutions must be able to resolve issues and protect themselves against cyber-attacks, as they rely on services and algorithms that can change rapidly and affect their funds (BIS, 2023).

In its latest Financial Stability Review, the European Central Bank examined how digital assets, artificial intelligence and cyber-attacks could cause major problems, as they can rapidly propagate shocks in the digital environment (European Central Bank, 2024). Digital financial services enhance the speed, accessibility and efficiency of financial transactions for individuals and businesses, whilst also making them more accessible and equitable; however, they also create new challenges and risks for the financial and technological systems that utilise them. A report by the International Monetary Fund (2024) notes that AI can help banks and other financial institutions to better coordinate their plans and strategies, but it will also make them more vulnerable to sudden and unpredictable market changes, which could cause problems for the entire system. Digitalisation is changing thinking about financial security, making risk management more complex and dependent on factors unrelated to the economy or the monetary system. Financial security is taking on a more comprehensive scope, encompassing digital infrastructure, data protection, and operational and financial systems that operate with a high degree of technological dependence. Consequently, the concept of financial security has undergone a significant transformation: from a predominantly macro-financial focus on stability and equilibrium to a more comprehensive understanding that encompasses systemic risks, adaptive capacity and digital challenges. Financial security is increasingly viewed as a multi-level category combining institutional, risk-oriented and technological aspects. At the same time, these dimensions are often analysed in isolation, without sufficient conceptual alignment. This is precisely why an integrated framework is needed – one that would combine institutional analysis of the economic system with the digital and risk-driven transformation of the financial environment.

The evolution of approaches to financial security shows that its meaning varies across different academic schools. The element that is emphasised – whether it be the stability of financial markets, institutional resilience, regulatory policy or socio-economic stability – depends significantly on the methodology and analytical context. Thus, in contemporary literature, it is useful to distinguish between two main conceptual traditions – the Anglo-American and the European – which differ both in terms of analytical tools and research priorities. The Anglo-American school views financial security primarily through the concepts of "financial stability" and "systemic risk" (Adrian & Brunnermeier, 2016; Gorton & Ordoñez, 2020). Within this approach, the main focus is on the emergence and spread of financial crises, the role of interbank linkages, contagion effects and the cyclical nature of financial markets (Gorton & Ordoñez, 2020). Research has continued along these lines within the macro-financial paradigm, analysing the relationship between financial cycles, the capitalisation of financial intermediaries and the build-up of systemic risk (He & Krishnamurthy, 2013; Bianchi & Mendoza, 2018). Within this framework, financial stability is understood primarily as the financial system's ability to reduce the likelihood of a systemic crisis or to limit its macroeconomic consequences through the use of macroprudential policy instruments and market discipline.

Against the backdrop of digitalisation, the Anglo-American school is increasingly integrating issues of operational resilience, cyber resilience and algorithmic risks into the broader context of financial stability (BIS, 2023). At the same time, even in the digital sphere, the focus remains on ensuring the functional continuity of market mechanisms and minimising systemic disruptions. The European tradition favours a more institutionally integrated and regulatory-oriented approach. Financial security is viewed as a multi-layered system combining macroprudential regulation, fiscal policy coordination, the activities of supranational supervisory bodies and digital mechanisms for protecting financial infrastructure. Particular attention is paid to financial resilience – the ability of institutions to adapt to external shocks and changes in the risk environment (European Central Bank, 2024).

In European research, the integration of the digital dimension of financial security is becoming increasingly important – taking into account cyber risks, the platformisation of financial services and regulatory mechanisms to ensure digital operational resilience (BIS, 2023). In this context, financial security goes beyond a narrow understanding of market stability and emerges as the institutionally underpinned capacity of the financial system to sustain economic development amidst growing uncertainty and technological change. The main difference between the schools lies in which aspect is primarily studied: the Anglo-American school examines the behaviour of financial markets and the mechanisms by which systemic

risks arise, whilst the European school focuses on the institutional structure and the multi-level regulatory system designed to ensure financial stability. However, this does not mean that there are markedly different views; rather, they simply highlight different aspects of a single overarching issue. A synthesis of the approaches from the Anglo-American and European traditions has shown that financial security should be viewed not only as an indicator of the stability of the financial system or the reduction of systemic risks, but also as a property of the economic system that is shaped by structural and digital changes, and which is multi-level and dynamic in nature.

The financial security of an economic system is the ongoing state and functioning of the financial sector, which demonstrates its capacity to ensure the stability of cash flows, to allocate and utilise financial resources effectively, and to withstand various risks – whether systemic, geopolitical or digital – with a view to sustaining stable socio-economic development. Financial security is a fundamental characteristic of the economic system, shaped by the institutional framework, the structure of financial relations and the level of development of digital technologies. It operates at two levels: the macro- and micro-levels. Financial security at the macro-level is determined by the soundness of the state's financial position, the stability of the banking system and the effective management of systemic risks. It reflects the state's ability to ensure debt sustainability, maintain macroeconomic equilibrium and preserve confidence in financial institutions. Macro-financial security is shaped by fiscal and monetary policy, macro-prudential regulation and the quality of the financial system's institutional architecture.

At the micro level, financial security is linked to the financial stability of businesses and households. It reflects their ability to maintain liquidity, solvency and investment activity in a changing environment. Key factors include capital structure, access to financial resources, the effectiveness of financial management and risk mitigation. The interdependence of these levels is crucial for ensuring the overall financial stability of the economy. The accumulation of imbalances at the micro level can turn into systemic risks, whilst macroeconomic instability leads to a rise in the cost of capital and an increase in financial risks for businesses. Consequently, the macro and micro levels form a single system of financial security (Table 1).

Table 1. Comparative characteristics of the macro- and micro-levels of financial security

Criterion	Macro-level of financial security	Micro-level of financial security
Object	The State, the financial system	Businesses, households
Objective	Ensuring macro-financial stability	Ensuring solvency and financial stability
Indicators	Public debt, budget deficit, inflation, systemic risk, stability of the banking system	Liquidity, profitability, capital structure, debt burden
Risks	Financial crises, currency shocks, debt instability, systemic risk	Insolvency, default, decline in profitability, financial distress
Supporting tools	Fiscal and monetary policy, macro-prudential regulation	Diversification of funding, risk mitigation
Outcome	Financial system stability and investor confidence	Business resilience and investment activity

Source: summarised by the authors

Table 1 illustrates the differences between the macro- and micro-levels of financial security in terms of the subject matter, indicators, risks and support instruments. At the same time, these levels do not operate in isolation, but form part of a single system of financial stability within the economic system. The macro- and micro-levels constantly interact, creating a unified system of financial stability (Fig. 1). When the financial condition of enterprises deteriorates, tax revenues fall and the debt burden increases. On the other hand, macroeconomic instability increases the cost of borrowing and the risks to business. In the digital economy, this interdependence becomes even greater due to the faster spread of financial crises and the emergence of new cyber risks.

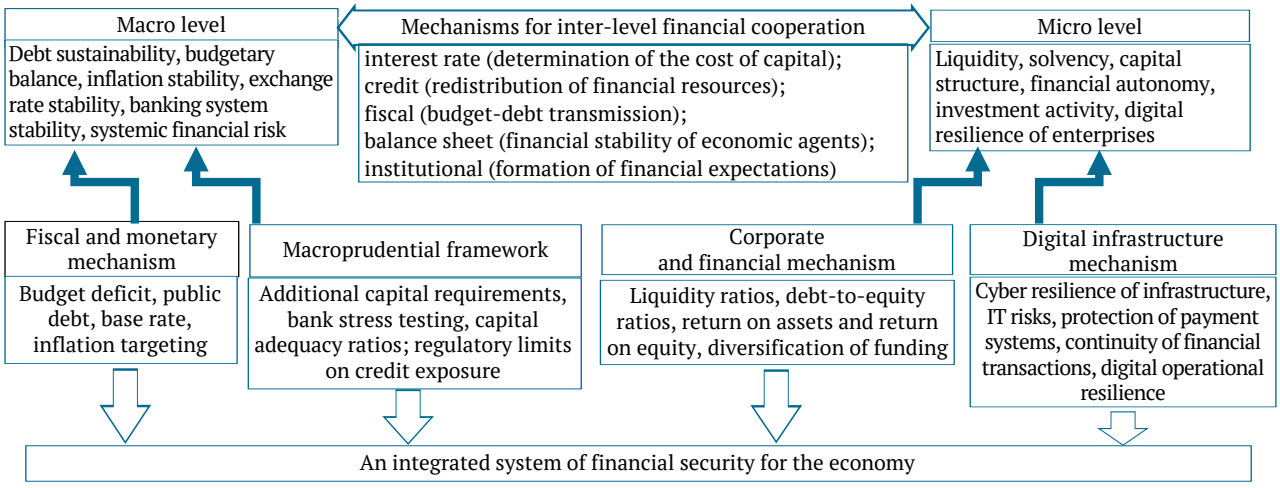

Figure 1. The mechanism of interaction between the macro- and micro-levels of financial security in the economic system
Source: compiled by the authors

The European Union demonstrates an integrated model for ensuring financial security, combining macro- and micro-level regulatory mechanisms. At the macro level, financial security is ensured through the coordination of fiscal policy within the framework of the Stability and Growth Pact, the development of macroprudential regulation, and the activities of supranational financial supervisory institutions. The functioning of the European Banking Union, uniform capital adequacy rules and the monitoring of systemic risks form the basis of system-wide financial stability. At the micro level, financial security is underpinned by corporate standards, transparency requirements for financial reporting, regulatory mechanisms to mitigate risks, and the protection of the rights of investors and consumers of financial services. In the current environment, the digital component of financial security is of particular importance: regulatory acts in the field of digital operational resilience (in particular the Digital Operational Resilience Act (DORA)) are aimed at enhancing the cyber resilience of financial institutions and minimising digital risks. Thus, the European model of financial security is characterised by the institutional integration of the macro- and micro-levels and the combination of traditional regulatory mechanisms with digital tools for ensuring resilience. Consequently, the financial security of the economic system is shaped through the interaction of the macro- and micro-levels, and European practice demonstrates their institutional integration. This approach allows financial security to be viewed not merely as a characteristic of public finances or corporate resilience, but as a systemic property of the economy, ensured through coordinated regulatory, market and digital mechanisms.

A generalisation of the multi-level structure of financial security and European practice regarding its institutional integration enables to move towards the formation of an integrated conceptual model for the transformation of financial security in economic systems within the context of the digital economy. In the digital economy, financial security ceases to be solely a function of macro-financial stability. It is transforming into a multi-level system for countering risks, integrating regulatory, market and digital mechanisms. In order to systematise these interrelationships, it is advisable to develop an integrated conceptual model of the transformation of the financial security of economic systems, which reflects the logic of interaction between the characteristics of the economic system, the risk environment, the instruments for ensuring security and the expected outcomes (Fig. 2).

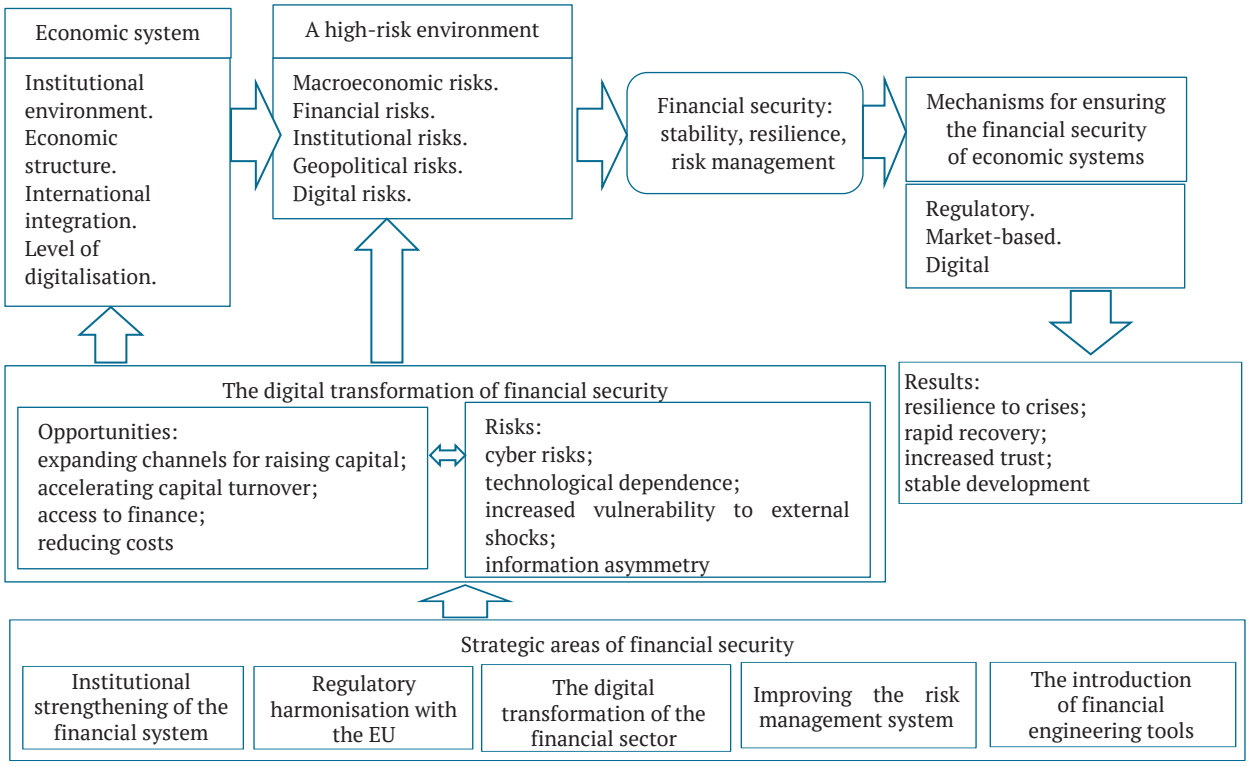

Figure 2. A conceptual model of the transformation of the financial security of economic systems
Source: compiled by the authors

The proposed integrated conceptual model reflects the systemic nature of financial security as a property of the economic system. It combines an institutional approach to the analysis of economic systems with risk-oriented and digital approaches to the interpretation of financial security. The model demonstrates that financial security is shaped by two interrelated components: the structural characteristics of the economic system (institutional architecture, level of openness, digital maturity) and changes in the risk environment (macroeconomic, financial, geopolitical and digital risks). Financial security takes centre stage as an integrative category, combining the stability of financial flows, resilience to shocks and risk manageability at all levels of the economic system. The European institutional

framework in the model serves as an example of a coordinated regulatory approach to ensuring financial security in the digital economy. It is precisely the integration of macroprudential policy, market mechanisms and digital risk mitigation tools that shapes the new architecture of financial security for economic systems. Thus, the proposed model has made it possible to conceptualise the transformation of financial security not as an isolated financial phenomenon, but as a systemic change in the mechanisms governing the functioning of the economic system in the context of digitalisation and growing uncertainty. Implementing the developed model requires taking into account the system of threats arising in the surrounding environment, which have a decisive impact on the financial security of economic systems at both the macro- and micro-levels.

This paper analyses academic and analytical publications concerning the nature, list and characteristics of threats to financial security in Europe and Ukraine. A study by S. Nermin (2025) analyses the current threat environment for European financial institutions against the backdrop of the digitalisation of the economy and growing geopolitical instability. The main focus is on cyber threats as one of the key factors destabilising the financial security of enterprises and financial institutions. It is emphasised that the digitalisation of financial processes, the proliferation of cloud services and automated payment systems, and reliance on third-party IT providers are giving rise to new threats to financial security that go beyond traditional economic risks. The most critical threats include DDoS attacks, ransomware, data breaches, phishing campaigns, social engineering attacks and the compromise of digital service providers. Such threats can result in financial losses, operational disruptions, breaches of business continuity and reputational damage. Attention is drawn to the impact of geopolitical processes on financial security: cyber incidents in the financial sector are increasingly linked to international conflicts, and financial institutions are becoming targets of attacks by both criminal groups and state actors. At the same time, the report emphasises the growing role of threats associated with the use of artificial intelligence, particularly for personalised phishing, automated fraud and the manipulation of digital financial data.

The study by S. Piserà *et al*. (2024) examines the impact of the Russia-Ukraine war on the systemic risk of European non-financial companies during the period 2021-2022. The authors analysed changes in the beta coefficient as an indicator of companies' sensitivity to market and geopolitical shocks, which allows for an assessment of the transformation of financial risks in crisis conditions. The results of the study showed that, following the outbreak of the military conflict, systemic risk for firms in Europe increased in a statistically significant manner, indicating a heightened vulnerability of the corporate sector to external shocks, in particular geopolitical instability, supply chain disruptions, energy crises and financial market volatility. At the same time, it was found that companies with a higher proportion of international sales exhibited a relatively lower level of risk, which can be explained by the diversification of their sales markets and reduced dependence on individual regions. This highlighted the role of globalisation as a factor in partially mitigating financial threats during periods of crisis. In the context of financial security, the study's findings demonstrated that geopolitical events can act as a systemic risk factor that directly affects the financial stability of businesses through changes in market expectations, the cost of capital and investment attractiveness. Thus, the financial security of enterprises in the current environment depends to a large extent on their ability to adapt to external shocks and to ensure geographical and operational diversification of their activities.

An analysis of reports by ENISA (European Union Agency for Cybersecurity, 2024a; 2024b; 2025) has shown that the financial security of enterprises in the EU is shaped by a hybrid cyber-economic threat, suggesting that cyber risks constitute a distinct systemic factor in business financial stability. The most critical of these remain ransomware attacks, phishing and other forms of social engineering, leaks of financial and personal data, as well as DDoS attacks that disrupt the availability of financial services. These threats lead to direct financial losses, the disruption of business processes, the disruption of payment transactions and a decline in confidence in financial institutions. A negative trend is the increasing structural complexity of cyber risks, particularly due to attacks on supply chains, growing reliance on cloud technologies and digital platforms, and the active use of artificial intelligence to automate cyberattacks and financial fraud. As a result, cyber threats extend beyond the purely technical sphere and are becoming a factor in macroeconomic and financial instability. It can be summarised that ENISA's reports view the modern cyberspace as an environment of hybrid threats, in which technological, economic and geopolitical factors interact and reinforce one another. The reports also highlight staff shortages as one of the threats to business security.

The study by Z. Varnalii & A. Mekhed (2022) examines the theoretical and practical aspects of ensuring the financial security of enterprises in the context of the digital transformation of the economy. The authors emphasised that the development of the digital economy is significantly altering the nature of threats to financial security, shifting them from traditional financial and economic factors to complex digital and cyber risks. The study emphasises that the digitalisation of business processes, the active implementation of fintech solutions, automated management systems and electronic financial services enhance the efficiency of enterprises' operations, but at the same time create new vulnerabilities. Key threats to financial security include cybercrime, leaks of confidential financial information, fraud in electronic payment systems, as well as risks associated with dependence on external digital platforms and IT service providers. The authors drew particular attention to the growing importance of systems for mitigating financial risks in the digital economy. They emphasised that businesses must implement modern cyber-security tools, improve staff digital literacy and ensure the diversification of their digital infrastructure to reduce dependence on individual technological solutions.

The authors, L. Dokiienko *et al*. (2024), investigated the system of determinants that shape the level of financial security of enterprises, with a focus on the impact of financial indicators and the risks associated with financing business operations. The publication emphasises that financial security is shaped by a combination of internal and external factors, among which the risks associated with financing a company's operations and the overall level of financial

stability are of particular significance. Accordingly, an increase in the risk of unbalanced financing or a decline in liquidity was considered a direct source of threats to financial security. The article by researchers V. Marchenko & O. Usyk (2025) emphasises that the financial security of enterprises is shaped by a complex of external and internal threats, amongst which macroeconomic instability, fluctuations in financial markets, rising inflation and limited access to investment resources play a particularly significant role. The article highlights the growing role of geopolitical factors, which are increasingly acting as systemic determinants of financial losses and the destabilisation of the business environment. Particular attention is paid to the impact of the digitalisation of the economy, which, on the one hand, helps to improve the efficiency of financial flow management, whilst on the other, creates new threats in the form of cyber risks, dependence on digital platforms, data breaches and increased vulnerability of companies' information systems. The article notes that digital transformation is changing the nature of financial threats, shifting them into the realm of technological and cyber risks.

An analytical report by Sayenko Kharenko (2025) examined the current state of the security environment for enterprises in Ukraine based on a survey of companies across various sectors of the economy. According to the survey results, a key trend identified is the maintenance of high business resilience despite the risks posed by the war: the overwhelming majority of companies do not plan to relocate, which indicates that businesses have adapted to crisis conditions. At the same time, the report highlights a significant increase in security expenditure, particularly on cyber defence, physical security and the development of digital infrastructure. In the context of threats to enterprises' financial security, the document highlights the growing role of cyber risks, which are becoming one of the key factors in financial losses. These include cyberattacks on corporate systems, disruptions to digital processes, attacks on remote infrastructure and the risk of data breaches. These threats directly impact financial stability through operational disruptions, loss of revenue and increased costs of system recovery. Particular emphasis is placed on the importance of investing in the digital resilience of businesses, including the development of cybersecurity and the protection of information systems as a key element of modern financial security. Thus, financial security was considered not only in terms of economic indicators but also in terms of the level of protection afforded to businesses' digital infrastructure.

The KPMG (2025) report examines the business environment in Ukraine during the period of a war economy, as well as the key factors influencing the investment attractiveness and financial resilience of enterprises. The report emphasises that the main systemic threat remains military risk, which directly affects the stability of cash flows, supply chains and infrastructure. The destruction of transport and energy systems during the war results in additional financial losses for businesses and increases the cost of operations. Macroeconomic instability, in particular inflationary pressures, currency restrictions and fluctuations in economic growth, has been identified as a significant group of threats. Such factors affect the availability of capital, investment decisions and the overall solvency of enterprises. At the same time, the report highlights the role of financial restrictions and regulatory changes introduced under martial law to stabilise the economy. Particular attention is paid to infrastructure and operational threats, which are exacerbated by the destruction of logistics routes, restrictions on transport accessibility and the risk of supply disruptions. This creates additional financial costs for enterprises and reduces the efficiency of their resource utilisation. At the same time, the report emphasises that, despite the high level of risks, the Ukrainian economy has demonstrated adaptability and resilience, in particular through the advancement of digitalisation, government business support programmes and international investment mechanisms for capital protection. This has partially offset the impact of these threats and contributed to the formation of a more resilient model of corporate financial security. Thus, a synthesis of the research findings has enabled the compilation of a list of threats to financial security in the context of a comparison between Europe and Ukraine (Table 2).

Table 2. Comparative analysis of threats to the financial security of the EU and Ukraine

Threat category	EU	Ukraine
Geopolitical threats	Geoeconomic competition (US-China-EU)	War as a systemic factor, destruction of assets, loss of markets, high war risks
Digital/cyber threats	Cyberattacks on banks and corporations (ransomware, DDoS), data breaches, dependence on Big Tech and cloud services	Massive cyber-attacks (including cyber-warfare), attacks on state registers, banks and the energy sector, financial fraud
Macroeconomic threats	Inflation, interest rate rises, financial market volatility, energy price fluctuations	Inflation, devaluation, GDP volatility, a sharp decline in investment and consumer demand
Infrastructure threats	Disruptions to global supply chains, dependence on critical technologies and logistics	Destruction of the power grid, disruptions to electricity and internet supply, disruption to logistics
Financial and market threats	Fintech risks, algorithmic errors, capital market instability	Limited access to credit, high cost of capital, dependence on international aid
Regulatory and institutional threats	Tighter digital regulation (GDPR, DORA), compliance costs, investment controls	Instability of the regulatory environment, weak institutional safeguards, corruption risks
Data and AI threats	Artificial intelligence risks (algorithmic errors), data manipulation, Big Data leaks	Limited digital security, low adoption of secure AI, poor cyber literacy
Human resources and social threats	Shortage of digital skills, need for reskilling	Brain drain (particularly in IT), population migration, labour force contraction
Operational digital threats	Dependence on SaaS and cloud platforms, third-party supplier risks	Low digital maturity of businesses, critical dependence on foreign software

Source: compiled by the authors

The data in Table 2 provide a systematic comparison of threats to the financial security of enterprises in the EU and Ukraine, organised by key risk categories. Both contexts are characterised by the multidimensional nature of the threats, which encompass geopolitical, digital, macroeconomic and institutional factors. At the same time, in the EU these threats are more manageable, as they arise in an environment where digitalisation and globalisation create predominantly structural challenges (cyber threats, dependence on technology platforms, fintech risks), which are mitigated by well-developed institutional mechanisms (GDPR, DORA, investment controls). For Ukraine, however, threats to financial security are cumulative and existential in nature. The war acts as a systemic factor, exacerbating other groups of threats – ranging from the destruction of infrastructure and disruption to logistics to restricted access to capital and high volatility in the macroeconomic environment. Digital threats in the Ukrainian context are also more intense due to cyber warfare, weaker infrastructure resilience and limited cyber defence resources.

It can therefore be argued that financial security threats to Ukraine are characterised by a higher level of intensity and mutual reinforcement, and a lower level of manageability. In the EU, digitalisation primarily gives rise to new regulatory and technological challenges within a stable environment; in Ukraine, however, it overlaps with military and macroeconomic shocks, creating a high concentration of risks of financial destabilisation for enterprises. The European experience in countering these complex threats is examined. On 24 January 2024, the European Commission presented a package of initiatives to strengthen the EU's economic security (the EU Economic Security Package), which covers foreign investment screening, export controls, monitoring of outbound investment, research security and support for dual-use technologies, aimed at strengthening the Union's economic security against a backdrop of growing geopolitical tensions and technological transformations. Supporting security is viewed as the EU's ability to minimise risks whilst maintaining the openness of the economy and the competitiveness of the internal market (European Commission, 2024a; 2024b). Four groups of strategic risks have been identified, namely: supply chain vulnerabilities; threats to critical infrastructure, including cyber infrastructure; risks to technological security and the leakage of critical technologies; and risks of economic coercion and the "weaponisation of dependencies" – the use of economic dependence as a tool of pressure. It is precisely these risks that should be regarded as key sources of potential destabilisation of the EU's financial and economic system.

To counter these threats, the European Commission (2024a) has proposed a comprehensive approach based on three strategic pillars: "promote – protect – partner". The first involves enhancing the competitiveness and resilience of the internal market through the development of the industrial, scientific and technological base. The second focuses on creating protective measures, in particular strengthening controls on foreign direct investment, improving export controls, monitoring outbound investment and enhancing the security of critical technologies. The third pillar involves expanding international partnerships with countries that share the EU's approach to economic security. Thus, the EU has proposed a model of proactive economic security, in which the key lies not only in responding to threats but also in pre-emptively countering them through regulatory, investment and technological instruments. In the context of corporate financial security, this entails a transition to a system where the stability of the business environment is ensured through the management of strategic risks, the strengthening of cyber and technological resilience, and the reduction of the EU economy's critical external dependencies. In the authors' view, this approach to ensuring and maintaining financial and economic security under contemporary conditions could be adapted for Ukraine, provided that due consideration is given to the country-specific risks and threats discussed above, particularly those associated with wartime conditions and infrastructures (Table 3).

Table 3. Adapting European experience in countering threats to financial security

Area of support	Ways of adapting to threats to financial security
"Promote" (development and strengthening of resilience)	Accelerating economic recovery and modernisation through the development of critical infrastructure, supporting the relocation of businesses, stimulating investment and expanding the digital transformation of business. Strengthening the financial resilience of businesses through access to capital, state loan guarantees and the development of financial recovery instruments. Developing mechanisms for insuring against war risks. Supporting the restoration of damaged production facilities. Diversifying logistics routes.
"Protect" (protection of strategic assets)	Strengthening cyber security in the financial sector, the energy sector and public registers, as well as developing a system to counter risks to critical infrastructure. Integrating the EU's expertise on investment controls, data protection and the regulation of digital platforms, whilst placing an emphasis on countering cyber warfare and hybrid threats. Protecting critical energy and transport infrastructure. Establishing contingency financial and logistical mechanisms to ensure the economy can continue to function in times of crisis
"Partner" (international cooperation)	Ensuring access to financial resources, technologies and security support mechanisms through integration into European cybersecurity and economic initiatives, participation in joint threat monitoring systems, and the expansion of cooperation with the EU in the field of critical technologies and economic recovery.

Source: compiled by the authors

It should be recognised that European mechanisms for ensuring financial security have been developed largely in the absence of large-scale military conflict on the territory of EU Member States. Consequently, their adaptation

to Ukrainian conditions does not provide a direct solution to the problems of physical destruction of assets or infrastructure, but is aimed at enhancing the economic system's resilience to the consequences of military shocks. In particular, the development of digital infrastructure, cyber-security mechanisms, financial support for businesses, credit guarantee instruments and the enhancement of the state's institutional capacity helps to minimise economic losses, accelerate the recovery of economic activity and strengthen the financial resilience of economic actors in wartime. Thus, in the authors' view, what is most relevant for Ukraine is not the direct replication of the model, but its adaptation as a system for countering cumulative crisis threats, where economic security is directly linked to the financial and cyber resilience of businesses. In wartime, the function of "economic survival" and stabilisation of the business environment can be ensured through the implementation of the first "promote" pillar. Measures within the "protect" pillar can be implemented by integrating the EU's experience in investment controls, data protection and the regulation of digital platforms, which, in financial terms, should lead to a reduction in the risks of payment system failures, data loss and market destabilisation. The "partner" strand (international cooperation) is of strategic importance to Ukraine, as it provides access to the necessary financial resources, technologies and security support mechanisms, through expanded cooperation with the EU in the field of critical technologies and economic recovery.

Thus, adapting the European model for Ukraine entails a transition to an integrated system of economic and financial security, where risk mitigation combines military challenges, digital threats and financial instability, and where the key principle is not only defence but also active resilience and the recovery of the state's economic system. The study's findings confirmed that the financial security of modern economic systems is shaped not only by traditional macro-financial factors, but also by digital, geopolitical and cyber risks. These findings are consistent with the approaches of the European Central Bank (2024), according to which financial stability increasingly depends on the operational resilience of financial infrastructure, the level of cyber security and the ability of financial institutions to adapt to digital transformations. A review by the European Central Bank (2024) emphasises that cyber risks and the digital concentration of financial services can be a source of systemic instability and the rapid spread of financial shocks.

The approach proposed in this article to interpreting financial security as an integrated property of the economic system also correlates with the conclusions of the BIS (2024) regarding the transformation of the global financial architecture under the influence of digitalisation and artificial intelligence. The BIS (2024) report emphasises that the adoption of AI, the platformisation of financial services and reliance on digital technologies enhance the efficiency of the financial sector, but at the same time give rise to new systemic risks associated with cyber threats, algorithmic errors and the concentration of technological infrastructure. Particular attention is paid to risks associated with the use of generative artificial intelligence, the high concentration of cloud services and the dependence of financial institutions on Big Tech companies, which may increase the vulnerability of the global financial system to operational and systemic failures. The findings also corroborate the conclusions of recent studies regarding the growing role of cyber risks in the structure of financial security. In particular, J.C. Crisanto *et al*. (2021) demonstrated that the digitalisation of financial services contributes to the emergence of new channels for the propagation of systemic risks through cyber dependency and the concentration of digital infrastructure. The authors emphasise that cyber risks are not only technological but also systemic in nature, as their spread depends on the scale of digitalisation, the interconnectedness of financial institutions and the concentration of critical digital services. This has confirmed the need to integrate cyber resilience and digital operational resilience into the modern system for ensuring the financial security of economic systems.

A key finding of the study is the justification for the need to adopt a resilient approach to ensuring financial security. This is in line with contemporary academic concepts of "financial resilience" and "operational resilience", according to which the resilience of an economic system is determined not only by its ability to avoid crises, but also by its capacity to adapt, recover swiftly and undergo structural transformation following shocks. Recent research emphasises that, in the context of digitalisation and the growing interdependence of financial institutions, it is the operational resilience of the financial system that takes on key importance; this encompasses the ability to maintain critical functions, the continuity of financial services and confidence in financial institutions, even during large-scale disruptions or cyber-attacks. For instance, in the study by R. Adeney *et al*. (2024), operational resilience is defined as the ability of financial institutions and the financial system as a whole to prevent, adapt to, respond to and recover from operational disruptions that may pose systemic risks to financial stability. Furthermore, recent research on financial resilience has shown that the stability of the financial system increasingly depends on the ability to ensure not only financial liquidity but also digital and institutional continuity. In particular, Y.C. Lou *et al.* (2025) demonstrated that the use of financial technologies has a positive impact on companies' operational resilience by increasing the flexibility of business processes, the resilience of supply chains and the level of adaptability to the external environment.

A comparative analysis of threats to the financial security of the EU and Ukraine has shown that, in the Ukrainian context, digital risks overlap with military and macroeconomic shocks, creating a cumulative nature of threats. Similar conclusions are presented in recent international studies on the impact of geopolitical instability on financial markets and corporate resilience. In particular, W. Boungou & A. Yatié (2022) demonstrated that the outbreak of a full-scale Russian-Ukrainian war led to a significant decline in the returns of global stock markets and an increase in financial volatility, particularly in European countries, due to rising uncertainty, energy risks and disruptions to global economic linkages. A similar view was supported by S. Boubaker *et al.* (2022), who noted that geopolitical conflicts and military risks have a significant impact on financial stability through increased market volatility, heightened inflationary pressures, energy shocks

and rising levels of global uncertainty. This confirmed that geopolitical risks in the modern economy act as an independent factor in financial instability and the transformation of the financial security system.

The study also demonstrated that the European model of financial security is based on the integration of macroprudential regulation, digital operational resilience and mechanisms for protecting critical infrastructure. Of particular significance in this context is Regulation (EU) of the European Parliament and of the Council No. 2022/2554 (2022), which establishes uniform requirements for the identification of ICT risks, incident reporting, digital resilience testing and the management of risks associated with third-party ICT service providers in the EU financial sector. Similar conclusions are presented in the work by C.P. Buttigieg & B.B. Zimmermann (2024), where DORA is considered a key element in strengthening the digital operational resilience of the EU financial sector, although the author also highlighted challenges regarding supervisory convergence, coordination and the fragmentation of the control system. This confirmed that the current European model of financial security combines traditional financial stability regulation with digital mechanisms to ensure cyber resilience and the continuity of financial services. Thus, the study's findings confirmed the need to transition to an integrated model of financial security, within which financial stability is viewed as a comprehensive characteristic of the economic system, shaped by institutional, digital, financial and geopolitical factors. Unlike traditional approaches, the proposed model emphasises the interconnection between digital, geopolitical and institutional risks in the context of the transformation of economic systems and military instability. This broadens current academic understanding of financial security and provides a theoretical foundation for the development of new mechanisms to counter risks in the digital economy.

CONCLUSIONS

As a result of the study, the authors propose an original interpretation of financial security as an integrated property of the economic system, reflecting the financial subsystem's ability to ensure the continuity of financial flows, the efficient allocation of resources, and resilience to exogenous and endogenous risks and threats. A mechanism for the interaction between the macro- and micro-levels of financial security has been developed, and an integrated conceptual model of its transformation in the context of the digital economy has been formulated. It has been established that the current transformation of financial security is taking place under the influence of the digitalisation of financial services, the development of financial technologies, the spread of platformisation and growing dependence on digital infrastructure, which gives rise to new types of systemic risks and cyber threats.

The article summarises the distinctive features of the Anglo-American and European academic traditions in the interpretation of financial security. It has been established that the Anglo-American approach focuses primarily on the study of systemic risk and financial stability, whilst the European model is based on the institutional integration of macroprudential regulation, digital operational resilience and risk mitigation mechanisms. Based on a systemic approach, an integrated conceptual model of the transformation of financial security in economic systems has been developed, combining institutional, risk-oriented and digital approaches. The proposed model allows financial security to be viewed as a dynamic system of interaction between the macro- and micro-levels of the economy in the context of digital transformation and growing uncertainty. A comparative analysis of threats to the financial security of the EU and Ukraine was carried out; the results showed that, for European Union countries, the dominant challenges are digital, cyber and regulatory in nature, linked to the high level of digitalisation in the financial sector. In Ukraine, by contrast, digital risks compound military, macroeconomic and infrastructural threats, creating a cumulative nature of financial instability and increasing the economic system's vulnerability to systemic shocks.

An examination of European experience in ensuring financial security has revealed that the current EU model is based on the principles of proactive risk management, digital resilience and institutional coordination. Particular importance is attached to mechanisms for digital operational resilience, cybersecurity, and the protection of critical infrastructure, as established within the current EU regulatory framework, particularly through the DORA and the European Union's economic security policy. It is argued that the most promising approach for Ukraine is an adaptive one to utilising European experience, focused on establishing an integrated financial security system that combines mechanisms for macro-financial stabilisation, digital resilience, cyber resilience and countering military risks. The key areas of such adaptation are identified as strengthening cyber defence in the financial and military sectors, developing digital infrastructure, supporting the financial resilience of businesses, and integrating Ukraine into European security and financial mechanisms. The proposed approach has made it possible to integrate an institutional understanding of the economic system with a multi-level model of financial security and to incorporate the digital risk dimension as an independent factor in its transformation. Further research should focus on improving the system for countering financial risks at the meso- and micro-levels, taking into account the identified digital, macroeconomic and cyber threats, through the development of modern risk mitigation methods and the implementation of digital protection tools. Another promising area of research is the development of measures to enhance the financial stability and resilience of Ukrainian businesses in the context of post-war recovery.

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CONFLICT OF INTEREST

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Трансформація фінансово-економічної безпеки економічних систем: європейський досвід та виклики цифрової економіки

Анотація. Актуальність дослідження зумовлена необхідністю переосмислення підходів до забезпечення фінансової безпеки економічних систем в умовах цифрової трансформації, посилення геополітичної нестабільності та зростання системних ризиків. Метою статті було дослідження трансформації фінансової безпеки економічних систем в умовах цифрової економіки на основі інтеграції інституційного, ризик-орієнтованого та цифрового підходів, а також узагальнення європейського досвіду протидії фінансовим ризикам та загрозам фінансовій безпеці, і визначення можливостей його адаптації для України. Для досягнення поставленої мети використано методи теоретичного узагальнення, контент-аналізу наукових і аналітичних джерел, системного та порівняльного аналізу. Їх застосування дозволило дослідити еволюцію наукових підходів до трактування фінансової безпеки, визначити особливості її трансформації під впливом цифровізації та здійснити порівняльний аналіз загроз фінансовій безпеці в країнах Європейського Союзу та Україні. У результаті дослідження запропоновано авторське трактування фінансової безпеки як інтегрованої властивості економічної системи, розроблено механізм взаємодії макро- та мікрорівнів фінансової безпеки та сформовано інтегровану концептуальну модель її трансформації в умовах цифрової економіки. Встановлено, що цифровізація фінансового сектору суттєво змінює структуру загроз фінансовій безпеці через посилення кіберризиків, технологічної залежності та впливу цифрової інфраструктури на стійкість економічних систем. Виявлено відмінності у структурі загроз фінансовій безпеці ЄС та України. Визначено, що сучасна європейська модель забезпечення фінансової безпеки базується на принципах цифрової резильєнтності, інституційної координації та проактивної протидії ризикам. Практичне значення отриманих результатів полягає у можливості використання запропонованих підходів під час формування державної політики у сфері фінансової безпеки, розроблення стратегій цифрової трансформації фінансового сектору, підвищення цифрової резильєнтності та адаптації європейського досвіду до умов повоєнного відновлення економіки України

Ключові слова: діагностика; резильєнтність; фінансова стійкість; фінансовий інжиніринг; кредитне навантаження; цифрові технології; євроінтеграція

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Integration of statistical data in the comprehensive economic statistics system

Abstract. Modern society represents a complex socio-economic system, the development efficiency of which is determined by the economy's ability to maintain the stability of its elements over certain periods of time. The aim was to justify an integrative approach to the development of comprehensive economic statistics in the context of sustainable development by identifying systemic contradictions, assessing the consistency of statistical data, and determining directions for their harmonisation in accordance with the Sustainable Development Goals. The study utilised a set of general scientific and specialised methods, including: the analytical generalisation method – for identifying systemic problems in comprehensive economic statistics; comparative analysis – for evaluating data collection schemes and data reconciliation; systems approach – for forming an integrated view of statistics; structural-functional analysis – for determining the role of metadata; logical modelling – for constructing schemes of interrelations between the indicators of Sustainable Development Goals and statistical processes. It was established that the modern socio-economic system is characterised by instability and limited ability to restore equilibrium, which necessitates the integration of statistical systems. It is substantiated that the balance of components of sustainable development is achieved through the coordinated functioning of comprehensive economic statistics. Basic contradictions in accounting practice have been identified, as well as dependencies between sources of statistical errors and the methods used to correct them. The double effect of harmonising public finance data with international standards has been demonstrated. A general scheme of the interconnection between the issues of economic indicators of sustainable development and the directions for improving statistical work has been developed. The role of metadata in ensuring the integration of statistical systems and the inclusion of digital indicators into macroeconomic assessments has been identified. The practical significance of the obtained results lies in their potential to improve the consistency of statistical data, ensure international comparability, and substantiate managerial decisions at the national level within the context of implementing the Sustainable Development Goals

Keywords: sustainable development; integration; analytical assessment; comprehensive economic statistics; data consistency; types of metadata; comparative evaluation

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INTRODUCTION

The modern process of global economic development is characterised by complex interactions among national economies. In the process of forming a single economic space, interconnections among financial systems, international trade, and technological development have deepened, necessitating a qualitatively new level of statistical support for the state and the economy's development. The world economy is experiencing contradictory, slow economic growth. According to estimates by international organisations, including the World Bank (2019), IMF (2024), and the United Nations (n.d.), the growth rate of global GDP for 2024-2025 has been reduced to the level of 2008, and the medium-term forecast remains lower than before 2019. This situation exacerbates the problem of adequately measuring and interpreting macroeconomic processes at both the national and global levels. While deepening global interconnections requires a coherent statistical framework to form a single conceptual framework for analytical work, the slowdown and heterogeneity of growth make it critical to identify structural shifts, risks, and vulnerabilities using reliable data. Avoiding fragmentation of analytical work and the tendency to errors due to inconsistencies between sources ensures the integration process. The new demands of digital society exacerbate existing challenges in analytical work across all research fields, particularly in assessing the quality of source data, preventing errors during processing, and avoiding incorrect conclusions. They also require changes in the structure and methods of statistical work, mainly by shifting how economic data is collected. Therefore, preparing profile statistical data as the basis for current integration processes, grounded in general principles such as the use of core concepts, definitions, assessment methods, and data sources for the most accurate evaluation of sustainable development, remains essential.

J. Zwijnenburg (2026) describes the system of national accounts (SNA) as an international standard for compiling macroeconomic statistics, encompassing a set of interrelated tables that provide an overview of a country's economy. Using the GDP indicator in the SNA as a measure of social progress or the population's economic well-being reveals its limitations as a tool for assessing overall well-being. S. Liu (2023) proposed considering statistics as a tool for achieving the Sustainable Development Goals (SDGs) and their components, while emphasising unresolved statistical problems that hinder effective achievement of the SDGs: incompatibility between the SDGs and statistical data, and inequality in the statistical potential of different countries. T. Sanseverino (2023) examined the SDGs and concluded that effectively communicating economic co-benefits through SDG references can be challenging. Low-income countries (LICs) have shown relatively little progress towards SDG 1 and SDG 8. Therefore, the economic impact of, for example, carbon projects implemented in such countries has high potential for additionality. They also require changes in the structure and methods of statistical work, mainly by shifting how economic data is collected. The study of V.Y. Khaustova *et al*. (2024) is based on determining the impact of digitalisation factors on the economic development of countries around the world using a cognitive approach. The combination of the World Rankings of Digitalisation Levels with indicators of economic development worldwide (characterising GDP, gross value added, employment, production, and trade in ICT and computer communications goods and services) was carried out using a single information base from the World Bank. To prove the need to build a comprehensive system for measuring the parameters of the digital economy and the requirements it must meet, the most important directions in developing such a system have been identified. A comparative description of the views of supporters and opponents of changing the traditional conceptual foundations for measuring economic parameters under new conditions has made it possible to identify the main problems in developing an adequate information base for constructing indicators to account for elements of the digital economy. The described changes in the formation of demand for statistical information, the proposed ways to improve interaction with users of official statistical information proved the need for unification of practices for obtaining and disseminating the results of measuring the digital economy on an international scale, and also revealed the role of international organisations in the process of optimising and standardising various processes of producing official statistics at the national and international levels.

The aim of the article was to substantiate an integrative approach as a tool for interconnection, coordination, and unification of components in the formation of the Sustainable Development Strategy (SDS) under conditions of sustainable development by identifying systemic contradictions, assessing the consistency of statistical data, and justifying directions for their harmonisation in accordance with the SDGs. To achieve the goal, the following tasks have been identified: to identify systemic issues in the consistency of the ESS; to investigate contradictions between accounting and the SNA; to assess the impact of harmonising statistical data on their consistency; to justify the role of metadata in ensuring the integration of statistical systems; to develop an analytical framework for the interrelation of SDG indicators and the comprehensive economic statistics (CES). The scientific novelty lies in developing an integrated vision of the CES by aligning economic measures of sustainable development with its fundamental characteristics. The paper substantiates the relationship between sources of statistical error and mechanisms for their correction, develops principles for data harmonisation, further clarifies the role of metadata in the context of the digitalisation of the economy, and proposes using an analytical framework as a tool for interaction between SDG indicators and statistical practice.

MATERIALS AND METHODS

In the research process, a complex of general scientific and specialised methods was used, which ensured the systematic study of the problems of statistical support for monitoring SDG indicators, the assessment of the quality of statistical data, and the substantiation of areas for improving information and analytical support. The information base of the study comprised methodological documents of international organisations containing definitions, classifications, and instructions for collecting and calculating SDG indicators; standards of official statistics; materials from national statistical services; and scientific publications

devoted to improving the sustainable development monitoring system (State Statistics Service of Ukraine, n.d.; United Nations, 2013; Nilashi *et al*., 2023).

The selection of information sources was carried out according to the principles of officiality, methodological soundness, international recognition, relevance, comparability of statistical approaches and systematicity. Such a set of sources enabled simultaneous analysis of definitions, metadata, and procedures for collecting, processing, and harmonising data (United Nations, 2008; United Nations, 2013; Eurostat, 2021).

The research was carried out sequentially in several interconnected stages. The first stage involved an analysis of international methodological documents on the organisation of statistical support for SDG monitoring and quality management of official statistics. At the second stage, a comparative study was conducted of the methodologies for developing SDG indicators, sources of statistical information, mechanisms for collecting, processing, and harmonising data, as well as the features of their information support. At the third stage, the main sources of statistical errors, risks of information inconsistencies, and problems of ensuring the comparability of indicators that form the basis of the CES and are ambiguously reflected in the SNA were identified. At the final stage, logical models were constructed that reflect the relationships between SDG indicators, statistical processes, and data quality assurance mechanisms. This sequence allowed for the combination of theoretical understanding of SDG statistics with an applied analysis of their functioning.

The method of analytical generalisations was used to critically analyse methodological provisions and identify systemic problems in the statistical support of the SDGs, relating to data quality, completeness, consistency, isolation of the significance of economic indicators, and the possibility of their international comparability. This method allowed us to move from describing individual facts in achieving the SDGs to formulating systemic patterns of interaction between the CES and the SNA, as well as problematic issues of their coherence. The comparative analysis method was used to compare methodological approaches to the formation of statistical estimates, evaluate data collection, integration, and reconciliation schemes, and identify differences between existing recommendations and possible practices for their implementation. The result of the comparative analysis was the identification of typical situations regarding the organisation of data collection, as well as the identification of inconsistencies common to different statistical systems.

The systemic approach made it possible to consider the statistical support for SDG monitoring as a holistic, multi-level system, whose elements include data sources, statistical processes, metadata, quality control mechanisms, information flows, and users of statistical information. This provided a comprehensive study of the relationships between individual components of the system and their impact on the reliability of the final statistical results. The systems approach allowed us to focus on the relationships that determine the overall effectiveness of statistical support for the SDGs. Structural and functional analysis was used to determine the place and functions of metadata in the statistical support system for the SDGs, and to study their role in ensuring the transparency of the methodology, the reproducibility of statistical calculations, the interpretation of indicators, the assessment of their quality, and the international comparability of statistical results. This method allowed us to show that metadata is a functionally central part of the statistical system. The logic modelling method was used to construct a diagram of the relationships between the CES and SDG indicators, sources of statistical data based on the SNA, stages of statistical production, potential sources of errors and mechanisms for their prevention or correction. The constructed models made it possible to systematise the factors affecting the quality of statistical indicators and to substantiate the directions for improving the processes of forming the information and analytical base for monitoring the SDGs. Logic models became a tool for visualising and formalising ideas about how statistical processes are arranged in the context of the SDGs and where it is appropriate to introduce changes.

RESULTS AND DISCUSSION

Coordination of statistical activities based on reliable and complete data to achieve the SDGs has traditionally been considered as the interaction of the United Nations (2008) with the United Nations (2013), which was reflected in the documents of the IMF (n.d.), Eurostat (2021). The integration of statistical data is the methodological basis of the system of comprehensive economic statistics (CES), which involves harmonising, first of all, the SNA, balance of payments, employment, and other macroeconomic sources on the basis of common concepts, classifications, and research periods in order to ensure their compatibility, integrity, and international comparability. Such an integrated system makes it possible not only to quantify the contribution of individual factors to the slowdown in global growth, but also to track the redistribution between countries and sectors and to monitor the achievement of the Sustainable Development Goals (SDGs). The recommendations outline a general framework for integrated economic statistics, based on the principles of the national statistical system's statistical infrastructure and applying best practices in modern business architecture (United Nations, 2013). The framework is suitable for use in statistical systems at different stages of development and can operate under centralised or decentralised models.

The definition of sustainable development serves as the basis for creating a macroeconomic model that balances economic growth with consumer needs, requiring adherence to the principle of international consistency. This compliance applies both to concepts, classifications, and accounting rules reflected in the system of national accounts (United Nations, 2008), and to a networked approach to coordinating economic relations, the advantages of human capital and information, the prioritisation of service sector development, and the growth of investments in creative industries based on the legitimate use of data. It is worth noting that the relevant documents, from their implementation to the present day, have served as a macroeconomic standard for the global community in shaping a modern, multidimensional system for assessing development based on the principles of evidence-based policy, under conditions of statistical data harmonisation. The constant compromise between the interests of national

economies and the need to align them with generally accepted rules for assessing sustainable development, which enable a correct comparative analysis between countries, has led to the emergence of a large number of clarifying, declarative, and normative-instructional documents. At the same time, such documents cannot fully satisfy the interests of all participants in the specified process.

In Ukraine, the adoption of Resolution of the Cabinet of Ministers of Ukraine No. 989 (2023) is linked to the implementation of the Decree of the President of Ukraine No. 722/2019 (2019), and the Order of the Cabinet of Ministers of Ukraine No. 686-2019-r. (2019), which aim to harmonise the national statistical system with international and European norms and standards. In line with the Sustainable Development Goals (SDGs), the modern model of economic growth aims to balance economic, social, and environmental components while maintaining equilibrium among the world's leading economic regions. Achieving this balance is ensured through a set of actions and decisions that are based on a system of quantitative and qualitative characteristics. The totality of such economic and statistical characteristics, which provide a consistent and comprehensive understanding of economic activity, is represented by CES, which serve as the methodological foundation for assessing and monitoring sustainable processes. The purpose of CES (United Nations, 2013) is to characterise the state and dynamics of economic activity by combining different groups of economic-statistical data into a single logical system, ensuring the coordination of interactions between national and global initiatives in the field of sustainable development. It is worth considering that if the comprehensiveness of economic statistics is achieved through specially designed systems of interconnected indicators that cover as many key aspects of the economy as possible, then accurately measuring economic activity in a globalised world- assuming data consistency and continuity- facilitates the process of integration. The use of CES (United Nations, 2013) offers the opportunity to:

- achieve relative consistency and transparency in the application of concepts and definitions of economic development through unified approaches and tools,
- improve the accuracy of economic data by reconciling discrepancies between data obtained from different sources through integration processes,
- align data between short-term indicators and macroeconomic development data during critical phases of economic growth,
- coordinate the distribution among sectors of the economy by different types of products, industries, or regions,
- harmonise the distribution of macroeconomic indicators across countries,
- Accelerate the satisfaction of consumer needs by leveraging integrated references.

Despite efforts to implement sustainable development principles, the CES (Liu, 2023; ENECE Statistics, 2024) faces a number of systemic challenges. Thus, even with agreed standards, the level of statistical capacity varies significantly between countries, which complicates the production of reliable and comparable indicators, and the lack of up-to-date, complete and comparable data on numerous indicators related to the Sustainable Development Goals in the regions and the failure to reflect the new requirements of the sustainable development context in traditional statistical indicators - creates inconsistencies between existing methodologies and the needs of monitoring development goals. Finally, the varying paces of implementation and the use of alternative sources of information and big data across countries exacerbate problems with data quality, representativeness and coherence. It has been established that the classical definition of CES (Table 1) differs from the integrative approach in its conceptualisation of sustainable development.

Table 1. The classical definition of CES

The overall structure of the traditional CES system				
CES Blocks				
Conceptual-methodological	Informational	Indicator system	Processing and analysis methods	Organisational and institutional
Basic characteristics				
■ formation of the theoretical basis; ■ determination of the methodology for constructing indicators	■ primary sources; ■ auxiliary sources	■ macroeconomic indicators; ■ sectoral and structural indicators	■ collection and preparation of data; ■ selection of analytical tools	■ separation of statistical bodies and other data producers; ■ coordination of the regulatory framework and infrastructure

Source: prepared by the authors based on O.Yu. Guseva *et al*. (2020)

The connection between the blocks of the specified CES structure is designed to facilitate the integration of economic measurement across macro, meso, and micro levels. In contrast to the general understanding of the systematisation of the integration process (United Nations, 2013), the integration process requires a systemic approach, the basis of which is the use of the SNA as a conceptual organisational framework for economic statistics, ensuring coherence and interconnection of elements contributing to the preparation of statistical data, as well as creating favourable conditions for the integration of the statistical sphere. The study demonstrates that the integration of economic statistics in the context of the SDGs (Table 2) is aimed at ensuring the interconnection of the most complete monitoring of existing sustainable development processes, eliminating data fragmentation with the creation of a reliable information and analytical base for the development of policies aimed at balancing economic growth, social justice, and environmental sustainability. The observed differences provide grounds to argue for a need to connect economic theory and economic statistics at the international level through the consistency of concepts, definitions, and classifications across different data sets, as well as through the quantitative consistency of data obtained from different sources. However, different countries may have different definitions and levels

of evaluation for similar phenomena and processes. The SNA and accounting both consider economic phenomena based on the principle of double entry. However, while the SNA focuses on macroeconomic flows across the entire economy, accounting records transactions for individual entities. Both use double-entry based on balancing each transaction, but they differ in scope, transaction types, and balancing methods. In particular, it should be noted that in accounting, double-entry bookkeeping maintains the balance between assets and liabilities by recording transactions so that the debit in one account (assets/expenses) matches the credit in another (liabilities/income) (Structure of the national accounts, n.d.; Bilova, 2012). The primary focus is on profit, depreciation, and reserves. In the SNA, transactions are recorded across sectors of the economy, ensuring that each entry is balanced within a sector or between sectors. This involves detailed recording – effectively twice – when resources equal their usage, and twice between sellers and buyers, covering aspects such as mixed incomes, product taxes, and transfers. More accurate responses to questions come from those who understand the accounting definitions, but if additional information is needed, understanding the sector's operations at the reporting unit level is essential.

Table 2. Modern vision of the CES system

Components of the CES system			
Scale of integration	**Elements of statistical infrastructure**		
Basic characteristics			
Classification of statistical activities	SNA	Institutional mechanisms	Preparation of statistical data
Definition system			
Structuring types of economic activities	As a standard of economic accounts at the international level	Delegation of responsibility for the formation of an effective statistical research program	Information on consumer requests
Structuring sectors of the economy	Reconciliation of statistical data	Inter-sectoral coordination in statistics and strategic planning	Combining information from statistical units and basic units of the SNA

Source: prepared by the authors based on UNDP (2018), United Nations (2013), World Bank (2019)

During the process of statistical data reconciliation, adjustments must be made (United Nations, 2008; United Nations, 2018; Matkovskyi *et al*., 2022) at the aggregated level in order to eliminate discrepancies in definitions. To achieve methodological consistency, measures such as harmonisation of methodologies, recategorisation of data, and the implementation of special transformations aimed at aligning flows and stocks are employed. Thus, the significance of the presented results lies in the fact that the principles of the accounting standard are consistent with the principles of the SNA, in that economic substance should take precedence over legal form. Discrepancies between accounting records and the SNA should be corrected in the survey data to eliminate statistical inconsistencies, primarily caused by double-counting or incomplete coverage (Table 3).

Table 3. General correspondence concerning the types of adjustments to the sources of errors

Typical sources of error	Primary sources of error	Main types of adjustments
Principles of valuation	Accounting – emphasis on historical cost. SNA emphasises market (factor) costs.	Survey data are converted from market prices to comparable figures, taking into account inflation and SNA methodology.
Coverage of economic activity	A lack of equality between assets and liabilities is a variant of arithmetic o r recording errors.	Adjustments are made for sectors where accounting reports are supplemented by surveys, ensuring that discrepancies caused by the shadow economy or illegal activities are eliminated.
Data aggregation methods	The discrepancy between debit and credit turnovers in synthetic accounts (incomplete data; duplicate entries) distorts the aggregated data for the SNA.	Corrected by balancing the SNA accounts using the commodity flow method, where sector indicators are reconciled without sequential aggregation, which reduces errors from primary sources, including accounting data.

Source: prepared by the authors based on research by M. Kulynych (2024)

The principles of SNA 2008 involve an iterative process of integrating primary sources, addressing discrepancies, and consolidating data through account balancing and ongoing corrections In this context, primary data sources in accounting and statistical systems are understood as documents or records that record economic transactions at the moment they occur, serving as the basis for the formation of registers and reports, ensuring the accuracy, completeness, and timeliness of the informational representation of economic processes. Based on this, from a practical point of view, it is advisable to expand the data collection sources, enabling a more thorough comparative analysis. Reliable statistics form the basis of this work, serving both as a method of accounting and a tool for analysis. Historically, official statistics have been the primary source of data for countries worldwide. However, the quality of official data remains a critical concern for national statistical offices. The ongoing reforms in public sector accounting, especially regarding the alignment and differences between International Public Sector Accounting Standards and public finance reporting principles, offer an opportunity. They can enhance the information database for comparisons and help identify issues arising from incompatible data.

It has been shown that achieving an appropriate level of consistency in economic data depends on the research purpose. Public sector accounting and public finance

statistics have different purposes. If accounting is aimed at reflecting and presenting financial information on the financial results of an economic structure in the public sector, then public finance statistics are aimed at determining the impact of the general government sector on the economy and providing information for macroeconomic accounting. These functions differ in how they define, measure, and classify data. Public sector accounting relies on International Public Sector Accounting Standards (IPSAS), which standardise data for public finance statistics under the accrual basis IPSAS (2025), ensuring an accurate view of the financial position during the reporting period. If the scope of reporting government finance statistics is determined by market opportunities and based on current market value, then International Standards are based on the principle of consolidation to increase efficiency, simplify management, and obtain a complete picture of the financial or operational situation. Only this basic difference necessitates adjustments to the process of collecting public finance statistics.

The consistency and even partial resolution of the issues above are reflected in the International Public Sector Accounting Standards (IPSAS, 2019), which ensure comparability with both previous financial reports and those of other organisations. However, full adoption of these standards is not compulsory for countries worldwide. The significance of the presented results lies in the difficulty of determining the extent of implementation of the specified standards at a global level, when, within the national economies of a particular country, accounting requirements may differ between central government bodies and non-central and territorial authorities. It should be noted that the research has certain limitations in its data collection system, which can be summarised as: the comparison of concepts, definitions, and classifications, as well as the regularity of using statistical tools. If the process of comparing concepts, definitions, and classifications aims to facilitate their application both within the statistical system itself and outside it, then gathering a complete set of data through regular aggregation will help reflect the organisational structure of all statistical units within the economy of a given country. If the current data collection system in most countries involves integrating information from each subdivision of a specific economic sector into the GNI, then the latest method of combining economic statistics is based on the potential to harmonise survey methods and assessments across various sectors of the economy (Table 4). The overall framework for comparing the approaches outlined above is as follows.

Table 4. Comparative characteristics of data collection schemes: basic definitions

Traditional		Modern	
Advantages	Disadvantages	Advantages	Disadvantages
availability of access to data by specific segments of the economy	inconsistency in the timing of data receipt with user needs	enhancement of the accuracy and consistency of information for users, unification of micro- and macro-data, introduction of agreed methods of data editing	inability to develop a single approach to the implementation of comprehensive economic statistics

Source: prepared by the authors based on United Nations (2013), United Nations (2018), World Bank (2019)

The basic approaches in statistics, data warehouses, and data quality management that enable the determination of the sequence of information aggregation are bottom-up and top-down data collection. The general definition of these systems is provided in Table 5. The "bottom-up" data collection procedure is aimed at the efficient use of limited resources and meeting user needs in the context of the desire to update and expand statistical research. When collecting data using this procedure, there is a risk of incompatibility, which can be reduced through standardisation and control at the integration stages. The reverse "top-down" procedure is based on the use of aggregated macroeconomic indicators, formed within the framework of national accounts, and is more focused on ensuring the benefit of obtaining accurate and consistent data.

Table 5. General scheme of the data collection procedure

Data collection procedure			
bottom-up system		**top-down system**	
Foundations			
use of general concepts, definitions, assessment methods, and data sources		unification of the tools for sample surveys and methods of data collection and calculation	
Advantages	Disadvantages	Advantages	Disadvantages
Consistency, scalability	Slow start	Speed, flexibility	Risk of inconsistency
Result of the application			
improving data consistency, reducing the burden on respondents, implementing automated data editing methods		resolving discrepancies in registers, using familiar data sources and methods of their assessment as basic conditions for improving data consistency, consistency of micro- and macro-data with each other	
Specifics of statistical estimation			
reduction of the likelihood of errors, improvement of data accuracy		possibility of seasonal adjustments, ensuring data balance, and extrapolation	

Source: prepared by the authors based on S.R. Shakil (n.d.), Top-down versus bottom-up data quality approach (n.d.), Recommendations for creating data warehouses and examples of their use (2024)

It should be noted that the issue of forming a general data collection scheme is of a discursive nature. Different countries use various procedures for data collection and methods of processing them, which leads to discrepancies in the results of the conducted research, complicates the integration of statistical information, and leaves open the question at what level the data should be harmonised under comparison conditions. In the practice of Eurostat (2021), the "bottom-up" approach is applied through a system of sample surveys and administrative registers, which allows for the collection of representative data considering the specific development of regions. Meanwhile, the "top-down" approach within the SNA (United Nations, 2008) provides the possibility for international comparisons to facilitate global monitoring of the achievement of Sustainable Development Goals. It is worth emphasising that, at the same time, the advantages of one method to some extent constitute a disadvantage of another: the "bottom-up" approach provides depth of analysis but can lead to fragmentation of information, whereas the "top-down" approach guarantees systematisation but often loses local specificity.

Summarising the above, it can be concluded that the problem of data collection in KECS lies in the need to choose between alternative approaches or their combination. According to the authors, it is advisable to proceed from the premise that results obtained by different methods should mutually correct each other. It seems legitimate, in accordance with current demands and the specific development of regions, to utilise a hybrid approach that allows for the maximum possible balancing of accuracy, consistency, and analytical value of the data. The practical value of the obtained data lies in the possibility of further application of the indicator system, which provides answers to the question of analytical consistency of measures and procedures regarding the assessment of the sustainability of countries worldwide in accordance with the SDGs, and at the same time, serve as tools for monitoring economic development through the SNA. National statistical offices play a vital role in implementing SDG indicators, overseeing data collection, validation, and monitoring for national sustainable development strategies. However, methodological inconsistencies, resource limitations, and data-related challenges hinder the integration of these indicators into official statistics.

In the modern concept of sustainable development, the role of system-forming indicators from Ministry of Economic Development and Trade of Ukraine (2017), V. Ivanchuk & N. Moshniaha (2021) is performed by economic indicators, because they allow us to assess not only the pace of economic growth, but also its inclusiveness, resource efficiency, environmental sustainability, and social effectiveness. Economic growth in itself does not guarantee sustainable development, but it creates the necessary financial and institutional prerequisites for achieving most global goals. These goals are based on intersectoral linkages, in which GDP, labour productivity, employment levels, and inequality reduction act as catalysts for positive change.

The basic indicator of economic development of countries is traditionally GDP (SDG 8.1.1), the dynamics of which determine the resource capabilities for achieving a wide range of SDGs, the growth of which by only 1% provides: 51% of expenditure on social CSER 15 or funding for 70% of the global goals or the opportunity to address environmental CSER 13. The inclusiveness of economic growth is ensured by the employment indicator of the population aged 20-64 years (SDG 8.5.1), positive changes in which contribute to reducing poverty (SDG 1), expanding access to quality education (SDG 4), and reducing economic inequality (SDG 10). The determining factor of long-term economic development is labour productivity (SDG 8.2.1), which ensures the resource efficiency of economic systems by stimulating the creation of high-tech and "green" jobs, the development of innovative infrastructure (SDGs 7-9), and also generating a 1:3 multiplier effect on social outcomes. The indicator of economic inequality is measured by the Gini coefficient (SDG 10.1.1); a reduction of 0.05 improves 40% of social indicators, while values greater than 0.3 impede the achievement of SDGs 1-5, exacerbating poverty. The National System of SDGs of Ukraine includes 183 indicators (Order of the Cabinet of Ministers of Ukraine No. 686-r, 2019; State Statistics Service of Ukraine, n.d.), which are mainly economic: SDGs 8 (decent work and economic growth), SDG 9 (Innovations and Infrastructure), SDG 10 (reducing inequality), SDG 12 (responsible consumption and production), which form the information and analytical basis for a comprehensive assessment of the achievement of the SDGs in the country. Therefore, economic indicators characterise not only the outcomes of economic and business activity but also provide a quantitative assessment of decisions regarding the achievement of the SDGs.

In particular, it should be noted that the most complex to collect data on SDG, economic indicators require detailed microdata, which aligns with a "bottom-up" data collection system, namely data from the informal sector or private financial flows, where standardised sources and statistical capacity are lacking (OECD, 2025; Landau *et al*. 2025). It is believed that filling the gaps in complex SDG economic indicators will be achieved through the integration of statistical systems, even temporarily, ensuring the accuracy of assessments without losing compatibility with official standards – by using a hybrid approach to data collection (Pietras, 2023; OECD, 2025). The primary element ensuring the transparency and reliability of assessments, especially for complex SDG economic indicators, is the evaluation of uncertainty in methods for filling gaps in statistical data. This includes a quantitative assessment of errors and risks associated with imputation or modelling, utilising standard statistical approaches. The overall view of the interconnection between the main issues of the SDG economic indicators under the conditions of improving the SES is shown in Table 6. Considering that statistical practice involves tracking data over time, it is advisable to pay attention to natural shifts in the data. To assess the consistency of the data, it is necessary to introduce certain metrics that will enable monitoring of the situation and quick identification of problems. Table 7 shows a general framework of how data consistency metrics interact with time delays during their verification. A compromise between data consistency and delay is advisable to be calculated using multi-criteria optimisation, where consistency and integrity are maximised, and delay is minimised using weighting coefficients or Pareto optimality. This solution cannot be improved in all parameters simultaneously.

Table 6. General scheme for improving statistical work to address issues with SDG economic indicators

Problems with economic indicators			
insufficient data quality	methodological and conceptual limitations	inequality of statistical capacity	limited coverage and level of detail
⇧ ⇩			
Inequality and distributions (SDG 10)	The labour market and productivity (SDG 8)	Innovations and investments (SDG 9)	Financial flows (SDG 17)
SDG economic indicators that are the most difficult to collect data on			
⇧ ⇩			
A combination of modelling methods	Integration of alternative sources	Hybrid approaches and standardisation	
Methods for filling gaps in complex economic indicators			
⇧ ⇩			
Standard statistical methods	Model approaches	Assessment for hybrid sources	
Uncertainty assessment in gap-filling methods			
⇧			
Use of new sources	Modernisation of national statistical systems	Use of operational forecasting and gap-filling models	Optimisation of the frequency and design of surveys
Methods for improving statistics for SDGs			

Source: prepared by the authors based on M. Nilashi *et al*. (2023), T. Sanseverino (2023), OECD (2025)

In the modern information society, ensuring the quality, consistency, and interpretability of statistical data is of key importance. Metadata plays a leading role in the formation of an effective statistical system, which, within the CES, serves not only as an auxiliary element but also as an integral part of the methodological infrastructure. In the CES, they provide the overall context, quality, and interpretation of data for the analysis of macroeconomic processes, national accounts, and sustainable development indicators. Metadata are not just data about data; they are a set of permissible structured descriptions that are explicitly available and intended to help locate the object. Their purpose is to provide the context for the correct interpretation of statistical indicators, which is especially important in integrating diverse data sources. At the same time, the role of metadata in modern analytical practice remains a subject of debate due to the contradiction between standardisation and flexibility, resource limitations, and the increasing demands for data quality in the digital age, as well as the necessity to strike a balance between the level of detail and practical usability. If the excessive complexity of metadata makes their utilisation difficult, then simplifying them reduces their analytical value. The absence of a universal metadata model results in a variety of approaches (IMF, UNSD, SNA, Eurostat) to the formation and use of metadata. At the same time, it should be noted that metadata's complexity stems from its substantive nature: it can simultaneously enhance data quality and complicate data processing.

Table 7. General diagram of the interaction between the metrics for assessing consistent data and time delay

Metrics for assessing data consistency		**Time delay metric for data consistency**	
Metrics	Characteristic	Metrics	Characteristic
Partial metrics of matches and discrepancies	Proportion of records among sources with completely matching key fields	Normalisation of time windows	Proportion of matches in normalised windows, where the shift is optimised based on historical lags
	Share of discrepancies exceeding the tolerance threshold		
Metrics of aggregate consistency	Average and median relative divergence between sources for each indicator	Lag and timeliness metrics	Tracking the median lag between the event date and the availability of data from a specific source. Corrective component = relative discrepancy * dependence coefficient on the lag
	Maximum deviation and the number of "critical" deviations as an indicator		
Logical consistency and business rules	Number or proportion of violations of logical rules and business rules	Dynamic divergence thresholds	Definition of the threshold depending on time, with the presence of new and old data: * new data (lag < 1 week) – strict threshold of 2%; * old data (lag > 1 month) – strict threshold up to 10%
	Consistency index, according to the rules, is a percentage of successfully passed tests		
Co-regency and stability over time	Comparison of trends between sources, the proportion of periods during which the sign of change coincides	Trend and causal time concordance	Consistency by levels and dynamics. Calculation of the trend correlation coefficient considering a time shift
	Definition of divergence stability		
Composite indices of consistency quality	Definition of the integrated weighted consistency index is the product of the proportion of matching records, the proportion of cells with deviations below the threshold, the index according to business rules, and trend stability	Monitoring and alerts for lags	Anomaly detection using the "lag* divergence" matrix
	Number of cases of inconsistency requiring manual correction		The action of alerts occurs when the discrepancy grows faster than the lag

Source: prepared by the authors based on O. Pyshchulina (2020), L.V. Batchchenko & O.V. Reva (2023), V.Y. Khaustov *et al.* (2024)

According to the authors, it is advisable to proceed from the need for an optimal balance between the level of detail of metadata and their practical value for users, which requires further development of methodological approaches to the identification and management of metadata to achieve global Sustainable Development Goals. From an analytical perspective, the use of classifications alongside metadata as a key element of the economic classification system is of interest, as they provide structuring, description, and standardisation of data for the analysis of economic processes. In this context, if metadata describe the content, origin, and characteristics of statistical data, then classifications organise observation objects for comparison at both national and international levels. Metadata links classifications with data through models, enabling automated tracing from sources to analytical cubes. In Ukrainian practice, aligned with international standards, this is implemented through the State Statistics Service's systems for SDG monitoring and the digital economy. Such an approach minimises errors in time series and improves data quality assessment.

In national statistics, several main types of metadata are used, which are standardised according to the GSIM and SDMX models to support the tracking, promotion, and interpretation of data quality. In accordance with UN standards for data integration into the IES, particularly for monitoring sustainable development through the SDGs, GSIM provides a conceptual framework for describing statistical objects and processes; that is, it focuses on the conceptual model of information, while SDMX standardises data and metadata exchange, that is, it focuses on the technical standard for data and metadata exchange. Recommendations for integrating GSIM and SDMX in national statistical offices for IES are based on the principles of gradual implementation, with an emphasis on IT infrastructure. The use of GSIM for modelling metadata for digital processes and SDMX for automated data exchange with Eurostat and/or UNSD ensures compatibility with IES. The rapid evolution of technology leads to an underestimation of data, which is addressed by Big Data analytics and ongoing data processing procedures at national statistical offices.

The use of GSIM and SDMX standards involves integrating indicators of digital technologies, such as AI, Big Data, and e-commerce, into national accounts, thereby more accurately measuring their contribution to GDP and the SDGs, considering the actual contribution of these technologies to growth. However, it complicates the methodology due to the specifics of intangible assets and non-monetary transactions. Regarding this, the question of the impact of digitalisation on the economy and its reflection in the CES (Table 8) remains a matter for discussion. The problems mentioned in including digital services in GDP complicate traditional methods of national accounts. Double counting in accounting for platform services in GDP arises from platforms' intermediary role, where their commissions overlap with basic transactions. The availability of detailed data on value chains, transactions, and intermediate costs, standardised according to SNA 2008 and IES, will enable the avoidance of double-counting by fixing the value-added indicator.

Table 8. Comparative assessment of arguments regarding the measurement of economic parameters in the context of digital transformations of the economy

Advantages	Disadvantages
Purely economic aspect	
Taking into account the utility of free goods and their impact on productivity in macroeconomic indicators	Digitalisation has made free help, which existed before, accessible and widespread. Therefore, it should not be taken into account now
Taking into account the benefits that consumers have received due to the growth of digitalisation in the world	GDP changes its structure when taking into account the benefits of the product
Correctness of accounting for goods that have undergone significant changes	It is not the product or service itself that changes, but the way it is ordered and delivered
General analytical assessment	
Digital sector integration boosts GDP by 5-20% by capturing value added from AI, Big Data and e-commerce	Rapid depreciation of digital assets leads to significant GDP fluctuations
Allows to correct underestimation of free services through satellite accounts, ensuring comparability with OECD and/or Eurostat standards	The ambiguity of classification features according to NACE complicates data collection
	Requires significant resources for Big Data processing, with the risk of overestimation, and without taking into account the quality of the results
	Subjectivity of utility assessment

Source: prepared by the authors based on N. Ryzhikova *et al.* (2022), I. Sierova (2024)

Thus, the contentious nature of the issue is due, on the one hand, to the fact that digitalisation significantly transforms traditional economic processes, leading to the emergence of new forms of value creation, and on the other hand, because existing statistical approaches do not always fully account for these transformations, complicating the provision of completeness, comparability, and consistency of indicators. The adoption of the updated version of the United Nations (2025) is aimed precisely at taking into account the above provisions. Therefore, further research is needed to develop approaches for integrating digital economy indicators into the System of National Accounts to enhance its analytical value and alignment with modern development conditions. Based on the conducted analysis, it has been established that the integration of economic statistics is a key prerequisite for ensuring the consistency of economic development assessments. It has been determined that the balance of sustainable development components is formed through the systematic interaction of economic indicators, which serve as the fundamental metrics for evaluating development effectiveness.

The results of the study confirmed the high level of ambiguity in applying the CES to achieve the SDGs and, at the same time, the complete dependence of strategic decisions on sustainable development on the completeness and accuracy of the assessment of economic processes. The basis for the consistency of the SDG and CES indicators is the 2008 SNA, which today requires ensuring methodological compatibility between the requirements for measuring sustainable development and the realities of globalisation, digitalisation, and society's environmental sensitivity. Given that the study's methodological basis is a systematic approach, it is legitimate to prioritise a comparative assessment of the working and updated versions of the SNA (United Nations, 2025), which enabled us to identify the following differences. The SNA 2025 focuses not only on measuring market economic activity through GDP but also on indicators of non-market phenomena such as unpaid work, social capital, and quality of life, thereby reducing the systemic gap between what is measured by the CES and what is needed for monitoring the SDGs. SDG indicators related to innovation, industrialisation, and global partnership should be properly integrated into the CES. A sufficient level of data consistency across international statistical systems is aimed at reducing discrepancies in definitions, classifications, and assessment methods, and the availability of updated unified SNA 2025 guidelines is considered an opportunity to reduce methodological discrepancies between countries for direct comparisons. The expansion of data disaggregation in the SDGs aims to establish a connection between macroeconomic aggregates and indicators of quality of life and sustainability, which, from the perspective of the CES, requires new approaches to the sectoral assessment of economic processes, including the isolation of observation units and their integration with administrative sources.

According to J. Jansen & X. Wang (2024), developing policies for economic growth measured by GDP distracts from sustainable well-being. The new UN initiative "Valuing what matters" provides an opportunity to establish and institutionalise a global measurement of indicators that go beyond GDP. It addresses the lack of interdisciplinary collaboration by providing a single measurement approach; it eliminates the confusion caused by numerous alternatives beyond GDP by offering a structured analysis of 65 indicators and outlining their measurement objectives; and it narrows the gap between scientific proposals and country-specific approaches. The study by J. Tebrake (2026) demonstrated the importance of developing and maintaining international statistical standards for measuring economic activity and argued that statistical methodology is increasingly a continuous process that will ensure a timely response to the emergence of new economic phenomena.

Scientists M.A. Sánchez Turner & J.M. Graña (2026) critically examined the limitations of system of national accounts (SNA) in capturing key economic flows. The authors propose extended accounts within the SNA framework that include mechanisms for transferring surpluses between sectors, thereby allowing for a more accurate reflection of the dynamics of economic development. The differences between the United Nations (2008) and the United Nations (2025) have led to existing contradictions between the SNA and the SDGs, which can be summarised as follows.

If the current system of statistical information on which the assessment of SDG achievement is based is not representative of a full assessment of sustainable development, and economic goals for ensuring sustainability and productive employment often do not have clear limitations, then, in the absence of a unified approach, the question arises of assessing the trade-offs between economic benefits and environmental losses. The United Nations (2025) methods for assessing well-being involve constructing aggregated indicators, such as GDP per capita, average income, and the human development index, which are well-suited to international comparisons; however, to reflect inequality and differentiation, they require a high level of disaggregation. Therefore, a contradiction arises due to limited data on countries, their incompleteness, and disaggregation or methodological inconsistencies; comparability over time between aggregated and disaggregated indicators, as well as trends in their dynamics, is affected. It is determined that the same assessment system can give opposite results regarding development trends depending on the level of aggregation.

According to M. Nilashi *et al*. (2023), considering the SDGs as a set of specific, measurable, and time-bound national development goals, it is necessary to focus on the low quality, outdated, and incomplete data, their critical shortage for tracking progress in different countries. The issue of the lack of available data is defined as an obstacle to assessing progress in achieving the SDGs, incomplete data complicates the accurate measurement of the results of the SDG implementation and making management decisions, making it impossible to accurately predict indicators. The authors proposed the use of big data analytics as an effective alternative to address data quality problems and improve monitoring of progress in achieving the SDGs. The SNA is traditionally focused on short- and medium-term data flows, whereas sustainable development requires a long-term perspective, creating a contradiction between indicators of current economic efficiency, such as the GDP growth rate, and indicators of long-term sustainability, such as ecological limits and trends in determining a country's wealth.

The SDGs and the SNA 2025 are positioned as universal frameworks, but national economic models, levels of development, institutional systems, and environmental conditions vary significantly between countries, and indicators such as GDP per capita, energy intensity, and the proportion of the poor population may have different meanings for well-being in different contexts. A review of the new elements included in the 2025 SNA (Zwijnenburg, 2026) that identified modern aspects of the impact on well-being, which will change the vision of the conceptual foundations of comparative assessment, and in the future, reduce the conflict between the requirement for international comparability and the need to take into account national specifics. Contradictions between monetary and non-monetary assessments arise from a lack of a unified approach to weighing these components in composite indices, methodological uncertainty in the monetary assessment of intangible goods, and differing dynamics between monetary and non-monetary components. As a result, there is methodological inconsistency across integral indices because changing the weights or methods

for evaluating individual components can radically alter the overall view of the economic situation.

The parallel use within one country of different assessment tools that have their own weighting logic, sets of indicators, and normalisation methods leads to contradictions in the choice of the basic tool for assessing sustainable development and to different trends across indices for one country. Thus, the SNA 2025 has increased its emphasis on integrating statistical data, as reflected in clearer requirements for consistency among national accounts, balance of payments, financial statistics, price statistics, and employment. This requires statistical authorities to use common classifications and the same collection periods and data from different sources, to reuse the same microdata or aggregated data in different subsystems, to apply cross-checking of data between sources to identify inconsistencies and, as a result, to ensure the integration of metadata into a single statistical information management system and to enable users to track the chain "source → processing → SNA aggregate". In the SNA 2025, the requirements for metadata quality and assessment transparency are set within the framework of the quality of official statistics, with an emphasis on the specifics of national accounts as an integrated macroeconomic system. The process of integrating statistical data into the CES according to the requirements of the SNA 2025 provided for the possibility of tracking how the same microdata or aggregated data are used in different subsystems, but without a clear description of the methods, assumptions and reconciliation procedures, users will not be able to correctly interpret complex indicators, especially in periods of crises, military operations, and rapid structural shifts. At the same time, a detailed description of concepts, sources, and methods, contributing to the interconnection of the CES with the SDGs and the formation of sustainable development indicators based on national accounts and related statistical systems, makes it impossible to compare information across countries if detailed requirements for comparison are not met.

The author R. Dell'Anno (2024) considers a hybrid approach that combines data from the Eurostat tabular approach to determine the exhaustiveness of national accounts with theoretical hypotheses for macroeconomic estimation. This helps fill the gap in demand for reliable estimates for international comparisons, given the limited availability of official national accounts statistics. However, this approach is only considered as a driving force for estimating the shadow, informal, and illegal economy. Under the considered conditions, the question arises of ensuring comparability of the time series when transitioning to the new SNA 2025 standards, because the specified procedure determines the accuracy of the macroeconomic indicators used to characterise sustainable development. The validity of the specified issue was determined by Yu.M. Kharazishvili (2019) and remains valid to this day, which makes it possible to quantitatively assess the level of "break" (level break) between the dynamics series of indicators and analyse the change in their structure.

From a statistical point of view, the most complete option for ensuring comparability is provided by retrospective re-estimation of series (backcasting) construction of complete time series according to the new methodology for as long a period in the past as possible. Statistical services should review all available data from previous years, taking into account new definitions, classifications, and methods, and compile a single series of dynamics in terms of the 2025 SNA, covering both the period "before" and "after" the official transition. This ensures not only maximum comparability over time but also enables the analysis of long-term trends without methodological gaps. The optimality of accounting for changes over time is offset by the need for significant resources and a phased implementation, given the availability of new data sources or additional resources. The rapid development of digital technologies and the spread of big data have fundamentally changed not only approaches to statistical analysis, but also the very structure of the SNA. The comprehensive impact of digitalisation on the economy and the lack of an agreed-upon definition have made it difficult to assess the volume of the digital economy.

The basic challenges that have arisen in statistical activities due to the global spread of digital technologies have been examined by scientists. The directions for the development of the system of statistical measurement of the parameters of the digital economy were highlighted by I.O. Artemieva (2020), who demonstrated the need to build a comprehensive system of measurement for these parameters and outlined the requirements it must meet. This is consistent with early findings from the IMF (2024), which reviews the challenges of measuring the digital economy within the NPA framework. However, the findings of this study suggest that the structure and dynamics of digital industries vary across countries and over time, and the estimates themselves depend heavily on the data sources used. The need to improve data sources to better identify the impact of digitalisation and facilitate policy-making that takes into account the economic benefits of this process remains a basic requirement for the coherence of analytical work over time.

The consistency of the development of digital technologies and their reflection in the CES and the SNA for the achievement of the SDGs is determined by the requirement of mandatory consideration of the "country-region-enterprise" relationship, since it is at the junction of these levels that data flows, added value and digital assets are formed, which form the basis of modern economic statistics. The study by L.V. Batchchenko & O.V. Reva (2023) demonstrated the effectiveness of implementing comprehensive development strategies, both at the state level and at the level of a region or an individual enterprise, under conditions of forecasting the processes accompanying the digital transformation of the economy. If the SNA 2025 aims to expand the accounting methodology, the digital statistical analysis system, in turn, enables the aggregation of indicators from lower levels to the macro level in real time, thereby ensuring the integrity of statistical monitoring of digital transformation and its consistency with the SDGs. This study highlighted several important findings regarding the relationship between the CES and the SDGs. First, the study is based on a thorough comparative analysis of the CES, SNA and SDG methodologies. Second, the adoption of the 2025 SNA introduces a number of important conceptual changes that expand the scope of measuring economic activity, assets, welfare and sustainable development, but is, above

all, highly dependent on the quality of primary statistical information, the need for integration with other statistical systems and limited operational efficiency of statistical estimates. These limitations do not affect the overall reliability of the results obtained but determine the directions of further scientific research.

CONCLUSIONS

The study showed that the CES is a key tool for ensuring the coherence of economic development assessments in the context of implementing the SDGs. Based on the fact that the SNA should provide a consistent and coherent description of economic activity at different levels of data aggregation, it is argued that unification of common definitions and characteristics of macro- and micro-data reduces duplication of requests for similar information, prevents confusion and unreliable reporting, reduces the burden on respondents and increases the accuracy of information. However, the practical implementation of this depends on developing a methodological framework for selecting statistical units for data collection and analysis. The CES is a sustainable development assessment tool that integrates economic, social, and environmental indicators using GSIM, SDMX, and SDG indicators. The CES has been proven to contribute to economic growth through the accurate measurement of indicators, which should be based on harmonised data from different sources.

It has been established that classical statistical methods demonstrate systemic limitations in the context of digitalisation. The lack of detailed microdata leads to an underestimation of current GDP and a distortion of the coefficients of inequality in countries' development. It is evident that eliminating data gaps in complex indicators is possible only by integrating official statistical systems with alternative Big Data sources. The optimal approach for eliminating the trade-off between data efficiency and accuracy is to apply multi-criteria optimisation according to the Pareto principle. The feasibility of implementing a system to control data discrepancies based on their time lag, which affects the construction of forecast estimates, has been demonstrated. Automation of this process minimises subjectivity in the assessment and optimises survey frequency.

The reasons for the inconsistency of economic statistics data that directly affect the process of measuring SDG indicators are identified, which can be summarised as follows: the process of collecting data recorded in the reporting forms of different types of activities or sectors is not coordinated with each other; the application of agreed classifications to all statistical indicators is impossible; national statistical services refuse to fully implement international standards that define not only general concepts, but also the interpretation of interdependent elements of the process of preparing statistical data; the process of data integration depends on the degree of centralisation or decentralisation of national statistical systems; the level of digitalisation and regional disparities in the GSIM and SDMX systems are not fully taken into account; there are no unified approaches to the validation and integration of Big Data with official statistics. Thus, in the future, it is of interest to form basic and, at the same time, unambiguous requirements for data collection and processing, agreed upon at the international and national levels by all statistical services in order to be able to conduct a real assessment of the level of sustainable development of countries around the world.

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Інтеграція статистичних даних у системі комплексної економічної статистики

Анотація. Сучасне суспільство представляє собою складну соціально-економічну систему, ефективність розвитку якої визначається здатністю економіки підтримувати стійкість її елементів протягом певних періодів часу. Метою було обґрунтування інтеграційного підходу до формування комплексної економічної статистики в умовах сталого розвитку шляхом виявлення системних протиріч, оцінки узгодженості статистичних даних та визначення напрямів їх гармонізації відповідно до Цілей сталого розвитку. У дослідженні використано сукупність загальнонаукових і спеціальних методів, зокрема: метод аналітичних узагальнень – для ідентифікації системних проблем комплексної економічної статистики; порівняльний аналіз – для оцінки схем збирання та узгодження даних; системний підхід – для формування інтеграційного бачення статистики; структурно-функціональний аналіз – для визначення ролі метаданих; логічне моделювання – для побудови схем взаємозв'язків між індикаторами Цілей сталого розвитку та статистичними процесами. Встановлено, що сучасна соціально-економічна система характеризується нестійкістю та обмеженою здатністю до відновлення рівноваги, що зумовлює необхідність інтеграції статистичних систем. Обґрунтовано, що баланс складових сталого розвитку досягається через узгоджене функціонування комплексної економічної статистики. Виявлено базові протиріччя в обліковій практиці, а також встановлено залежності між джерелами статистичних помилок і методами їх коригування. Доведено подвійний ефект гармонізації даних державних фінансів із міжнародними стандартами. Розроблено загальну схему взаємозв'язку між проблемами економічних індикаторів сталого розвитку й напрямами вдосконалення статистичної роботи. Визначено роль метаданих у забезпеченні інтеграції статистичних систем і включенні цифрових показників до макроекономічних оцінок. Практичне значення одержаних результатів полягає у можливості їх використання для підвищення узгодженості статистичних даних, забезпечення їх міжнародного порівняння та обґрунтованості управлінських рішень на рівні національних економік у контексті реалізації Цілей сталого розвитку

Ключові слова: сталий розвиток; інтеграція; аналітична оцінка; комплексна економічна статистика; узгодженість даних; типи метаданих; порівняльна оцінка

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