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Analysis of fluctuations in the national economy: Models and development scenarios

Abstract. The purpose of the study was to analyse the prospects for the development of the Ukrainian economy, taking into account the cyclicality and fluctuations of economic processes, which are provoked by both evolutionary trends and fluctuations in force majeure circumstances. The construction of a cluster analysis model made it possible to identify priority types of economic activity and prove the significance of their impact on the country's economic development. The analysis of trends in the development of the economy and its priority types of economic activity was studied for two periods of development: normal and force majeure. The study showed that economic processes in the country have non-linear development trajectories. Therefore, to forecast the development of the country's economy the spectral analysis method and the adaptive forecasting method were used. The analysis of the non-linearity of the development of priority types

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*Corresponding author

of economic activity showed their impact on the wave nature of the development of the national economy. "Agriculture, Forestry and Fishing", "Manufacturing" and "Wholesale and Retail Trade; Repair of Motor Vehicles and Motorcycles" were identified as the most prevalent economic activity types by the cluster analysis. Analysis of the development of cyclical components using spectral analysis showed the formation of cointegration effects when cyclical components at the resonance of crisis points intensify the general economic crisis. Local bifurcation points as crisis points of the national economy were identified and it was proven that they are provoked by economic fluctuations of its priority types of economic activity. As a result, three main scenarios for managing the national economy were developed – a support scenario, a crisis scenario, and a growth scenario; for each scenario, general recommendations for regulating the national economy were developed

Keywords: types of economic activity; cycle; time series; adaptive forecasting model; scenario of development

INTRODUCTION

The national economy as a complex system, which includes a huge number of economic agents of different types of economic activity (TEAs), develops along a non-linear trajectory. Achieving stability of the behaviour of this system should be based on modelling wave processes and their special case – cyclic processes (Kosarchyn, 2023). The problem of cyclical fluctuations is gaining particular importance both at the national level and in the international arena, which is connected with the transition of economically developed countries from an industrial to an information society. The cyclical nature of the behaviour of the economic system is characterised by a permanent transition from one phase of development to the next for the formation of operational, medium-term, final, and final cycles. There is a periodic transition from one equally important state to another equally important state through a transitional crisis period, which is characterised by increased instability, a decline in production, force majeure changes, and a surplus economic structure. In this situation, the economic system adapts to new global sentiments and national changes, striving for stability and sustainability.

To accelerate and control the passage of the economic cycle and develop effective state tools, V. Mykhailov & R. Kulynych (2023) studied the essence and causes of macroeconomic instability, manifestations of unemployment and inflation. They believed that cyclicality should be considered as a movement of the national economy, a form of its development and improvement. A. Tkacova & B. Gavurova (2023) claimed that the turbulent process of economic cycles of the EU countries constantly demonstrates the need for quality forecasting mechanisms. Therefore, it is necessary to choose the economic sentiment indicator (ESI) as a predictive indicator. The authors proved that the ESI and its components are capable of providing high-quality forecasting of the economic cycle. X. Li & Z. He (2023) for the study of business cycles and economic growth proposed to use an economic model that includes both deterministic trends and stable fluctuations obtained as a result of the general process of generating economic data obtained using the dimensionless NLARI – nonlinear autoregressive integrated. The authors proposed a unified test to study the nature and causes of economic fluctuations and growth. This test allows to determine whether the mechanism of formation of economic data is stable fixed points, unit roots, cyclical fluctuations or chaos.

To analyse macroeconomic trends, including economic cycles and unforeseen/prolonged crises, A. Husenova *et al*. (2022) presented a model toolkit that allows to assess the relationship between the calculated indices of economic sentiment and confidence for the main TEAs. The authors also established the nature of the economic sentiment index and investigated its forecasting capabilities regarding monthly and annual growth rates of real gross domestic product (GDP) using autoregression and error correction models. E. Ahmadova (2021) studied the problem of identifying cyclical components from the general dynamics of the country's economic situation. In order to solve this problem, the author proposed to use the algorithm of asynchronous harmonic analysis based on spectral analysis and the algorithm of decomposition filtering. It is proposed to use GDP or gross value added by TEAs as an information basis.

To effectively manage waves and, as a special case, cyclical processes in the economy, it is necessary to create and maintain the effective functioning of monitoring systems based on the widespread use of the latest information and communication technologies, big data techniques, data mining tools, etc. In addition, important components of the monitoring system are the database as an information space for analysis and the knowledge base as a set of approaches, methods, classifiers, methods, and models that allow building a monitoring strategy and tactics. The article aimed to study the prospects for the development of the Ukrainian economy, taking into account the cyclicality and nonlinearity of the development of TEAs caused by both the established evolutionary trends and fluctuations in force majeure circumstances in 2022-2024. The conceptual basis of this study is the following hypotheses. Hypothesis 1: economic changes can be cyclical and fluctuating in nature. The first is due to the evolution of the development of the economic process; the second is of an irregular nature and is associated with the technological and innovative shocks of the 21st century. Hypothesis 2: to identify local bifurcation points in the development cycles of economic processes, it is advisable to use spectral analysis; to forecast crisis points in irregular fluctuation processes caused, for example, by force majeure circumstances, it is advisable to use adaptive forecasting methods. Hypothesis 3: the emergence of crisis points in the cyclical development of the national economy is caused by economic fluctuations in priority TEAs.

MATERIALS AND METHODS

The hypotheses formed the basis of the conceptual model of the study, the sequence of stages of which reveals the logic of the study (Fig. 1). The methodological basis for

constructing the model was formed by the systemic, structural-logical, and functional approaches, which made it possible to form: the structure of the model as a sequence of stages for achieving the research goal; a set of tasks for each stage, the solution of which allows to confirm or refute the hypotheses put forward in the study; economic and mathematical tools for solving problems to achieve the main function of the model, namely monitoring changes in the country's macroeconomic environment, considering the nonlinear nature of the development of economic processes.

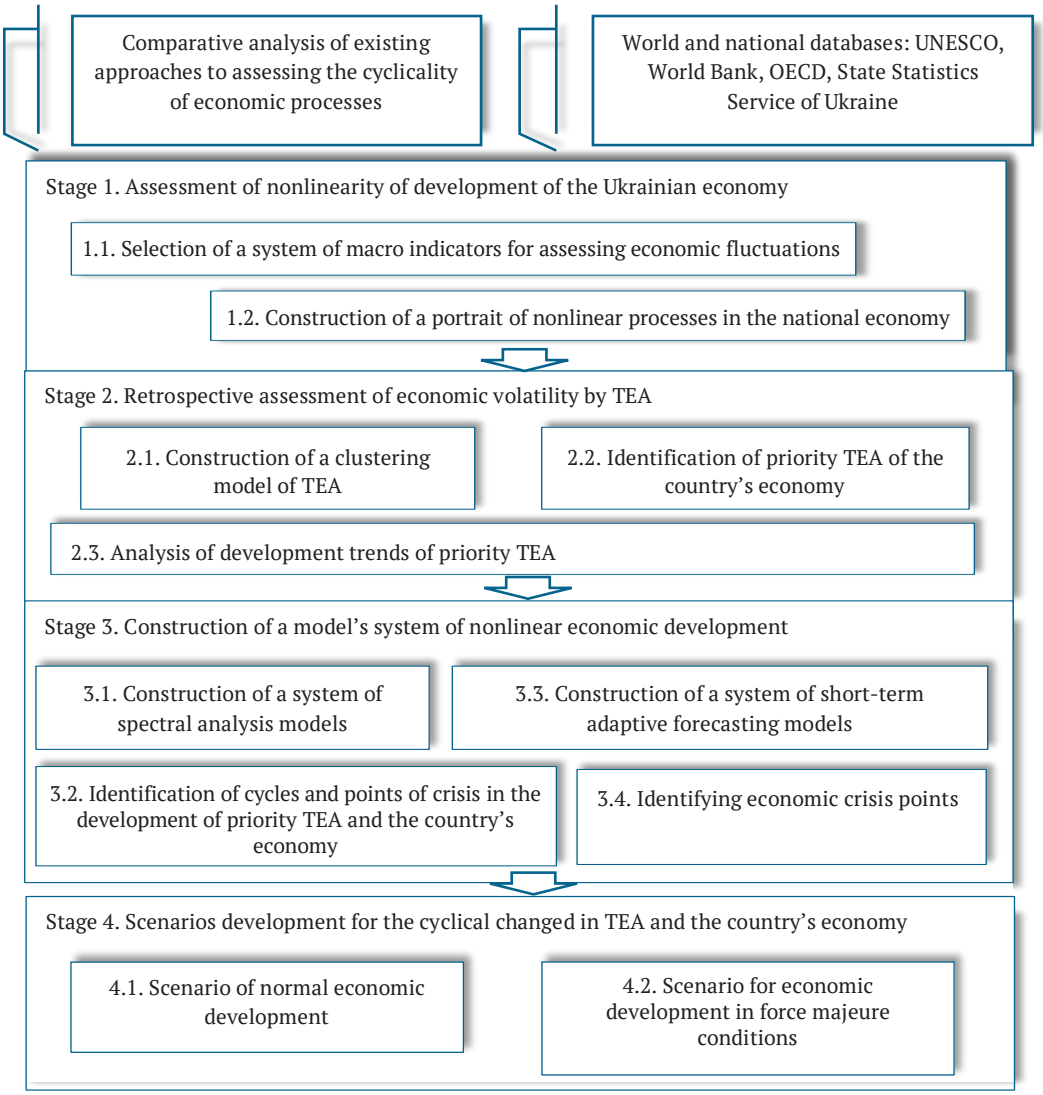

Figure 1. Conceptual model of the study

Source: developed by the authors

The methods and models of each stage of the model should be considered in more detail. To address the tasks of Stage 1 of the study, several methods were employed. These included the information search method, as well as the monographic analysis of literary sources (Ahmadova, 2021; Li & He, 2023; Tkacova & Gavurova, 2023). Additionally, the comparative method was used alongside graphical, structural, and dynamic analysis (Rayevnyeva *et al.*, 2023a; Rayevnyeva *et al.*, 2023b; Wang & Kong, 2023). Furthermore, the study relied on the works of T.O. Pasichnyk (2024), V. Rădulescu *et al.* (2024) and S. Zhe (2024) for further theoretical and methodological insights. This toolkit made it possible to create a list of indicators that should be used to assess economic fluctuations in the country. The information basis for solving the tasks of this stage is the analysis of macroeconomic indicators of the development of Ukraine for the period 1987-2024. The sources of statistical information are international and national statistical institutions (OECD, n.d.; State Statistics Service of Ukraine, n.d.; UNESCO Institute for Statistics, n.d.; World Bank, n.d.).

At Stage 2, tasks related to the assessment of economic volatility of TEAs from shocks of macroeconomic development were solved. To construct homogeneous clusters of the contribution of foreign economic activities to the country's GDP, one of the methods of artificial, non-hierarchical classifiers (partitioning algorithms) was used – the *k* means method, which allowed for the decomposition of foreign economic activities. One of its advantages is the ability to form the number of clusters required for the study, which improves the quality of their economic

interpretation. The criterion for selecting optimal clusters was the minimum value of the total within-cluster variation (W_{total}) (Fair, 2025):

$$W_{total} = \sum_k W(C_k) \to \min, \quad (1)$$

where $W(C_k)$ – within-cluster variation for each cluster; k – number of clusters. The selection of the optimal number of clusters was carried out based on the use of the "elbow method", which considered the nature of the change in the spread W_{total} with an increase in the number of groups. To solve the clusterisation task, a multidimensional clustering model was built using the software Statistica 13.0. The information space was formed by indicators of gross value added (GVA), wages of employees, and gross profit by TEAs for the period 2010-2022. The identification of priority activities in the country's economic development was carried out based on the use of the results of cluster and structural-dynamic analysis. This made it possible to identify priority types of foreign economic activity based on their contribution to the country's GDP.

To solve the tasks of Stage 3, the study used spectral analysis models (Task 3.1; 3.2) and adaptive forecasting models (Task 3.3; 3.4). Since many economic processes in Ukraine are strongly influenced by external factors caused by force majeure circumstances, they demonstrate periodic behaviour. This justifies the appropriateness of using spectral analysis in the study (Prymostka & Chub, 2021). The covariance of a time series is represented by a spectral density function using a periodogram. The latter expresses the square of the correlation between the time series and the cos and sin functions of different frequencies that are present in the time series:

$$f(x) \sim \frac{a_0}{2} + \sum_{n-1}^{\infty} (a_n \cos_{nx} + b_n \sin nx), \quad (2)$$

where $a_n = \frac{1}{\pi}\int_{-\pi}^{\pi} f(x) cos\ nxdx$, $n = 0, 1, 2, \ldots$; $b_n = \frac{1}{\pi}\int_{-\pi}^{\pi} f(x) sin\ nxdx$, $n = 1, 2, 3, \ldots$ Identification of periodic dependencies made it possible to determine the coincidence/mismatch of periods of occurrence of local points of the crisis of various TEAs and to determine points of the global crisis in the development of the country's economy. To construct a system of spectral analysis models, models of cyclic components of a time series were developed based on its decomposition. The type of decomposition model was determined based on the graph of the corresponding series and its multiplicative form of the following type was proven:

$$Y(t) = T(t) \times C(t) \times S(t) \times I, \quad (3)$$

where $T(t)$ – trend component; $C(t)$ – cyclic component; $S(t)$ – seasonal component; I – residual. The application of adaptive forecasting models is especially relevant when analysed time series are characterised by high volatility and strong variability of factors that influence it. Adaptation in models is provided by small discrete shifts, which are calculated as the deviation of the forecast from its actual value. The resulting error is used to adjust the model parameters when calculating each new value of the series. Thus, this model is appropriate for forecasting crisis points of TEAs in force majeure conditions of the development of the Ukrainian economy in 2022-2023. The calculations of the models were carried out using the Statistica 13.0 software; the criterion for selecting an adequate model was the mean percentage absolute error (MAPE) in percent, which is calculated using the following formula:

$$MAPE = \frac{1}{n}\sum_{i=1}^{n} \frac{|Y_t - \hat{Y}_t|}{Y_t} \times 100, \quad (4)$$

where Y_t – actual indicator value; $(\hat{Y}_t)$ – model indicator value; n – length of the series. The initial data for solving the tasks of construction of a model's system of nonlinear economic development is the amount of GVA of the priority TEAs for the period 2001-2022 in a quarterly section.

RESULTS

Stage 1. Assessment of nonlinearity of development of the Ukrainian economy

Task 1.1: Selection of a system of macro indicators for assessing economic fluctuations. Based on the research, the following list of indicators was formed, namely: the volume of GDP, the level of inflation, the level of the unemployed in the economy, the volume of currency reserves of countries. Task 1.2: Construction of a portrait of nonlinear processes in the national economy. Figure 2 shows the non-linear nature of the development of the Ukrainian economy. During the analysed period, several periods of decline and rise in the development of the country's economy were distinguished.

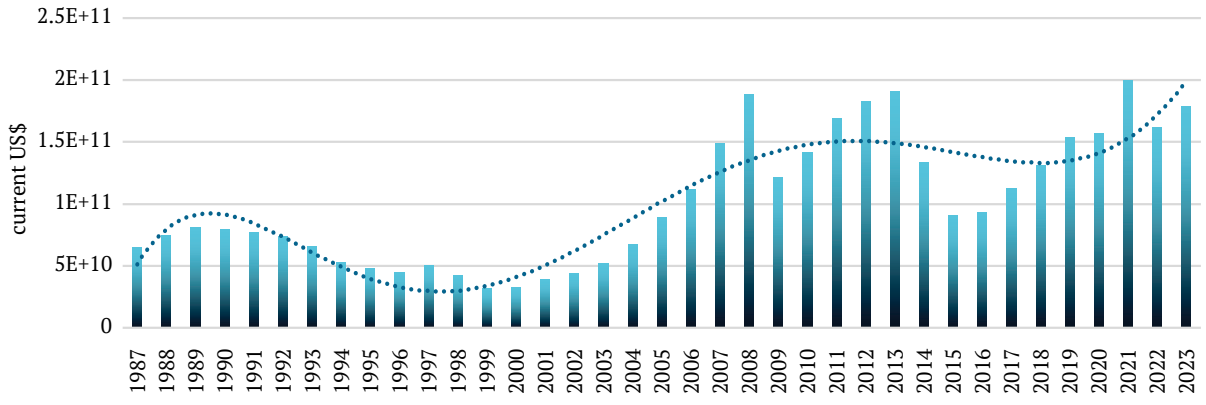

Figure 2. Dynamics of changes in the country's GDP, current US$

Source: created by the authors based on World Development Indicators (n.d.)

The first period (1991-2000) was a period of decline, provoked by the collapse of the Soviet Union, the emergence of independent Ukraine, changes in the form of ownership and the formation of market mechanisms. This period is characterised by a low level of production of competitive goods in the conditions of a free market, the presence of a commodity deficit, and a low level of income of the population. The second period (2001-2013) was a period of growth, adaptation of the economy to market rules of doing business, rapid growth of the country's GDP, which indicates the country's high economic development. The fall in GDP in 2009 was a response of the economy to the global financial, and subsequently political and economic crisis. But, the weak integration of Ukraine's economy into the world economic market made it possible to restore economic activity in 3 years and in 2013 to reach the GDP level of 2008. The third period (2014-2015) was an economic decline caused by political changes in the country's development. The fourth period (2016-2023) was a period of fluctuating growth. This period is characterised by a general upward trend in the development of the country's economy, its adaptation both to global force majeure conditions (the COVID-19 pandemic) and to the military conflict on the territory of the country.

Figure 3 shows the non-linear trend of changes in the inflation rate in the country. Thus, during the period 1993-2000, the level of inflation in the country decreased rapidly and already in 2003 it was 8.2%. However, in 2004 inflation accelerated to 12.3%, in 2005-2006 its level decreased. Starting from 2007 to 2009, there was a gradual increase in the level of inflation, and from 2009 to 2012, the opposite dynamics was observed. Ukraine ended 2012 with deflation of 0.2%. Before that, the last time this happened was in 2002, when deflation was 0.6%. Over the entire period under study, the lowest level of inflation was recorded in 2013 and amounted to 0.5%, but then it began to rise to a record: in 2014, the price increase was 24.9%, in 2015 – 43.3%. Starting from 2016 to 2020, a period of decreasing inflation was observed, and from 2021, a period of growth again. All this indicates that this economic indicator has a wave nature of development.

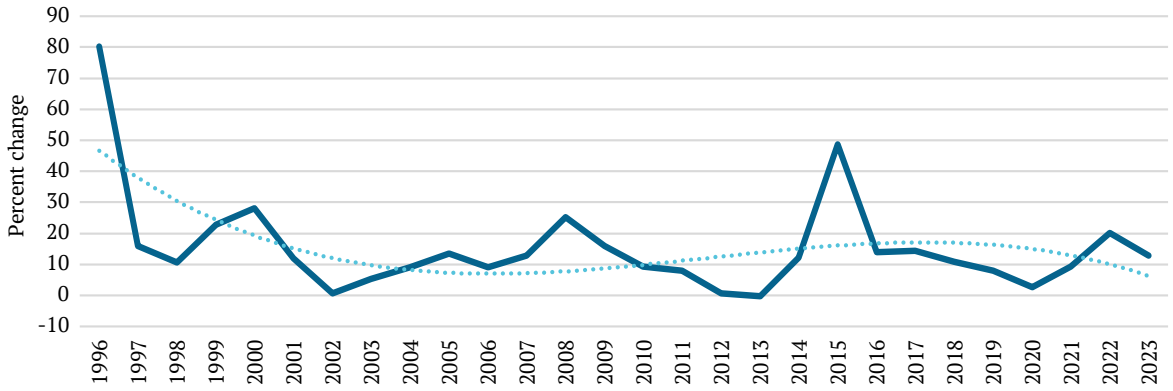

Figure 3. Dynamics of changes in the inflation rate, %

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

Figure 4 shows the trend of changes in the unemployment rate indicator. The level of unemployment in Ukraine also has a non-linear nature of development. From 1995 to 2023, several periods of decline/rise can be distinguished. The recession periods were 1990-1997, 2000-2008, 2010-2013, 2017-2019, 2023-present. During these periods, there was a decrease in the number of the unemployed population, which indicates an increase in the welfare of the population and the economic development of the country. Boom period (1998-1999, 2009, 2014-2016, 2022) reflects an increase in the number of unemployed people, unstable economic development of the country, which is associated with political and economic crises and the military conflict on the territory of Ukraine.

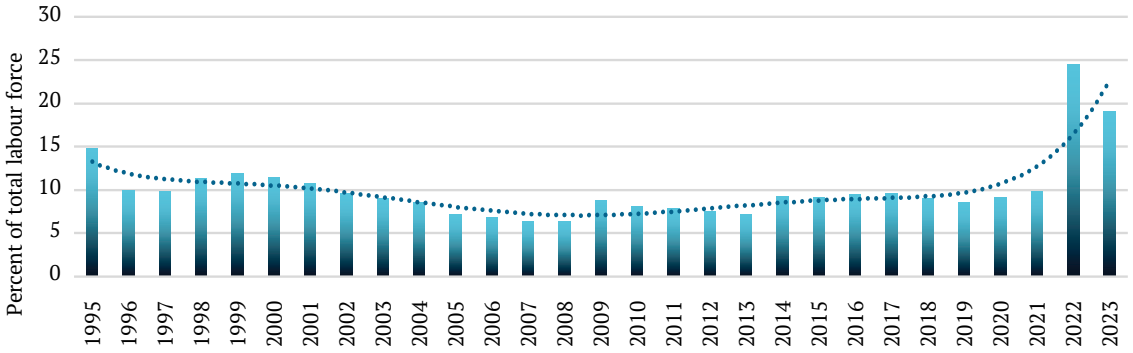

Figure 4. Dynamics of changes in the unemployment rate, %

Source: created by the authors based on State Statistics Service of Ukraine (n.d.)

Figure 5 shows the dynamics of changes in the volume of foreign exchange reserves. The analysis made it possible to distinguish several periods. The first period (1993-2007) was the formation and development of the country as an independent state that had sufficiently large reserves for stable economic development. The second period (2008-2009) was a decline associated with the global financial crisis. The third period (2010-2014) was a period of significant decrease in the volume of the country's currency reserve. The largest drop in the volume of gold and foreign exchange reserves took place in 2012 and amounted to 7.25 billion dollars by 21 absolute indicators, with a relative indicator of a 22.8% decrease compared to the volumes of 2011. The fall in the National Bank of Ukraine reserves this year was largely related to the desire to maintain the hryvnia exchange rate on the eve of the 2012 parliamentary elections. In the following 2013-2014, the steady trend towards a decrease in gold and foreign exchange reserves continued, reaching the mark of 7.533 billion dollars as of January 1, 2015. 2014 became the leader in reducing the volume of foreign exchange reserves by 63.1% compared to 2013. The main reason for the decrease in reserves during this period was repayment of International Monetary Fund loans, entry into the foreign exchange market with interventions, payments on state bonds loans.

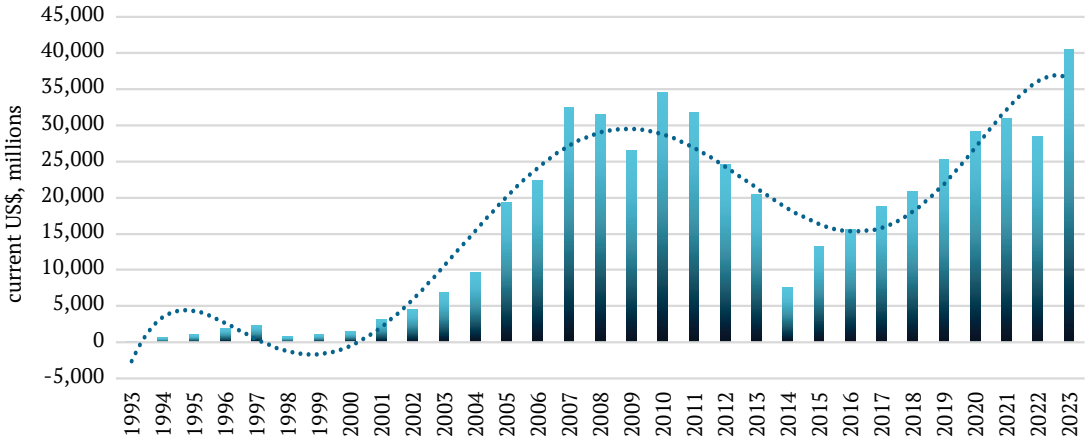

Figure 5. Dynamics of the volume of the country's currency reserve, current US$, millions
Source: compiled by the authors based on Statista (n.d.), International Monetary Fund (2024)

The fourth period (2015-2021) was characterised by growth of gold and foreign exchange reserves of Ukraine, due to the increase of assets in convertible currencies (securities, currency and deposits). In 2022, there was a sharp reduction in the country's currency reserves due to the full-scale invasion of Russia on the territory of Ukraine, which is a force majeure circumstance for the country. However, starting from 2023, Ukraine began to gradually adapt to force majeure circumstances. Thus, the analysis of the main macroeconomic indicators of the country showed the presence of non-linearity in their development.

Stage 2. Retrospective assessment of economic volatility by TEAs

Task 2.1: Construction of a clustering model of TEAs (Table 1). For a clearer view of the results presented, the results of the cluster analysis are shown separately in Table 2.

Table 1. Clusterisation of TEAs

Cluster	Cluster features	Type of economic activity
1	TEAs that have a strong impact on the country's GDP	"Agriculture, Forestry and Fishing"; "Manufacturing"; "Wholesale and Retail Trade; Repair of Motor Vehicles and Motorcycles"
2	TEAs that have an average impact on the country's GDP	"Mining and Quarrying"; "Transportation and Storage"; "Information and Communication"; "Real Estate Activities"; "Public Administration and Defence; Compulsory Social Security"; "Education"
3	TEAs that have a low impact on the country's GDP	"Electricity, Gas, Steam and Air Conditioning Supply"; "Water Supply; Sewerage, Waste Management and Remediation Activities"; "Construction"; "Accommodation and Food Service Activities"; "Financial and Insurance Activities"; "Professional, Scientific and Technical Activities"; "Administrative and Support Service Activities"; "Human Health and Social Work Activities"; "Arts, Entertainment and Recreation"; other service activities

Source: developed by the authors

Table 2. Cluster analysis data

Year	Parameters	Agriculture, Forestry and Fishing	Mining and Quarrying	Manufacturing	Electricity, Gas, Steam and Air Conditioning Supply	Water Supply; Sewerage, Waste Management and Remediation Activities	Construction	Wholesale and Retail Trade; Repair of Motor Vehicles and Motorcycles	Transportation and Storage	Accommodation and Food Service Activities	Information and Communication	Financial and Insurance Activities	Real Estate Activities	Professional, Scientific and Technical Activities	Administrative and Support Service Activities	Public Administration and Defence; Compulsory Social Security	Education	Human Health and Social Work Activities	Arts, Entertainment and Recreation	Other service activities
2010	GVA	80,385	63,436	142,700	30,295	7,736	35,366	154,994	83,027	8,932	33,011	61,263	57,699	27,265	11,832	49,863	53,462	38,555	6,074	8,577
	Remuneration of employees	17,301	34,171	92,794	21,297	6,562	17,435	65,116	44,437	4,370	17,079	27,791	10,333	17,462	6,589	45,757	48,547	32,970	4,985	3,188
	Gross profit	63,381	35,008	47,287	8,718	1,201	17,401	86,531	37,805	4,375	16,274	32,703	46,988	9,313	5,145	4,048	4,823	5,891	1,627	5,118
2011	GVA	106,555	84,872	154,675	39,994	7,302	39,575	193,357	103,179	10,256	38,390	58,213	69,035	30,471	14,300	53,464	59,377	41,855	7,161	10,527
	Remuneration of employees	21,988	40,577	112,260	26,928	7,121	22,298	81,140	54,666	5,137	19,287	29,932	14,185	18,080	7,916	49,748	54,171	35,315	6,004	3,862
	Gross profit	84,861	51,134	38,336	12,440	295	16,784	109,221	47,713	4,875	19,038	27,408	54,465	11,867	6,331	3,662	5,115	6,280	1,870	6,351
2012	GVA	109,785	81,660	173,912	43,491	6,625	39,049	200,763	98,859	10,122	43,379	61,055	83,502	41,966	16,135	59,752	71,771	49,234	9,727	12,282
	Remuneration of employees	25,920	44,232	125,284	25,232	7,416	23,167	95,098	63,275	6,070	22,120	33,226	20,243	26,873	11,206	53,933	65,544	42,542	8,935	5,521
	Gross profit	83,694	53,926	43,375	24,324	404	14,655	102,315	33,925	3,693	19,360	27,000	64,372	14,635	3,422	5,756	6,120	6,393	4,271	6,377
2013	GVA	128,738	81,259	165,055	42,366	6,573	36,902	212,090	104,483	10,150	48,372	66,232	95,272	47,712	17,715	68,225	77,986	48,247	12,704	13,731
	Remuneration of employees	30,055	48,599	114,931	25,276	7,276	22,118	100,108	64,945	5,995	23,924	33,576	21,920	29,908	11,991	63,162	70,562	40,705	9,815	5,787
	Gross profit	97,968	45,721	44,563	17,562	-400	13,449	107,387	38,444	3,747	23,389	31,806	73,158	16,048	4,940	4,998	7,323	7,399	5,246	7,474
2014	GVA	161,145	79,120	194,050	44,836	7,236	36,876	233,702	100,889	9,927	52,724	70,601	99,144	47,139	18,061	78,731	76,068	46,250	12,339	13,881
	Remuneration of employees	31,274	34,726	123,632	29,586	6,710	20,998	102,761	62,100	5,859	24,075	32,733	19,238	30,355	13,601	72,538	69,059	39,267	9,912	6,519
	Gross profit	128,518	51,989	64,374	22,767	1,771	14,680	126,510	37,721	3,641	26,952	36,471	82,144	15,448	3,690	6,102	6,902	6,795	4,420	6,886
2015	GVA	239,806	95,141	236,692	53,385	7,924	38,928	273,989	134978	11,946	72,596	67,512	123,021	55,789	21,624	95,085	82,778	51,480	12,357	14,356
	Remuneration of employees	35,131	34,219	132,968	32,641	8,028	20,060	101,419	73,271	5,858	26,268	26,996	15,976	29,001	14,724	86,329	74,753	43,041	10,181	6,782
	Gross profit	203,286	61,307	97,161	24,393	765	17,256	168,601	60,418	5,778	43,472	38,747	106,303	25,183	6,111	8,638	7,895	8,100	4,504	7,069
2016	GVA	279,701	131,650	291,471	73,809	8,502	47,457	318,075	156,745	15,551	89,268	65,445	145,984	68,460	29,584	123,065	88,996	58,858	13,554	17,053
	Remuneration of employees	40,834	39,644	137,331	36,899	7,944	22,419	115,838	81,551	6,724	29,621	30,797	16,129	32,351	17,863	111,927	78,640	49,065	10,622	7,630
	Gross profit	238,555	93,433	150,706	37,283	913	24,509	199,123	75,478	8,550	59,401	32,619	129,220	35,191	11,364	11,064	10,272	9,824	5,589	9,100
2017	GVA	303,949	177,170	359,867	85,970	9,880	64,431	409,994	191,209	18,727	110,296	81,369	171,674	86,537	35,471	163,798	133,213	76,140	17,376	22,490
	Remuneration of employees	54,657	50,939	186,003	43,444	9,779	31,614	153,059	113,473	7,805	37,074	37,211	19,189	45,942	22,716	148,689	120,015	63,889	14,626	10,623
	Gross profit	252,566	127,963	170,374	43,691	685	32,169	253,203	78,851	10,497	71,652	41,776	151,860	39,516	12,283	15,044	13,098	12,365	6,846	11,424
2018	GVA	361,173	214,260	411,467	111,856	11,394	81,259	471,844	227,256	25,112	138,828	97,807	206,085	113,354	48,571	212,789	158,620	77,130	20,375	29,010
	Remuneration of employees	74,229	62,668	231,364	52,791	11,355	41,595	195,824	150,596	9,827	47,536	47,274	23,300	58,543	29,044	192,600	142,888	69,475	17,708	13,704
	Gross profit	287,131	153,705	178,302	59,882	1,092	38,795	271,946	77,728	14,704	89,350	48,097	181,900	53,418	18,923	20,120	15,586	7,587	7,652	14,726
2019	GVA	356,795	222,352	430,228	124,908	14,436	107,430	526,299	264,866	35,311	182,667	114,658	241,493	141,523	62,238	266,656	172,645	95,435	24,053	38,837
	Remuneration of employees	82,016	69,471	258,311	63,163	15,748	53,305	242,153	158,825	14,547	64,193	56,692	29,173	68,838	40,077	241,747	153,930	83,004	20,438	17,142
	Gross profit	274,742	155,643	170,344	61,363	617	52,949	279,603	107,757	19,967	115,726	54,571	211,360	71,056	21,281	24,823	18,514	12,304	8,306	20,967
2020	GVA	393,077	193,120	426,483	122,878	16,257	119,441	588,365	262,453	30,834	209,394	131,903	268,980	137,192	59,895	306,533	186,049	113,642	24,338	35,891
	Remuneration of employees	84,882	66,402	254,649	74,656	18,558	57,871	258,345	158,860	11,137	69,408	61,561	30,075	75,519	40,834	272,271	162,522	102,683	21,508	15,472
	Gross profit	305,119	128,695	168,767	47,781	750	61,281	322,356	106,214	15,075	135,404	67,813	236,629	61,002	17,681	30,716	18,276	10,312	6,366	17,719
2021	GVA	580,519	364,199	562,471	183,176	19,240	151,826	755,201	303,614	38,002	246,021	165,316	304,060	159,284	69,275	341,242	236,599	140,401	30,729	40,444
	Remuneration of employees	140,755	84,671	315,464	88,058	22,149	79,720	315,519	178,072	14,353	77,154	69,873	39,592	72,858	44,131	302,141	207,131	133,802	27,231	18,532
	Gross profit	472,991	290,882	263,560	104,360	3,270	79,240	452,026	135,233	21,426	161,475	91,935	266,602	84,211	20,210	36,235	29,881	7,504	8,734	22,971
2022	GVA	426,817	295,550	393,312	231,492	15,818	62,782	641,703	204,547	34,605	238,589	148,269	253,176	96,163	38,987	1,097,257	215,550	126,905	22,669	36,202
	Remuneration of employees	140,755	84,671	315,464	88,058	22,149	79,720	315,519	178,072	14,353	77,154	69,873	39,592	72,858	44,131	302,141	207,131	133,802	27,231	18,532
	Gross profit	472,991	290,882	263,560	104,360	3,270	79,240	452,026	135,233	21,426	161,475	91,935	266,602	84,211	20,210	36,235	29,881	7,504	8,734	22,971

Source: created by the authors based on State Statistics Service of Ukraine (n.d.)

Task 2.2: Identification of priority TEAs of the country's economy. Figure 6 graphically presents the contribution to the country's GDP of certain TEAs in 2022. Based on the comparison of the results of structural-dynamic (Fig. 6) and cluster analysis (Table 2), the dominant TEAs were identified: "Agriculture, Forestry and Fishing", "Manufacturing" and "Wholesale and Retail Trade; Repair of Motor Vehicles and Motorcycles". These TEAs form a third of the country's GDP.

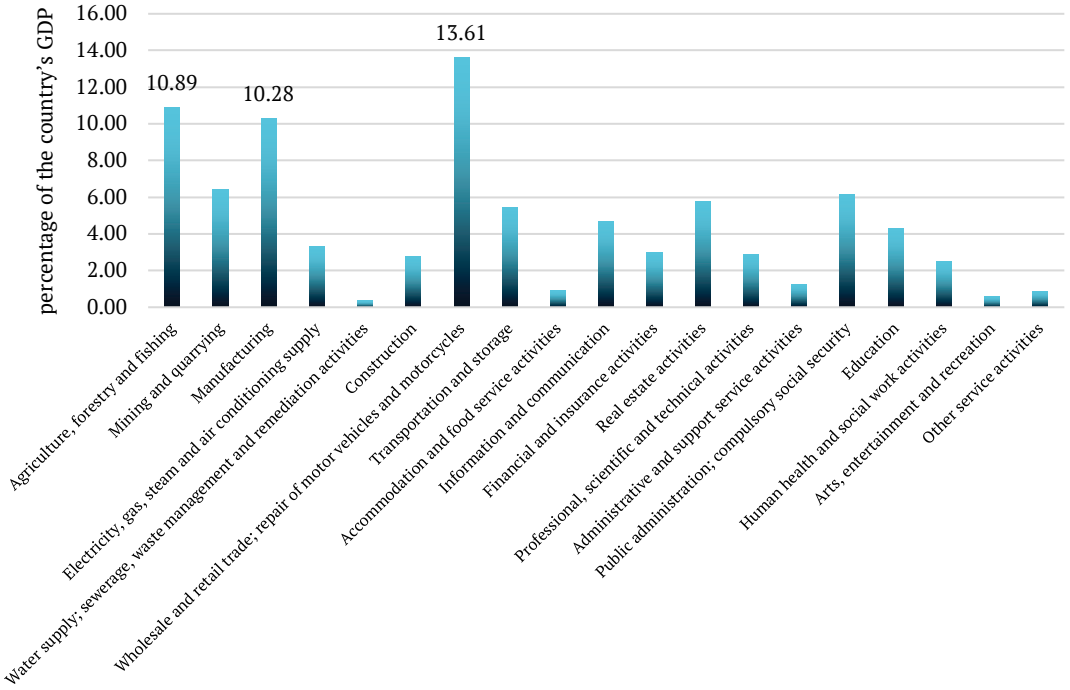

Figure 6. The structure of the contribution of TEAs to the development of the country's GDP in 2022, %
Source: created by the authors based on State Statistics Service of Ukraine (n.d.)

Task 2.3: Analysis of development trends of priority TEAs. Priority TEAs have a significant impact on the country's economy, which is confirmed by the nature of their development (Fig. 7).

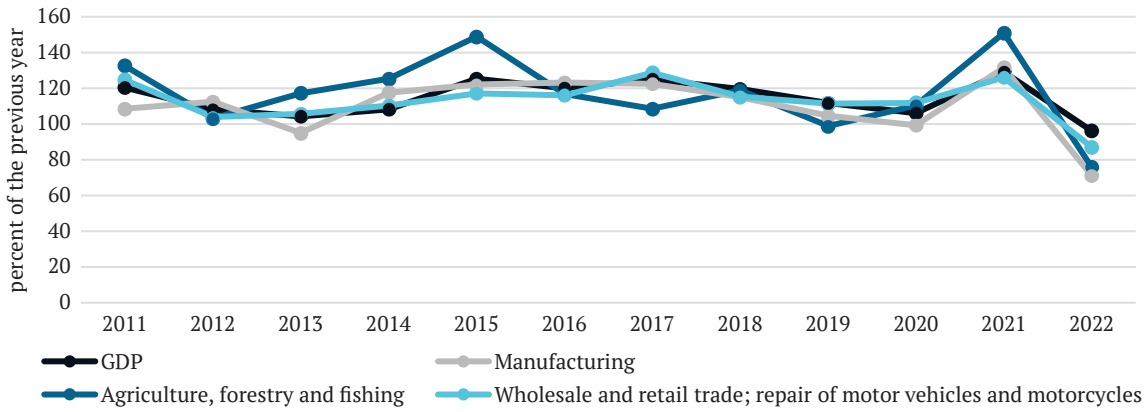

Figure 7. Growth rates of the country's GDP and priority TEAs (in % compared to the previous year)
Source: created by the authors based on State Statistics Service of Ukraine (n.d.)

In terms of tempo, they have practically a unidirectional trend of their development with the economy of Ukraine. But the question of co-integration of the development of the priority TEAs with the general cyclical development of the country is open for research.

Stage 3. Construction of a model's system of nonlinear economic development

The initial data for solving the tasks of this stage is the amount of GVA of the priority TEAs for the period 2001-2022 in a quarterly section. Figure 8 reflects the trends in GVA change for priority TEAs.

Task 3.1: Construction of a system of spectral analysis models. To build the models of cyclic components of the time series, the following steps were taken. Step 1: Decomposition of the time series on the determination and irregular parts. The results of eliminating the seasonal factor for the three studied time series are shown in Table 3.

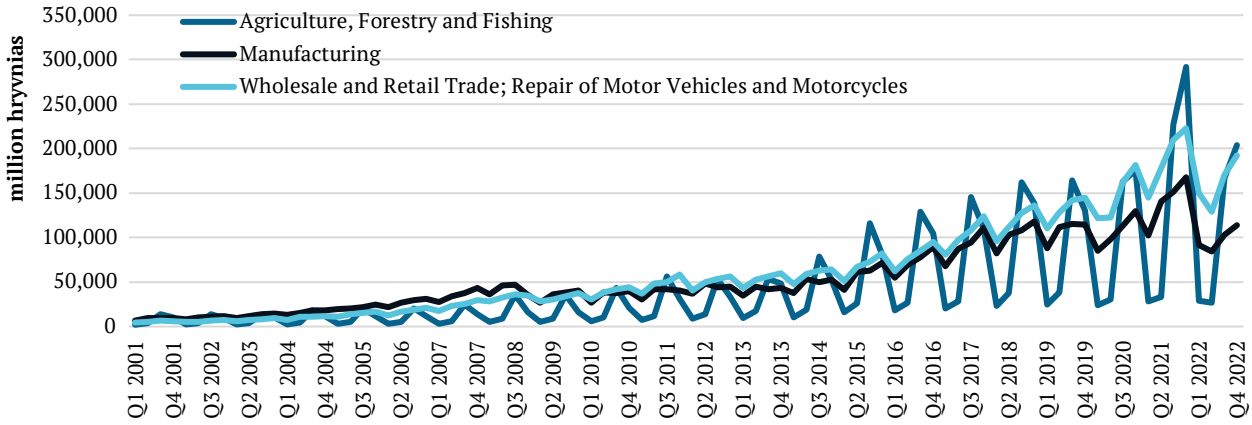

Figure 8. Dynamics of the volume of GVA of priority TEAs
Source: created by the authors based on State Statistics Service of Ukraine (n.d.)

Table 3. Seasonal factors for three time series

Number of the quarter in the year	Type of the economic activity		
	Agriculture, Forestry and Fishing	Manufacturing	Wholesale and Retail Trade; Repair of Motor Vehicles and Motorcycles
1	31.2288	83.0888	85.1996
2	47.5210	103.3685	98.8435
3	190.2583	104.9755	105.4314
4	130.9919	108.5672	110.5255

Source: calculated by the authors

Calculations have shown that the highest values of seasonal factors occur in the Q3 and Q4. While the Q1 has the lowest value of the seasonal factor. On the other hand, Table 3 shows that agriculture, forestry, and fishery have the highest value of seasonal factor. This means that this type of economic activity is more dependent on seasonal fluctuations than others. Step 2: Determination of the trend component. At this step, the smoothed trend-cyclic component was studied, the trend type was found, and the parameters of trend models were calculated. Based on the analysis of the graph, it was concluded to use a linear trend in the work. The parameters of the trend components are given in Table 4.

Table 4. Parameters of trend models and criteria for model adequacy

	Agriculture, Forestry and Fishing	Manufacturing	Wholesale and Retail Trade; Repair of Motor Vehicles and Motorcycles
Models	$Y(t) = -16{,}243 + 1{,}299.7t$	$Y(t) = -5{,}827 + 1{,}344.6t$	$Y(t) = -24{,}812 + 1{,}973.2t$
Determination coefficients (R^2)	0.85	0.81	0.88

Source: calculated by the authors

The values of the determination coefficient are high, which indicates the high quality of trend models. Also, the correlation coefficients show the influence of trend components, and R^2 shows the influence of cyclical components. Thus, it is concluded that the variability of the values of the analysed time series is strongly determined by the trend and weakly depends on cyclical changes. Step 3: Determination of the cyclic components. To calculate the cyclical components of the series, it is necessary to divide the smoothed trend-cyclical components by the trend values. The graphs of the cyclical components are presented in Figure 9.

Figure 9 shows that there are abnormal observations in the cyclic components. There are two reasons for this. The first reason is the multiplicative type of the decomposition model since negative values are in trend. The second reason is the presence of long-term memory in the time series. Therefore, it is necessary to select an observation to study the cyclic components. The analysis of the cyclic components gives an observation interval from 17 to 84 observations. The graphs of the new cyclic components are shown in Figure 10.

Step 4: Calculation of the cyclic models for cyclic components. Fourier spectral analysis was used to determine local cyclic components (harmonics). The calculations performed allowed to identify six fundamental harmonics based on spectral densities. The values of the sine, cosine coefficients, period, and spectral periodogram are in Table 5.

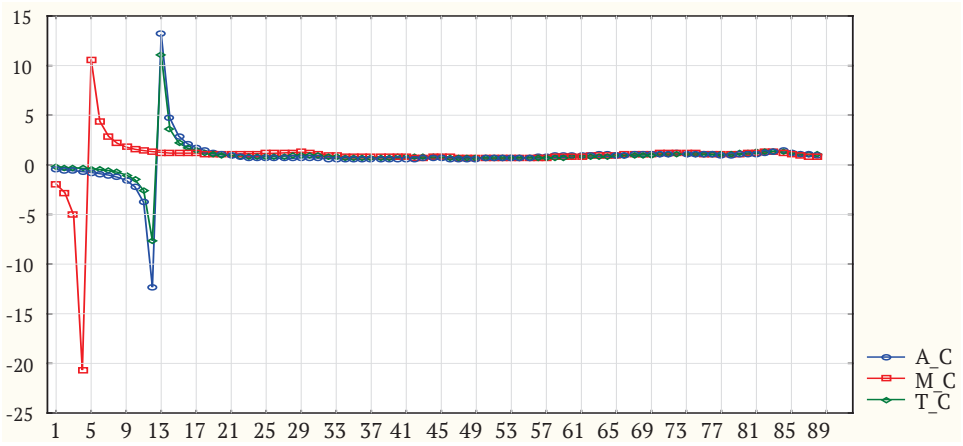

Figure 9. Cyclic components of the time series
Note: A_C – cyclic component of the "Agriculture, Forestry and Fishing"; M_C – cyclic component of the "Manufacturing"; T_C – cyclic component of the "Wholesale and Retail Trade; Repair of Motor Vehicles and Motorcycles"
Source: calculated by the authors

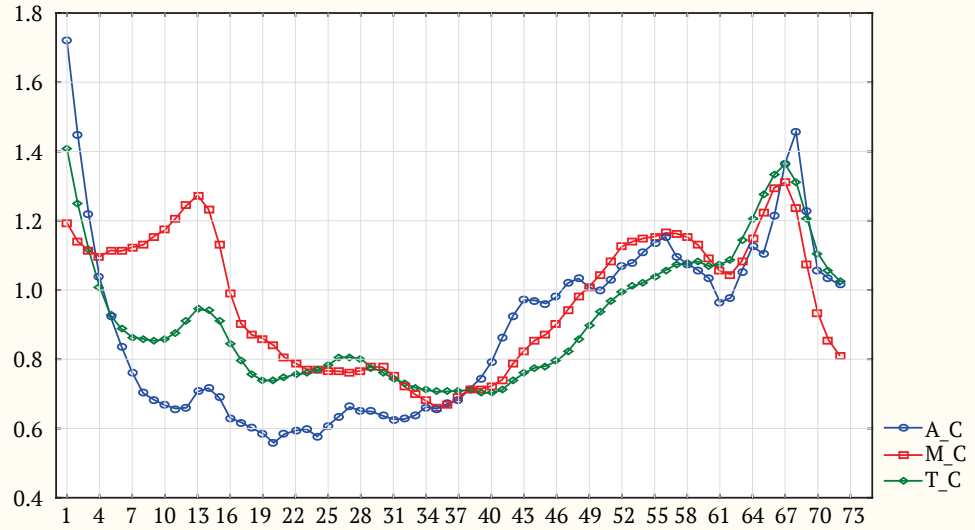

Figure 10. Part of the cyclic components
Note: A_C – cyclic component of the "Agriculture, Forestry and Fishing"; M_C – cyclic component of the "Manufacturing"; T_C – cyclic component of the "Wholesale and Retail Trade; Repair of Motor Vehicles and Motorcycles"
Source: calculated by the authors

Table 5. Main characteristics of Fourier spectral analysis

Period (*T*)	Cosine coefficients	Sine coefficients	Periodogram	Part of the periodogram
Agriculture, Forestry and Fishing				
72.0000	0.171879	−0.125808	1.633323	62.3%
24.0000	0.091755	0.011950	0.308222	11.8%
36.0000	0.071132	0.053613	0.285627	10.9%
10.2857	0.010016	0.065944	0.160163	6.1%
6.5455	0.036036	0.044928	0.119414	4.6%
9.0000	0.017255	0.053659	0.114374	4.4%
Manufacturing				
72.0000	0.209922	−0.067399	1.749956	71.9%
36.0000	−0.070868	0.062543	0.321624	13.2%
18.0000	−0.044843	−0.033275	0.112253	4.6%
9.0000	−0.006106	0.050149	0.091880	3.8%
24.0000	−0.029728	0.039586	0.088228	3.6%
10.2857	−0.005209	0.043955	0.070530	2.9%

Table 5. Continued

Period (*T*)	Cosine coefficients	Sine coefficients	Periodogram	Part of the periodogram
Wholesale and Retail Trade; Repair of Motor Vehicles and Motorcycles				
72.0000	0.202028	–0.041643	1.531776	86.1%
10.2857	0.006363	0.045753	0.076818	4.3%
12.0000	0.015501	0.037313	0.058772	3.3%
9.0000	0.008455	0.038164	0.055006	3.1%
36.0000	0.008774	–0.027278	0.029559	1.7%
24.0000	0.023713	0.013128	0.026446	1.5%

Source: calculated by the authors

Table 5 shows that $T = 72$ quarters is the most powerful long-term cycle, which is typical for all TEAs. This is especially true for "Wholesale and Retail Trade; Repair of Motor Vehicles and Motorcycles" (86.1%). Medium-term cycles ($T = 18/24/36$ quarters) are more important for "Agriculture, Forestry and Fishing" (22.7%), and "Manufacturing" (21.4%). For retail trade, they account for 3.2%, which indicates their insignificant impact on the trend of foreign economic activity development. Short-term cycles ($T = 10.3/9/6.5$ quarters) have a strong influence on retail trade (10.8%). In "Agriculture, Forestry and Fishing", and "Manufacturing" they have an average influence on the trends of foreign economic activity development 15.1 and 6.7%, respectively).

Task 3.2: Identification of cycles and points of crisis in the development of priority TEAs and the country's economy. The study calculated theoretical/model values of the cycle components to identify cycles and crisis points in the development of priority TEAs (Fig. 11-13). Step 1: Agriculture, Forestry and Fishing (Fig. 11). Step 2: Manufacturing (Fig. 12). Crisis phenomena in agriculture began to form from the Q2 of 2001, which characterises the descending stage of the cycle with the point of local minimum in the 18th period (Q2 2005). The period of the 18th period – 38th period (Q2 2010) reflects the period of the global crisis, after which the trend of development of foreign economic activity gradually moves to the stage of ascending development.

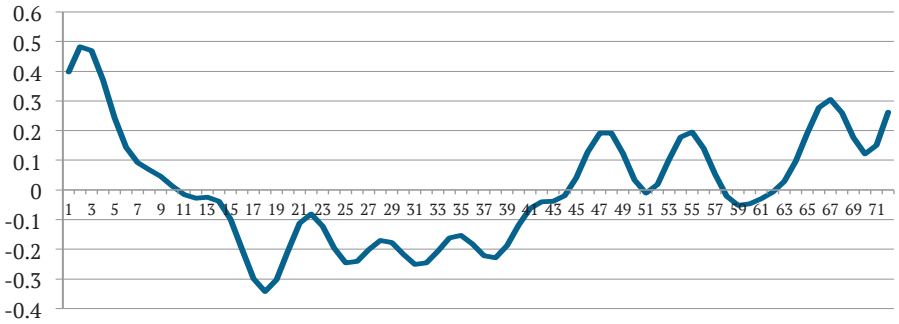

Figure 11. Cyclic component for the "Agriculture, Forestry and Fishing"

Source: calculated by the authors

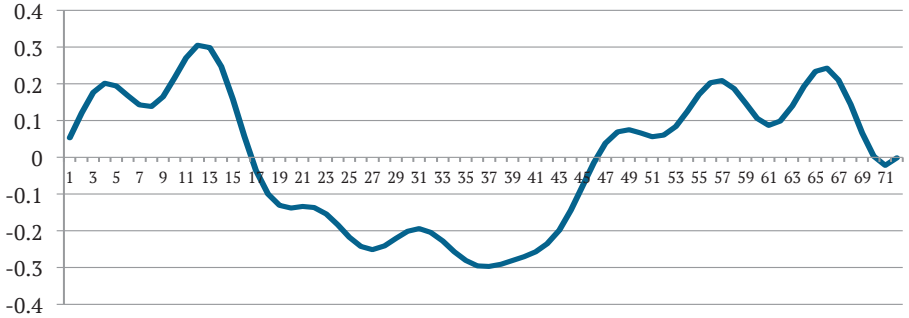

Figure 12. Cyclic component of the "Manufacturing"

Source: calculated by the authors

Crisis phenomena in the industry began to form from the 14th period (Q2 2004) and reached a local minimum point in the 37th period (Q1 2010). Then the TEA moved to the ascending stage of development, which continued until the local maximum point in the 67th period (Q3 2017), where the trend changed. The TEA moved to the descending stage of development. Step 3: Wholesale and Retail Trade; Repair of Motor Vehicles and Motorcycles (Fig. 13).

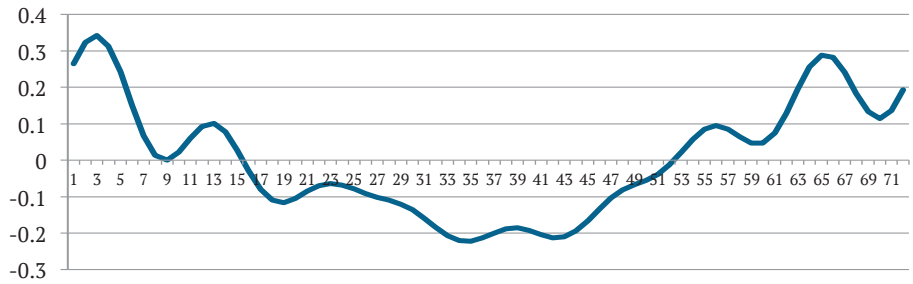

Figure 13. Cyclic component of the "Wholesale and Retail Trade; Repair of Motor Vehicles and Motorcycles"
Source: calculated by the authors

The deterioration of the situation in the TEA began in fourth period (Q1 2002) and continued until 34th period – the point of local crisis, which corresponds to Q2 2009. From periods 34 to 43, an unstable trend in the development of the TEA was observed, which then moved to an ascending stage of development. The global crisis for this TEA covers periods 19-43 (Q3 2005-Q3 2012) and is the longest among priority TEAs. Thus, the analysis of cyclical components shows similar trends in long-term and short-term cycles. This is determined by the wave nature of economic activity and the similar nature of the development of priority foreign economic activities within the national economy.

Task 3.3: Construction of a system of short-term adaptive forecasting models. Force majeure conditions of military aggression from Russia provoked significant destructive changes in the development of all TEAs. This required the use of adaptive methods of short-term forecasting in the study. Several model experiments were conducted in the software Statistica 13.0 and, according to the criterion of minimising the MAPE value, models for forecasting GVA for priority TEAs were built (Table 6).

Table 6. Results of the construction of forecast models

The name of the TEA	Model	MAPE	Forecast value			
			Q1 2023	Q2 2023	Q3 2023	Q4 2023
Agriculture Forestry and Fishing	Model with a seasonal component and no trend	2.40	44,253.8	72,224.5	300,731.5	203,023.3
Manufacturing	Model with a seasonal component and no trend	1.39	87,002.3	108,375.5	110,078.6	113,832.6
Wholesale and Retail Trade; Repair of Motor Vehicles and Motorcycles	Model with a seasonal component and no trend	2.37	138,448.2	154,232.1	177,885.1	191,067.4

Source: calculated by the authors

Task 3.4: Identifying economic crisis points. Figures 14-16 show graphs of actual and forecast values of the gross value added indicator for priority TEAs. Analysis of the obtained dynamics allows to conclude that the most sensitive to external fluctuations in foreign economic activity is "Agriculture, Forestry and Fishing". Figure 14 shows that since 2014, "Agriculture, Forestry and Fishing" had high volatility of the indicator values and a gradually increasing range of its values. The forecast values support the formed trend, but the range of values is decreasing. "Agriculture, Forestry and Fishing", due to the preferences opened by Europe for Ukraine, is at a weak ascending stage of its development and is a source of replenishment of the country's budget.

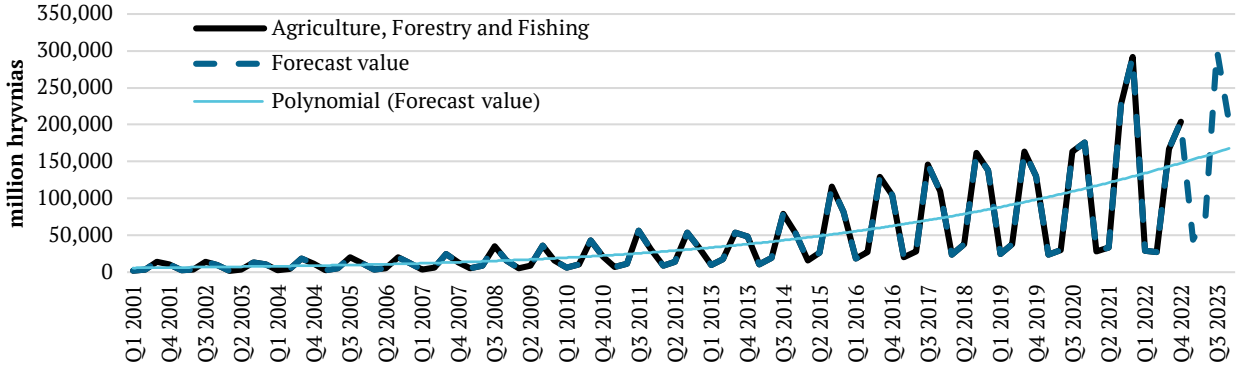

Figure 14. Forecast model of GVA "Agriculture, Forestry and Fishing"
Source: calculated by the authors

"Manufacturing" (Fig. 15) has always been a key source of budget replenishment before Russia's aggression against the eastern regions of Ukraine, where the country's industry is concentrated.

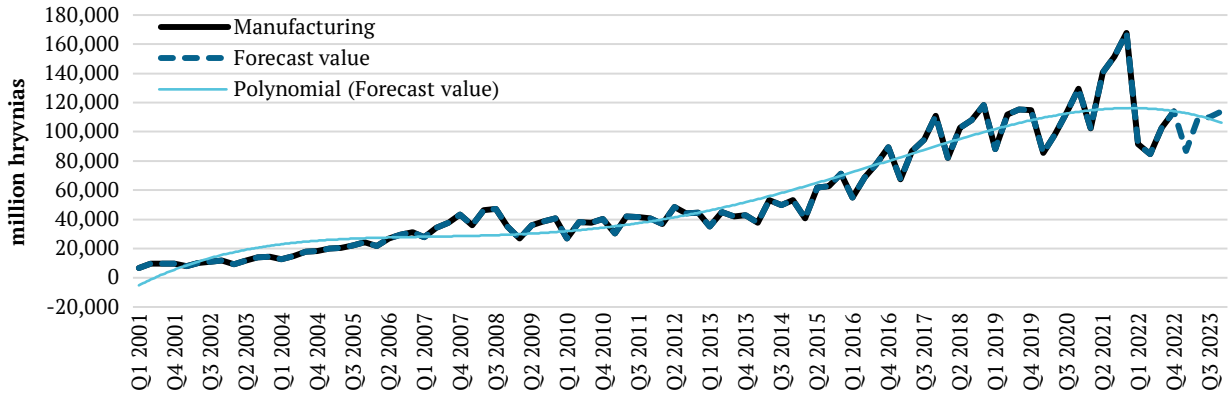

Figure 15. Forecast model of GVA "Manufacturing"
Source: calculated by the authors

The forecast of GVA "Wholesale and Retail Trade; Repair of Motor Vehicles and Motorcycles" (Fig. 16) shows a decrease in the indicator values, but no clear trend reversal is observed. This TEA is in the fluctuation zone and its further development will be associated with changes in the economic situation in the country.

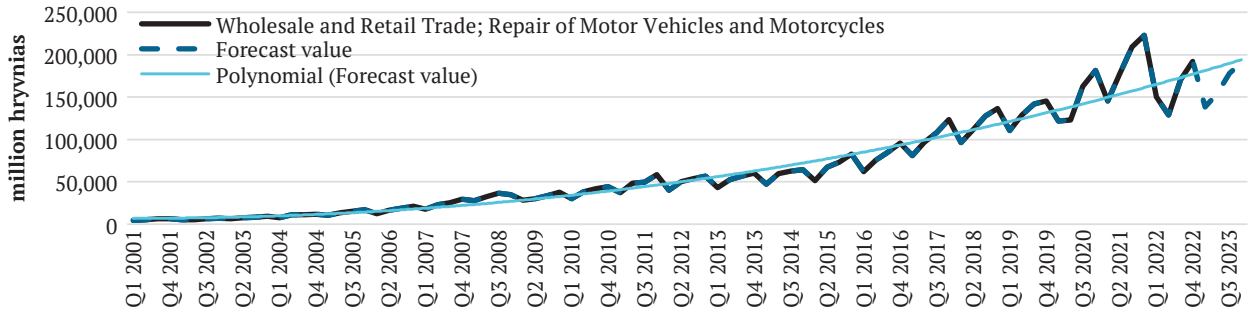

Figure 16. Forecast model of GVA "Wholesale and Retail Trade; Repair of Motor Vehicles and Motorcycles"
Source: calculated by the authors

This TEA has a high growth rate until the Q4 2021, which characterises it as low-sensitive to economic fluctuations and political changes. Starting from the Q1 2022, these rates began to decline significantly. Manufacturing entered a stage of downward development, which was provoked by the military conflict.

Stage 4. Scenarios development for the cyclical changed in TEAs and the country's economy

Analysis and forecasting of the nonlinear nature of the development of economic processes in the country is a strong signal for the development of strategy and tactics of the behaviour of agents of economic relations in the market. Therefore, the study developed 2 main scenarios – normal and force majeure for the development of the country's economy and its main types of activity. Task 4.1: Scenario of normal economic development. At Stage 2 and Stage 3 of the conceptual model (Fig. 1), three priority TEAs that determine the development of the national economy were identified, and a set of models of their cyclical behaviour is developed. Therefore, to understand the cyclical nature of the development of the economy as a whole, it is necessary to combine these models into one (Fig. 17).

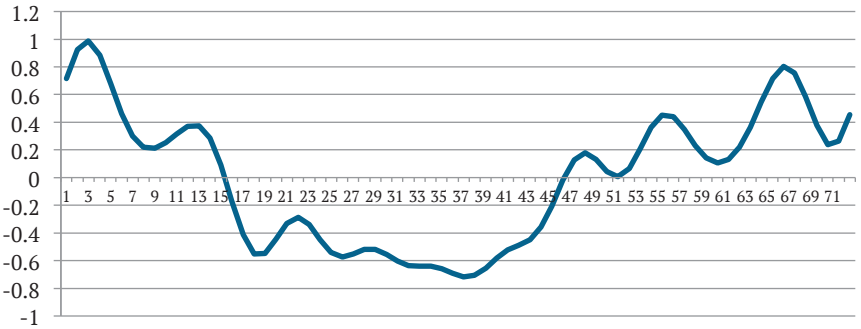

Figure 17. Combination of the cyclic components of the three investigated industries
Source: calculated by the authors

The analysis of the dynamics of Figure 17 allowed to propose three main scenarios for managing the national economy. "Support" scenario: this scenario begins to be implemented in the event of a decrease in the values of the national economic activity indicator. To slow down the rate of decline and stabilise the trend of the indicator, it is necessary to use measures to support the national economy. It is important that if a trend of a significant decline in the national economic indicator has formed, it is necessary to introduce measures to stabilise the development of priority TEAs since they make a significant contribution to the country's budget. In this case, a synergistic effect of the interaction of TEAs occurs, which will stabilise the general state of the macroeconomic system. Examples of such compensatory measures are an increase in government procurement; the formation of a preferential complex for industry; protection of foreign economic activity from imports, etc.

"Crisis" scenario is a scenario for periods of global crises in economic activity. It is advisable to implement this scenario at a point of low development – at a bifurcation point. In such a state, the economy cannot overcome the crisis on its own, so it is important to develop various actions to reverse the crisis trends and shorten the crisis period. An important tool in this scenario is subsidising TEAs, supporting them with various legislative initiatives, and creating conditions for activating the functioning of business entities.

"Growth" scenario is used during periods of upward trends in economic activity and is aimed at creating conditions for increasing the growth period and preparing for the trend reversal point. This scenario requires actions related to non-interference in the development of economic systems, creating conditions for stimulating growth. These government initiatives will increase the period of sustainable development of enterprises and, as a result, change the period of occurrence of the bifurcation point in the macroeconomic cycle and create prerequisites for the formation of a new upward trend. This period provides an opportunity to prepare for a new positive crisis and create a basis for a higher cycle of economic development, bypassing the decline stage. Based on the research results, a timeline for various scenarios was developed (Fig. 18).

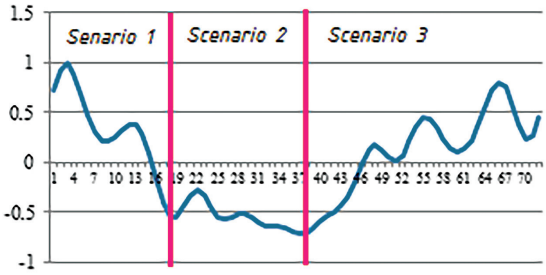

Figure 18. Timeline of the normal economic development scenario
Source: calculated by the authors

Scenario 1 ("Support" scenario) should be used from the first to the 18th period, Scenario 2 ("Crisis" scenario) should be used from the 19th to the 38th period, and Scenario 3 ("Growth" scenario) should be used from the 39th to the end. The third scenario is the longest scenario in the study. Based on the developed timeline, starting from the 68th period (Q4 2020), the economy will move to Scenario 1, which requires state support for key TEAs. This will prevent the emergence of a systemic crisis in the country's economy and will create conditions for shortening the period of economic decline.

Task 4.2: Scenario for economic development in force majeure conditions. An analysis of the contribution of the dominant TEAs (Fig. 6) and the forecast values of their GVA (Fig. 14-16) allowed to formulate the following development scenario. For "Wholesale and Retail Trade; Repair of Motor Vehicles and Motorcycles", the turning point of the trend from ascending to descending (the point of negative crisis) corresponds to Q1 2022. These TEAs are highly sensitive to force majeure circumstances. But, the reasons for such sensitivity are different. Thus, for "Manufacturing", this is the conduct of active military actions in eastern Ukraine, where the country's industry is concentrated; for "Wholesale and Retail Trade; Repair of Motor Vehicles and Motorcycles", this is a sharp drop in the purchasing power of the population, caused by its movement both within and outside the country, loss of sources of income.

For "Agriculture, Forestry and Fishing", the GVA values decreased, but there was no trend reversal. This foreign economic activity is at the stage of weakly ascending development due to the assistance of the European and world community. However, the force majeure situation associated with the war contributes to the threat to global food security, for example, due to the blockade of Ukrainian ports or interruptions in the supply of mineral fertilizers and fuel. This requires solutions that go beyond the economic or trade policy agenda. In particular, the financial capacity of both the domestic government and international partners may not be sufficient in the short term to ensure Ukraine's economic recovery. Therefore, it is important to ensure the most favourable conditions for the development of the private sector, which would help generate and attract private capital to overcome the economic consequences of the war.

The question of the temporary nature of the change in the sensitivity of individual TEA to crisis phenomena remains open. In the authors' opinion, to solve this problem, it is necessary to combine crisis diagnostics with the identification of specific factors that provoke its onset. The task of managing the economic situation in order to overcome crises is interesting. The study proposed to focus attention on three system-forming TEAs, namely to analyse the trends of their non-linear development taking into account the maximisation of their GVA contribution to the country's GDP. According to Hypothesis 3, it has been proven that the significant contribution of these TEAs to the country's budget requires primary attention to the trends of their development by the state, the identification of crisis points that arise in them provokes the emergence of a general economic crisis.

The novelty of the article is the justified application of different classes of models for the formation of two scenarios of the behaviour of economic systems – in the case of standard development and in the presence of force majeure circumstances. In the standard development scenario, spectral analysis methods were used, for force majeure circumstances, adaptive forecasting methods were used, which allowed to increase the prognostic quality of

models in conditions of high level of unpredictability of the behaviour of the external environment in the future. The use of such a combination of methods allowed to confirm Hypothesis 2. That is, the occurrence of crisis points in a stable economic process is expedient to forecast by building models of the cyclical component and determining the dominant harmonics; if the process is inherently fluctuating, then it is proposed to use adaptive methods to determine future crisis points, where the adaptation parameter makes it possible to take into account fluctuating fluctuations that do not correspond to the evolution of the economic process. Thus, the obtained results fully confirmed the hypotheses formed in the study and made it possible to develop corresponding scenarios for the nonlinear development of macroeconomic processes. This is the basis for managing the enterprise's behaviour, which must adapt to the variability of the market environment.

DISCUSSION

The source of such attention to this problem by scientists and practitioners is the high level of dynamism and unpredictability of market processes, which is caused by the existence of global markets. Questions such as the choice of the indicator space of analysis, the justification of the feasibility of applying economic and mathematical methods of forecasting nonlinear processes, the creation of support systems and decision-making based on the results of determining the future trends of the development of processes – these are the main problems of scientific and practical research and research. The article reflects the author's approach to solving these problems. The results of studies of the main indicators of the development of the national economy made it possible to determine the wave nature of the course of macroeconomic processes, which is confirmed by the corresponding developments by the P. Adair & O. Nezhyvenko (2021) and C. Li (2024). Although the authors considered cyclicality more from a theoretical point of view, this made it possible in the current research to put forward a hypothesis about the presence of cyclicality in the indicators under study, which was successfully proven.

A. Brandt & S. Manzoni (2020) investigated the use of the Fourier transform as the main tool of spectral analysis. This transformation has become a set of mathematical tools for research. With the help of this transformation, harmonics were obtained, which represent local cycles with different lengths and amplitudes, which allowed to study short-term and long-term cycles in TEAs. The different periodicity of harmonics in their additive composition allows to construct an analytical function that can be used to predict the cyclical component of the development of the national economy. The study has proven this nonlinear nature, which allowed to analyse the long-term and short-term components of economic development and develop effective development scenarios.

O. Dobrovolska *et al*. (2024) studied the dynamics of the Ukrainian economy and proved that the uneven growth of the Ukrainian economy in the short term was shaped by shocks of external conditions, and in the medium term by institutional economic cycles, which, in turn, influenced the formation of the long-term trend of the development of domestic commodity production. This allowed the study to consider the cyclical component in this research as one that forms shocks for the scenarios of the development of the economic system. Unlike S. Bosi & T. Ha-Huy (2024), who observed the emergence of cycles and their negative impact on the reproduction processes in the case of describing such processes in the form of a logistic law, the current work proved the presence of cycles in the main macroeconomic processes, and that cyclicality is not a negative factor of reproductive processes. Cyclicality within the framework of the authors' study is a natural process of development of socio-economic phenomena, which can have both a crisis component and a growth component.

The obtained results of the study of fluctuations in the national economy fully correlate with the results of the study by G. Petrakos *et al*. (2023), who noted in their work that there is a high correlation between the quality of governance and economic growth. It should be noted that there is a strong causal relationship between the quality of governance and economic growth and a weak relationship in the opposite direction. R.K. Fair (2025) covered a wide range of indicators and factors, including inflation and unemployment, the magnitude of wealth effects, the behaviour of the Federal Reserve and its impact on the economy, the impact of fiscal policy, Okun's law, as well as contractions and expansions. This work is a continuation of research in the field of forecasting the macroeconomic state of the national economy. The study proved this non-linear nature, which made it possible to analyse the long-term and short-term components of economic development. Also, within the framework of the study, the TEAs that make a significant contribution to the national economic development of the country were identified and studied, which made it possible to form various scenarios for the development of TEAs and the national economy and propose measures to improve the economic situation. Similar studies were conducted within the framework of the studies of I. Sievidova *et al*. (2024), who considered the logic of modelling economic reforms and their impact on the development of Ukraine in the context of transformation processes. In addition, the authors considered various scenarios for increasing the rationality of modelling in the structure of transformation processes of the national economy. All this confirms the relevance of the research topic and the homogeneity of the areas of scientific research.

The study of the cyclical component was carried out using spectral analysis. Researchers such as E. Ahmadova (2021) modelled the economy of Azerbaijan using spectral analysis. In the authors' opinion, one of the most important aspects in the study of structural economic systems is not only modelling each indicator but also considering it in the context of cointegration with other macroeconomic factors. Therefore, in the future, it is important to use cross-spectral models to study the relationship of macroeconomic processes. An important feature of the studies of these authors is the use of wavelet analysis functions, which, unlike classical spectral analysis, can determine aperiodic functions. But in this case, this is a contradiction to the essence of the cyclical component, since the cycle has a certain frequency and amplitude, and in wavelet analysis, the wave has a variable frequency. J. Babirath *et al*. (2020) used spectral analysis to forecast stock price dynamics. An important condition for using this tool is the absence of stochasticity in the studied series. Therefore, the issue

of using the expansion of a stationary series into a Fourier series remains debatable, since a stationary time series should not contain dependencies on previous periods. The cyclic component is due to the wave nature and has a certain period of recurrence. In addition, with a decrease in the quantisation periods of the original time series, the influence of stochasticity increases, so spectral analysis is advisable to use with quantisation periods such as half a year, or a year. Of particular interest is the sensitivity of various TEAs to shock and crisis phenomena. The study showed that the definition of TEAs that react differently to crisis phenomena in the economy gives authorities an effective tool for forming measures to overcome the general economic crisis. That is, for example, TEAs with high sensitivity to the crisis should develop preventive decisions of a cardinal nature in advance to localise crisis phenomena, and TEAs with resistance to negative impacts can support further positive economic development. It is to solve this problem that cluster analysis is used in the study.

CONCLUSIONS

Based on the results of the research, it was proved that the country's economic system has a non-linear development, that is, there are economic fluctuations that are cyclical and fluctuating in nature. The cluster analysis model made it possible to identify the following TEAs as dominant: "Agriculture, Forestry and Fishing", "Manufacturing", "Wholesale and Retail Trade; Repair of Motor Vehicles and Motorcycles" and to justify their significant contribution to the country's GDP. The study of the time series of development of TEAs using the proposed tools allowed to determine the cyclical and fluctuation components of the development of the national economy, which confirmed Hypothesis 1.

The conducted analysis of the nonlinearity of the development of dominant TEAs showed their influence on the wave nature of the development of the national economy. Two main scenarios of nonlinear development of the economy and dominant foreign economic activities were developed: a scenario of normal development based on the use of spectral analysis; and a scenario of force majeure development using adaptive forecasting methods. Spectral analysis of the time series of dominant economic activities showed that their dynamics include long-term, medium-term, and short-term cycles. The use of spectral analysis and such decomposition into cycles of different lengths and amplitudes allowed to identify bifurcation points, which proved the proposed Hypothesis 2. Based on this, three main scenarios for managing the national economy under normal conditions were developed, namely, a support scenario, a crisis scenario, and a growth scenario. It was determined that the economy would be at the stage of weakly downward development, which suggests the use of a support scenario for its development.

Analysis of the development of cyclical components using spectral analysis showed the formation of cointegration effects when cyclical components at the resonance of crisis points intensify the general economic crisis, which allowed to confirm Hypothesis 3 regarding the nature of crises in the development of the national economy. In the force majeure conditions of military aggression, the stages of the development cycle of dominant foreign economic activities were determined, and bifurcation points were found for "Manufacturing" and "Wholesale and Retail Trade; Repair of Motor Vehicles and Motorcycles", which corresponds to Q1 2022. Further studies of the analysis and modelling of the behaviour of the country's economy lie in the classification of crises and the determination of specific factors that provoke their occurrence; determination of TEAs' sensitivity to different types of crisis phenomena; application of variance analysis to diagnose the mutual influence of non-linear development of the individual TEA.

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CONFLICT OF INTEREST

None.

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Аналіз коливань у національній економіці: моделі та сценарії розвитку

Анотація. Метою дослідження було проаналізувати перспективи розвитку української економіки з урахуванням циклічності та коливань економічних процесів, які спровоковані як еволюційними тенденціями, так і коливаннями форс-мажорних обставин. Побудова моделі кластерного аналізу дала змогу визначити пріоритетні види економічної діяльності та довести значущість їх впливу на економічний розвиток країни. Аналіз тенденцій розвитку економіки та її пріоритетних видів економічної діяльності досліджено для двох періодів розвитку: нормального та форс-мажорного. Дослідження показало, що економічні процеси в країні мають нелінійні траєкторії розвитку. Тому для прогнозування розвитку економіки країни використовувалися метод спектрального аналізу та метод адаптивного прогнозування. Аналіз нелінійності розвитку пріоритетних видів економічної діяльності показав їх вплив на хвилеподібний характер розвитку національної економіки. «Сільське, лісове та рибне господарство», «Переробна промисловість» та «Оптова та роздрібна торгівля; Ремонт автотранспортних засобів і мотоциклів» були визначені як найбільш домінуючі види економічної діяльності за результатами кластерного аналізу. Аналіз розвитку циклічних складових за допомогою спектрального аналізу підтвердив існування коінтеграційних ефектів, коли циклічні компоненти в резонансних точках кризи посилюють загальноекономічну кризу. Визначено локальні точки біфуркації як кризові точки національної економіки та доведено, що вони спровоковані економічними коливаннями її пріоритетних видів економічної діяльності. У результаті було розроблено три основні сценарії управління національною економікою – сценарій підтримки, сценарій кризи та сценарій зростання; для кожного сценарію розроблено загальні рекомендації щодо регулювання національної економіки

Ключові слова: види економічної діяльності; цикл; часові ряди; адаптивна модель прогнозування; сценарій розвитку

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Study of priority directions of economic recovery of Ukraine based on scenario modelling

Abstract. Determining the strategy of Ukraine's economic recovery in the post-war period is relevant, as it affects its sustainable development, attracting international aid and ensuring long-term economic growth. The purpose of the article was to identify the key factors that could determine the intensity of economic recovery, as well as the construction and evaluation of possible scenarios for the development of Ukraine after the end of the "hot" phase of the war. Non-parametric regression tools (spline functions) were used to study the peculiarities of the development of the economy of Ukraine. It was established that the development of the economy of Ukraine took place with a slowdown. The expediency of using scenario modelling in conditions of high uncertainty of Ukraine's development prospects was substantiated. Based on the SWOT analysis, the strengths and weaknesses of Ukraine's economy were determined as prerequisites for

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its renewal in the post-war period, and the key factors were highlighted, namely the level of international support for Ukraine (possibility of its reproduction); institutional environment (efficiency of economic reproduction). Four scenarios for the recovery of Ukraine's economy in the post-war period were constructed. The probability of their implementation was estimated. It was determined that the "Slow development" scenario is the most likely, which involved the formation of a "stimulating" institutional environment with a decrease in international support. Such an institutional environment should contribute to the reindustrialisation of the economy, increasing its competitiveness, eliminating current structural imbalances, developing institutions for financing scientific research, investment, and innovation activities, as well as increasing domestic demand. The development of industry should be based on the need to transition to the sixth technological system, which involved significant investments in the intellectual capital in the development and implementation of innovative technologies. The results of the conducted research could be used by state authorities when developing priority directions for the economic recovery in Ukraine

Keywords: post-war period; strategy; development; key factors; strengths and weaknesses

INTRODUCTION

The scientific community faced the need to solve the problem of assessing the socio-economic consequences of the war, which began in the centre of Europe in February 2022 with the full-scale invasion of the Russian Federation into Ukraine. Experts of the World Bank, J.-D. Guénette *et al*. (2022), noted that the war, in addition to the large humanitarian crisis in the region, the devastation of Ukraine's economy, caused "global ripple effects" that covered commodity markets, trade, and global financial flows, as a result of which uncertainty and geopolitical tensions are growing. This war also led to a slowdown in the world economy and an increase in global inflation. In addition, it led to increased food prices, disruption of supply chains. Experts such as N. Legrand (2023) expressed concern that the prolongation of the war could lead to a global food crisis and become an obstacle to the achievement of certain sustainable development goals. Therefore, ending the war and restoring the economy is an urgent problem for Ukraine, not only as a separate state but also as a component of the world economy. The problem of determining strategic directions for the recovery of Ukraine's economy after the end of the "hot" phase of the war needs to be solved now, since the renewal process is successful only if it is scientifically based and carried out systematically and purposefully.

The Ukrainian economic recovery is not an easy process, since, even before the start of the war in 2014, the Ukrainian economy needed structural restructuring in order to harmoniously integrate into the world economy. Thus, L. Malyarets *et al*. (2024) noted that Ukraine has a low level of structural dynamics of stable development. The military actions in the East and South of Ukraine led to the significant destruction of the old industrial regions, as a result of which it was impossible to focus on them as centres of recovery of the economy and the country as a whole. Economic recovery occurs in conditions of increased uncertainty. That is determined by various factors, the main ones of which are the following: the timing of the end of the "hot" phase of the war, the line of demarcation with the Russian Federation, the localisation and extent of the destruction of industrial infrastructure, the amount of available financial resources, etc.

The study of the problem of economic recovery was in the centre of attention of leading Ukrainian scientists since the beginning of the Russian military aggression against Ukraine in 2022. Thus, I. Pidorycheva (2022) analysed the experience of recovery of European countries after the Second World War and noted that the economic recovery should begin with structural transformation and include a transition to an industrial and innovative type. At the same time, Ukraine as a state should take the initiative in creating a high-tech digital Industry 4.0 and defend national interests. Investments, and especially innovations, could become a source of economic growth in the post-war period and stimulate the creation of new jobs, increase the productivity and competitiveness of Ukrainian industrial enterprises. This contributes to the development of related sectors of the national economy, as highlighted by M. Berdar *et al*. (2024). At the same time, Ukraine has significant systemic problems with the attraction of foreign capital, approaches to the solution of which should be determined even before the end of the war.

Particular attention was also paid to the definition of financing mechanisms for the economic recovery in Ukraine. Thus, M. Kocherov *et al*. (2023) noted that international financial assistance and foreign investment contributes to a rapid and sustainable economic recovery. Researchers emphasised that the success of the country's post-war recovery depends on the efficiency of the economic system and its ability to attract investments. At the same time, the war has a negative impact not only on the Ukrainian economy but also on global economic growth, which, according to I. Irtyshcheva *et al*. (2022), leads to a decrease in the possibility of attracting foreign investments for the reconstruction of Ukraine after the end of hostilities. N. Prykaziuk *et al*. (2023) pointed out that the national financial sector is characterised by significant macro-financial and macroeconomic disparities, which can negatively affect the development of the financial sector in the post-war period and the possibility of economic recovery as a whole. However, the problem of determining strategic directions for the reconstruction of Ukraine's economy, determining the factors that affected its effectiveness, remains unsolved. Therefore, the purpose of the conducted research was to determine the key factors (key uncertainties, KUs) that determined the intensity of economic recovery, as well as the construction and evaluation of possible scenarios for the development of Ukraine after the end of the "hot" phase of the war.

MATERIALS AND METHODS

The determination of the strategic directions of the post-war recovery of Ukraine's economy was based on the study of the peculiarities of its development. The use of spline

functions allowed to ensure high accuracy of approximation without increasing the degree of the polynomial used to describe the dynamics of the process and to have the possibility of a meaningful interpretation of the obtained results. Splines allowed avoiding the occurrence of "waves" and "false cyclicity" in the case of polynomial approximation, which do not exist in the dynamics of a real economic process. Mathematical splines were "segments" of power polynomials of low orders that described the dynamics of the process between nodal points. At the same time, the splines converged at the nodal points (nodes of the "lattice" function).

Then the function $F(t)$ defined and continuous on the segment $[T_1, T_2]$ was a polynomial spline of order m with nodes $t_j \in (T_1 \leqslant t_0 < t_1 < \cdots < t_n \leqslant T_2)$, if on each of the segments $[t_{j-1}, t_j)$, $F(t)$ was an algebraic polynomial of degree not exceeding m, and at each of the points t_j the derivative $F^{(v)}(t)$ could have a discontinuity. The parameters of the algebraic polynomials of the spline function had to have a meaningful interpretation, so their order did not exceed 2 ($m = 2$). That allowed to analyse the speed and/or acceleration (deceleration) of changes in the investigated process. Before calculating the spline function, it was necessary to eliminate the influence of random factors on the dynamics of product output. This led to the feasibility of pre-processing the data using exponential smoothing, which allowed for a smoothed series that reflected major trends and patterns while reducing noise (Liu & Wu, 2020). Exponential smoothing involved updating the smoothed value based on the weighted average value of the current observation and the previous smoothed value according to the recurrent formula:

$$S_t = \alpha y_t + \beta S_{t-1}, \quad (1)$$

where S_t is the value of the exponential average at time t; y_t is the actual value of the indicator at time t; α is the smoothing parameter, $\alpha = const$, $0 < \alpha < 1$; $\beta = 1 - \alpha$. The smoothing parameter α showed how much weight was given to the most recent observation. The choice of the parameter α was problematic, since to increase the weight of more recent observations, α should be increased, but to smooth out random fluctuations, the value of α should be decreased. These two requirements were in conflict, so the problem of the compromise value of the smoothing parameter α was a problem of model optimisation. In this study, α was taken at the level of 0.3, which allowed to consider the inertia of the development of the economy of Ukraine and reduce the influence of random factors. At the same time, $S_0 = y_0$.

To study product output dynamics using a spline function for the period 2000-2021, the years 2000, 2007, 2009, 2013, 2016 and 2021 were defined as nodes (Minfin archive..., n.d.; State Statistics Service of Ukraine, n.d.). The study did not use data for the year 2022, because in that year there was a sharp decrease in product output due to the full-scale military aggression of the Russian Federation against Ukraine. Scenario modelling as a method of future research involved the comprehensive use of research methods. To determine the factors that determined the effectiveness of the Ukrainian economy recovery and its strategic directions, an analysis of the external and internal environments was conducted. For that, a SWOT analysis was used, which allowed for the identification of a set of factors that determined the dynamics of the researched process. Determination of KUs as a basis for developing scenarios for the Ukrainian economy recovery, a theoretical generalisation of empirical information was used. The development of scenarios, which served as a description of the results of the impact of the KUs, was carried out by combining their positive and negative alternatives. For each scenario, the probability of their implementation was assessed, as well as the possibility of Ukrainian economic recovery. This allowed identifying priority directions of recovery to ensure its effectiveness in conditions of high unpredictability.

RESULTS AND DISCUSSION

As could be seen from Figure 1, during the years 2000-2022, product output in Ukraine was uneven. Its description is described by the following spline function:

$$F(t) = \begin{cases} F^1(t) = -4{,}422.0t^2 + 8{,}881.9t + 84{,}085.0, \text{for } t \in [2000{,}2007), \\ F^2(t) = -5{,}708.5t^2 + 7{,}789.0t + 296{,}459.0, \text{for } t \in [2007{,}2009), \\ F^3(t) = -4{,}523.9t^2 + 62{,}923.0t + 204{,}907.0, \text{for } t \in [2009{,}2013), \\ F^4(t) = 28{,}318.0t^2 - 207{,}640.0t + 581{,}675.0, \text{for } t \in [2013{,}2016), \\ F^5(t) = 910.9t^2 + 34{,}520.0t + 164{,}722.0, \text{for } t \in [2016{,}2021], \end{cases} \quad (2)$$

where $F^1(t)$, $F^2(t)$, $F^3(t)$, $F^4(t)$, $F^5(t)$ are polynomials of the second order that describe the dynamics of production in Ukraine by separate segments. For the defined components of the spline function, the coefficient of determination ranged from 0.9465 to 0.9999, which confirmed its statistical reliability. The coefficients of polynomial splines of low degrees had a meaningful interpretation. Thus, the coefficient at t characterises the rate of change of the indicator or process, and at t^2 – the acceleration (deceleration) of these changes. Thus, during 2000-2021, even in the "prosperous" periods of the development of the economy of Ukraine (2000-2007, 2009-2013), growth occurred with a slowdown, and in the period 2013-2016, the decrease occurred with acceleration. The situation improved in the period 2016-2021, during which growth accelerated. That indicated the low efficiency of management of the development of the Ukrainian economy. Maintaining such a trend does not allow the economy to be effectively restored after the end of the "hot" phase of the war. That allowed determining the strengths and weaknesses of the Ukrainian economy as a prerequisite for its recovery after the war (Table 1).

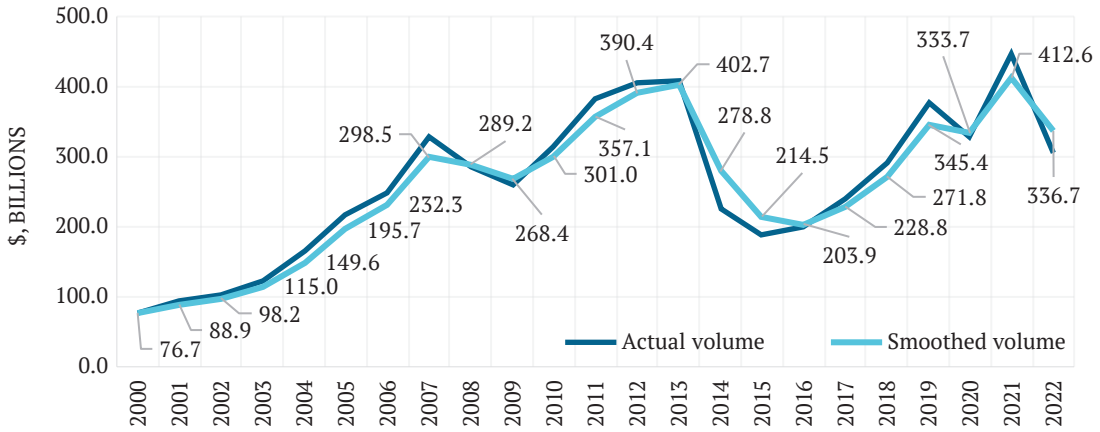

Figure 1. Change in product output at market prices in Ukraine, 2020-2022, USD
Source: created by the authors based on Minfin archive of exchange rates (n.d.), State Statistics Service of Ukraine (n.d.)

Table 1. SWOT analysis of prospects for economic recovery in Ukraine

Strengths	Weaknesses
1. Advantageous geographical location. 2. High resource potential. 3. Developed transport infrastructure. 4. Close cooperation with international institutions. 5. Relatively high quality of secondary technical and higher education. 6. Highly motivated people.	1. Military actions and occupation of more than 25% of the territory. 2. Technological backwardness of the main industries. 3. Ruined economy and large-scale destruction of infrastructure. 4. High dependence on imports. 5. Low competitiveness of the main sectors of the economy. 6. Lack of balanced state policy and effective regulation in the field of innovative activity. 7. Outflow of qualified personnel.
Opportunities	**Threats**
1. Strengthening cooperation with the EU and integration into the European market. 2. Growth of investment attractiveness. 3. High innovation potential. 4. Potential capacity for cooperation of research and production sectors. 5. Availability of information about NTP achievements. 6. Development of a "green" economy and transition to renewable energy sources. 7. Implementation of digital technologies. 8. Sufficiently high capacity of the domestic market.	1. Prolongation of the "hot" phase of the war in Ukraine and/or its spread to the territory of other European countries. 2. Uncertainty of developed countries regarding the degree of aid to Ukraine. 3. Deepening of global crisis phenomena. 4. Impact of hybrid threats. 5. High competition on the world market and significant entry barriers for Ukrainian businesses from transnational corporations. 6. Climatic changes. 7. Political and social instability in the country.

Source: created by the authors based on G. Mazhara *et al*. (2023), D. Melnychuk *et al*. (2023), Prohorova *et al*. (2024)

However, it is worth mentioning that strengthening cooperation with the EU, attracting international investments, realising innovative potential, implementing digital technologies, and developing a "green" economy can create potential opportunities for economic recovery. The realisation of these opportunities can be negatively affected by both the prolongation of the "hot" phase of the war in Ukraine and the associated political and social instability and the deepening of crisis phenomena in the world economy, as well as the emergence of new threats, in particular hybrid ones. On the basis of the results of the SWOT analysis, two complex KUs were identified, which determined the prospects for the recovery of the Ukrainian economy in the post-war period. KU1: the level of international support (political, economic, and financial) of the Ukrainian economy, which shaped the possibilities of its recovery. KU2: the country's institutional environment, which determined the efficiency of economic recovery. For each KU, two implementation alternatives were defined. As a positive alternative for KU1, the preservation or growth of international support, primarily financial; as a negative alternative – a decrease in international support.

Special attention was paid to the analysis of KU2, since Ukraine as a state is most interested in economic recovery, ensuring its competitiveness, and improving the quality of life of the population. As a positive alternative for KU2, the creation of such an institutional environment in Ukraine that would stimulate the reduction of the impact of inertial trends in the economy and the growth of the impact of acceleration factors was considered. That involved not only positive economic dynamics of reproduction but also ensuring a high level of economic security and reducing the riskiness of activities, in particular investment and innovation. At the same time, attention should be paid

to the prevention and reduction of hybrid threats, which became key aspects of the security policy discourse in developed countries after 2014 (Bajarunas, 2020). Hybrid operations are of particular threat because they are usually well-prepared and can wreak havoc with artificial intelligence. The effect could be even more devastating if a coordinated hybrid operation, in addition to the financial and banking sectors, also affected critical infrastructure and supply chains.

The negative alternative of KU2 involves the preservation of the existing institutional environment, which can result in high transaction costs, which is a brake on the growth of economic activity in the country, a decrease in the level of economic security, and a deterioration of the adaptive capacity of the national economy. This contributes to the preservation of inertial trends in the economy and, as a result, the further growth of structural imbalances and the "collapse" of economic activity. In the Table 2 scenarios for the recovery of Ukraine's economy are given. The scenarios were developed by researching combinations of positive and negative alternatives of the identified key alternatives.

Table 2. Scenarios for the recovery of Ukraine's economy in the post-war period

		KU1 – Level of international support	
		Positive alternative – the preservation or growth of international support	Negative alternative – the reduction in international support
KU2 – Institutional environment in Ukraine	Positive alternative – the creation of a "stimulating" institutional environment	Scenario 1 "Intensive development"	Scenario 2 "Slow development"
		This scenario is considered as an optimistic option, since when it is implemented, it becomes possible to structurally restructure the economy of Ukraine at the expense of funds from international financial institutions due to the improvement of the investment climate and the introduction of innovative technologies.	When this scenario is implemented, there could be a slow recovery of Ukraine's economy, since its own financial resources could not be enough to ensure rapid economic growth, significant research and development, and high investment and innovation activity. Also, the consequence of the implementation of such a scenario is the further ageing of the population, a very slow increase in the standard of living, and the preservation of a high level of emigration to developed countries.
	Negative alternative – the preservation of the established institutional environment	Scenario 3 "Lost opportunities"	Scenario 4 "Economy 'liquidation'"
		This scenario should be considered as a negative option for the development of Ukraine after the end of the "hot" phase of the war. Due to the imperfection of the institutional environment and the high level of corruption, opportunities for structural restructuring of the Ukrainian economy and its integration into the world economy could be lost. It could also negatively affect the standard of living of the population, which will lead to the emigration of the economically active and most educated population.	This scenario is the worst option for the development of Ukraine after the end of the war. When it is implemented, there can be a rapid degradation of the economy of Ukraine, its social sphere, and, as a result, a significant emigration of the population.

Source: created by the authors

Evaluating the probability of realisation of the developed scenarios of economic recovery in Ukraine, it should be noted that the "Intensive development" scenario has a low probability of realisation, because then Ukraine will become a competitor on the world market. This is undesirable even for countries that are allies (blocking of Ukrainian borders by Polish farmers, for example (Shubravska *et al.*, 2024)). It is also estimated that the probability of the realisation of the scenario "Lost opportunities" due to crisis phenomena in the economies of the world's leading countries and the world economy as a whole is not high. I. Liadze *et al*. (2023) noted that in 2022, due to the war in Ukraine, global inflation increased by 2%, and in 2023 – by 1%. Germany, France, and Italy suffered the greatest economic losses, and GDP in "Developing Europe" shrank by 30 %. This directly affected their ability to provide financial support to Ukraine. Even now, in the conditions of military operations, which might expand to the territory of other European countries, there are statements about a decrease in financial support for Ukraine.

The implementation of the scenario "Economy 'liquidation'" was assessed as more likely. At the same time, a complete lack of international support for Ukraine's economy, primarily financial, is unlikely; most likely it might be insufficient. However, maintaining an institutional environment with high transaction costs will not allow obtaining high efficiency from the use of international aid. The most likely scenario is the "Slow development" scenario, which involves the formation of a "stimulating" institutional environment with a decrease in international support. Such an "improvement" of the institutional environment is supposed to be forced, dictated by the need for Ukraine's survival as a state.

As shown by I. Pidorycheva (2022) and N. Struk (2024), Ukraine as a state and its citizens are interested in the effective recovery of the economy, which is quite understandable. Therefore, attention should be focused on internal transformations, namely, the institutional environment on a stimulating one through the creation of effective institutions for the reindustrialisation of the economy, increasing its competitiveness, the development of institutions for financing investment and innovation activities, and the development of domestic demand for Ukrainian products, which is also supported by O. Herus (2024). It was determined that in order to prevent the realisation of negative scenarios of the economic recovery of Ukraine, the main emphasis should be placed on the elimination of structural disparities, the development of industry

considering the specifics of different regions of Ukraine, and the creation of new jobs.

When elaborating a strategy for the development of industry, it is necessary to base it on the need to transition to the sixth technological system, which involved the use of non-traditional sources and thermonuclear energy; development of biotechnologies, nanotechnologies, photonics, optoelectronics, artificial intelligence, micromechanics, quantum technologies, genetic engineering, space technologies; promotion of virtual enterprises and automatic factories, as well as strengthening of state regulation of socio-economic processes to ensure uniform development of all regions of the country. This could create a competitive economy. However, such a transition is impossible without the development of intellectual capital. Its most important component is highly qualified human resources, motivated by the results of work and able to adapt to changes in the external and internal environment. Such adaptation is possible only under the condition of constant accumulation and updating of knowledge, improvement of professional skills, which involved a wider implementation of the concept of continuous education throughout life.

The structural restructuring of Ukraine's economy, its innovative development, as well as the reconstruction of the destroyed social and economic infrastructure are impossible without significant investments. However, even under the most favourable conditions, there is a shortage of financial resources. To ensure the effective use of available resources, there should be strict state control over the directions of the use of these funds. It does not have a positive effect without the implementation of anti-corruption measures, which would provide for the real punishment of corrupt officials. In addition, a strategy to support scientific research aimed at the development and implementation of innovative technologies should be implemented.

In general, agreeing with the opinion of M. Różycki (2019), it is worth mentioning that in conditions of rapid and essential changes in the internal and external environment of the economic system, the manifestations of its inertia also undergo significant changes. The growth of uncertainty in the institutional environment increases the unpredictability of the manifestation of inertia in the economic system, which reduces the ability to assess the effectiveness of its recovery after partial or complete destruction. V. Navickas & V. Bačiulienė (2021) noted that inertia in economic processes manifests itself in changes in the efficiency of investments, the volume of innovations, labour productivity, and the efficiency of economic transformations; that is, it determines the possibility of acceleration (slowdown) of economic growth. It is worth mentioning that in Ukraine, the main factors of such economic inertia are the preservation of the structure of the economy, which was formed during the times of the former USSR; disparities in the national and regional economy; an underdeveloped institutional environment and, as a result, high transaction costs, which inhibit and complicate economic development; reduction of scientific and innovative potential due to insufficient funding; lack of financial resources for renewal of non-current assets of enterprises; and significant disparities in wages and low incomes of the population. One of the consequences of the Russian Federation's military aggression against Ukraine was the destruction of the stable structure of the economy, as well as changes in the institutional environment. This affected the volume of investments, their direction, and effectiveness.

V. Prokhorova *et al*. (2023; 2024) noted that the Ukrainian economy is assumed to be influenced not only by internal factors but also by world crises. This affects not only the volume of production but also the general dynamics of processes and their dynamics. In such a situation, as M. Ramli *et al*. (2020) noted, it is advisable to use non-parametric regression methods, namely spline functions. Splines allow processing of data whose trends ("behaviour") change at certain subintervals. The prospects for the Ukrainian economic recovery have a very high level of uncertainty, and the current trends in its development could be considered non-stationary, that is, those that were the result of distribution shifts and stochastic trends. Incorrect consideration of the dynamics of stochastic processes leads to the formation of potentially erroneous relationships. It is necessary to agree with the opinion of J.L. Castle *et al*. (2021) that non-stationary processes are difficult to model and predict using a simple selection of the equation that would "best" describe the dynamics of the process or using "hundreds of empirical fits and selecting a preferred one". This necessitated the use of more flexible analysis tools to substantiate the economic recovery strategy, considering the factors that could become its drivers or brakes.

O. Kravchenko (2020) noted that in conditions of high instability of the external environment and, as a result, the non-stationary character of the development of the economy, an effective method of analysis is scenario modelling. It allowed studying the prospects for the development of the economy with a possible change in the factors of its external and internal environment. Unlike classical methods, the results of scenario analysis related mainly to strategic aspects of development, which allowed analysing possible options for the Ukrainian economy's recovery and determining its priority areas. Summarising the above, it should be noted that the conducted study is consistent with the research of other scientists. The approach proposed by the authors allows for assessing the effectiveness of alternative options for Ukrainian economic recovery in the post-war period based on the level of international support and the characteristics of the institutional environment, considering the dynamics and changes in the inertia of economic processes.

CONCLUSIONS

On the basis of the conducted research, it was determined that during 2000-2021, the management of the Ukrainian economy was ineffective, which negatively affected the possibilities of its recovery while maintaining current development trends. Potential opportunities for Ukraine's economic recovery are being formed both in its external environment (cooperation with the EU, international investments) and within the country (use of innovative potential, introduction of digital technologies). Therefore, the KUs that determine the intensity of the Ukrainian economy recovery in the post-war period are the level of international support (political, economic, and financial) for the Ukrainian economy, which shapes the possibilities of its reproduction, and the country's institutional environment, which determines the effectiveness of economic

reproduction. The deepening crisis phenomena in the global economy necessitate the need to focus attention on the level of development of the institutional environment as a factor stimulating the reduction of the impact of economic inertia on the intensity of its development and ensuring the acceleration of its recovery.

The analysis of possible scenarios for the recovery of the Ukrainian economy showed that the most likely scenario is the implementation of a scenario that involves the formation of a "stimulating" institutional environment. This ensures economic recovery, considering the limited available financial resources, in particular received from international support. The main emphasis should be on the country's reindustrialisation, eliminating structural imbalances, and creating a competitive economy. The reindustrialisation strategy should focus on the transition to the sixth technological system, the implementation of a "green" economy, and the development of intellectual capital. In addition, funding for the development of innovative technologies should be a priority. Further research should be directed to the development of strategies for the development of individual regions, considering their characteristics and capabilities. It is also necessary to solve the problem of determining the optimal ratio between the amount of investment in the economic recovery of Ukraine and the social support of the population.

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CONFLICT OF INTEREST

None.

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Дослідження пріоритетних напрямів відновлення економіки України на основі сценарного моделювання

Анотація. Визначення стратегії відновлення економіки України після завершення війни є актуальним, оскільки вона впливає на її стійкий розвиток, залучення міжнародної допомоги та забезпечення довгострокового економічного зростання. Метою статті стало визначення ключових факторів, що визначатимуть інтенсивність відновлення економіки, а також побудова і оцінювання можливих сценаріїв розвитку України після завершення «гарячої» фази війни. Для дослідження особливостей розвитку економіки України було використано інструментарій непараметричної регресії сплайн-функції. Встановлено, що розвиток економіки України відбувався з уповільненням. Обґрунтовано доцільність використання сценарного моделювання в умовах високої невизначеності перспектив розвитку України. На основі SWOT аналізу визначено сильні й слабкі сторони економіки України як передумови її відновлення після завершення війни та виділено ключові фактори відтворення, а саме рівень міжнародної підтримки України (можливості її відтворення); та інституційне середовище (ефективність відтворення економіки). Побудовано чотири сценарії відновлення економіки України після завершення війни. Оцінено ймовірність їх реалізації. Визначено, що найбільш ймовірним є сценарій «Повільний розвиток», який передбачає формування «стимулюючого» інституційного середовища при зниженні міжнародної підтримки. Таке інституційне середовище має сприяти реіндустріалізації економіки, підвищенню її конкурентоспроможності, усуненню існуючих структурних дисбалансів, розвитку інститутів фінансування науково-дослідних розробок, інвестиційної та інноваційної діяльності, а також збільшенню внутрішнього попиту. Розвиток промисловості має базуватися на необхідності переходу до шостого технологічного устрою, що передбачатиме значні інвестиції в розвиток інтелектуального капіталу, в розробку і впровадження інноваційних технологій. Результати проведеного дослідження можуть бути використані органами державної влади під час розробки стратегії економічного відтворення України

Ключові слова: післявоєнний період; стратегія; розвиток; ключові фактори; сильні та слабкі сторони

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Analysing innovation performance in the context of economic development

Abstract. The purpose of this study was to analyse the key characteristics of innovation in selected European countries and, based on this analysis, to determine the correlation between investment growth in innovative solutions and the dynamics of national economic development. The study examined such indicators of innovation processes as the volume of human capital, the number of scientific publications, the degree of digitalisation, public and private investment in innovation, intellectual assets, and the export of knowledge-intensive products across several European countries. A regression analysis was conducted to identify patterns in the development of national economies. The study covered the dynamics of innovation activity in Europe between 2016 and 2023, which allowed for identifying key development vectors in specific countries and determining the dependence of economic growth on financial investments in new technologies and the speed of their implementation. The results showed that Belgium and Denmark exhibited the highest levels of innovation activity, significantly exceeding the EU average, particularly in digitalisation, human capital development, and research attractiveness. Germany and France demonstrated stable but moderate growth in innovation indicators, while countries such as Poland and the Czech Republic showed positive but slower trends. Conversely, Bulgaria and Turkey ranked among the least innovative economies in the region. A regression analysis of the relationship between GDP and innovation index revealed that the correlation was not strictly linear. Some smaller economies with robust innovation policies outperformed larger ones in terms of innovation development. The findings highlighted the necessity of increasing both public and private investment in R&D, optimising funding mechanisms, and fostering stronger public-private partnerships to support innovation. The practical significance of the research lay in identifying predictable trends in innovation activity, highlighting the most promising areas for future investment, and pinpointing key applications for emerging technologies

Keywords: national economies; individual enterprises; efficiency; competitiveness improvement; investment in the future

INTRODUCTION

Each country's level of technological development determined its level of socioeconomic development. Experiments and research that led to the creation of new knowledge and technologies were what kept countries independent and in good health. In the context of the fifth technological mode, when the gap in economic development even for a few years could be critical for individual national economies, it was especially important to understand in advance the promising areas of science and technology development. Accordingly, the relevance of

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this research was to identify the experience of innovation activities of European countries and to guide investment flows to those branches of science and technology that will ensure the most intensive development soon. In addition, understanding the correlation between innovation activity and gross product will help to predict the potential of a particular national economy.

Equally important was the even innovation development of the regions. G.A. Kozhakhmetova & O.V. Lashkareva (2020), exploring the establishment and development of regional innovation systems in Kazakhstan, identified noticeable positive changes in the indicators of scientific-innovative development on the ground. They ranked the innovation activity of regions and major cities of the Republic of Kazakhstan and concluded that for maximum efficiency in several lagging regions (Turkestan, West Kazakhstan and Mangistau regions) it was necessary to establish special innovation clusters and ensure the exchange of information and experience with the leading regions.

An important aspect of innovation promotion was the budget allocated to research and development (R&D), as the full development of scientific research was impossible without the establishment of funding mechanisms and diversification of investment sources. This issue was discussed by N.K. Kuchukova & L.A. Talimova (2020), having determined that fundamental research financed from the state budget and private sources did not replace, but complemented each other. Therewith, the private sector was interested in exchanging information only at the early stages of new technology development, which meant that the state should have established a pool of consumers of scientific services, helping enterprises to buy the results of R&D through targeted funding of this sphere. Such a measure would increase the innovation activity of Kazakhstani enterprises and ensure the modernisation of the national economy.

In addition, the low level of Kazakhstani innovations was stated by G.I. Zholdasova (2021) – the share of R&D expenditures in Kazakhstan had decreased to 0.17% of gross domestic product (GDP), while in developed countries it had reached 4%. Therewith, such sphere of innovation application as the development of the digital economy was at a rather high level in the Republic of Kazakhstan, and according to the research by E.A. Georgieva *et al.* (2020), there was an increase in venture capital financing of digital projects and a positive impact of digital solutions on the labour market.

From the standpoint of sustainable development prospects, the work of G. Kalkabayeva *et al*. (2021) was of interest. The researcher noted the weak participation of Kazakhstan in the design and development of "green" technologies and eco-innovations, which increased the risks of maintaining a catch-up model of development and reduced the competitiveness of the national economy. As an alternative, the author proposed the establishment of a special institute for the development of the finance market by analogy with the special European Centre for the Development of Green Finance under the auspices of Organisation for Economic Co-operation and Development (OESD). Therewith, at this stage there was no fresh analysis of the degree of correlation between the level of innovation activity and the country's GDP. The purpose of this research was to cover this gap and to analyse the key indicators of innovation activity on the example of several European countries, and forecast the prospects for their development.

MATERIALS AND METHODS

During the research process, methods such as statistical analysis and forecasting were applied, and a regression analysis of indicators, along with the construction of a scatter diagram and the subsequent development of a trend, was carried out. The annual European Innovation Scoreboard (2023) provided a comparative assessment of the R&D and innovation activities of most countries in Europe and some other countries, analysing their strengths and weaknesses. It distinguished four main types of activity – key conditions, investment activity, innovation activity and impact factors – with 12 innovation dimensions covering a total of 32 indicators. Each major group included an equal number of indicators and was equally weighted in the average performance score, or the Composite Innovation Index.

Based on official data provided by the European Innovation Scoreboard (2023), the aggregate innovation index of ten national economies in Europe was analysed, and all key innovation parameters of this index were analysed. For the most representative sample, countries representing, according to the official terminology of the European Union, all four efficiency groups were selected. In particular, the group of innovation leaders was represented by Belgium and Denmark, the group of strong innovators by Germany and France, the group of moderate innovators by Italy and the Czech Republic, and the group of potential innovators by Bulgaria and Poland. In addition, two non-EU countries, the UK and Turkey, were included in the analysis for a more comprehensive assessment of the innovation situation in Europe.

For each country analysed, a total innovation index was considered, along with its 12 constituent innovation parameters. These parameters include the human resources growth index, which reflects the number of doctoral students, the proportion of the population with higher education, and the popularity of lifelong learning. Another key component was the index of attractive research systems, which assessed the accessibility and effectiveness of research institutions. The digitalisation index measured the proportion of areas covered by broadband internet and the number of individuals with digital literacy levels above the basic threshold. Additionally, finance and support include public sector R&D expenditure, venture capital investment, and state support for innovative businesses. The firm investments parameter evaluated the extent to which businesses allocate resources to innovation. An essential aspect of innovation was the indicator of the use of information technologies, which measured the penetration of IT solutions across various economic sectors. The innovators category assessed the proportion of enterprises engaged in product and process innovation. Moreover, the linkages indicator examined cooperation between innovative firms, as well as the mobility of human resources in technology-driven sectors. The intellectual assets parameter was calculated based on the total number of patents, trademark applications, and the number of intellectual property applications developed within the country. Furthermore, employment impacts reflect how innovation influences job creation and labour market dynamics. The

sales impacts parameter assessed the commercialisation of innovation-driven products and services. Lastly, environmental sustainability considered the implementation of eco-friendly technologies and resource-efficient production methods.

In addition, based on Eurostat (2023) data, a regression analysis between the innovation index of ten European states and their GDP was conducted. Based on the data obtained, a regression correlation was determined, and a linear trend was established after the construction of a scatter diagram to understand the prospects of innovation development in Europe and to determine the dependence of GDP on the innovative activity of a state and the success of its innovation projects. In addition, the innovation indices for the previous eight years were analysed for the selected countries. Although data for the European Innovation Scoreboard for 2024 were available, the analysis was conducted up to 2023 due to the lack of complete GDP data for all countries at the time of the study. Furthermore, the innovation indices for the selected countries were analysed for the previous eight years to understand the true dynamics, using the percentages of the innovation indices to the EU innovation average for 2016.

RESULTS

The EU's commitment to promoting an innovative culture was confirmed by the European Innovation Scoreboard (2023), which demonstrated a notable improvement in innovation performance of almost 8.5% since 2016. Twenty Member States saw a notable increase in their capacity for innovation during the last year, while only seven saw a decrease. During this time, the innovation performance of 25 countries increased, albeit more slowly than in the more recent years. However, nations with weaker innovation systems typically advance more slowly than the EU average. Since 2016, the majority of EU regions had seen an improvement in their innovation performance, according to the Regional Innovation Scoreboard. Some regional "pockets of excellence" were located in nations with comparatively poorer innovation performance, despite the fact that innovative regions were typically found in the most innovative nations. While the distance with Canada, the Republic of Korea, and the United States had widened, the EU was still performing marginally better than China and was catching up to Australia on a worldwide scale. Figure 1 depicts the annual percentage changes between two consecutive years and forms an overall dynamic trend.

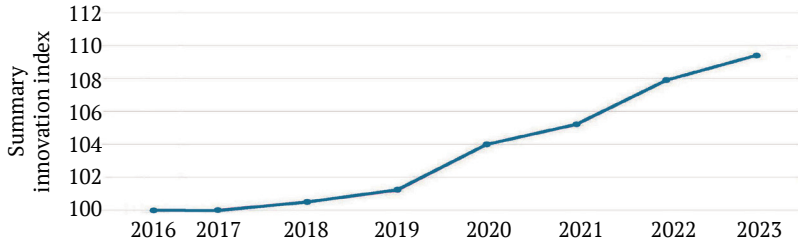

Figure 1. Improving innovation performance in the EU
Source: developed by the author based on European Innovation Scoreboard (2023)

When considering the 2023 results by country, the leaders with innovation ratios significantly above the EU average can be highlighted. In particular, Belgium demonstrated a result almost 30% higher than the EU average innovation coefficient. In addition, there was a significant excess of average indicators for most innovation parameters (Table 1).

Table 1. Key parameters for Belgium's innovative development in 2023

Indicator	Ratio to EU average
Human resources	124.8
Attractive research systems	155.6
Digitalisation	111.6
Finance and support	123.6
Firm investments	132
Use of information technologies	147.3
Innovators	146.5
Linkages	173.7
Intellectual assets	86.9
Employment impacts	150
Sales impacts	102.6
Environmental sustainability	101.7
Summary innovation index	125.8

Source: developed by the author based on European Innovation Scoreboard (2023)

This significant increase for Belgium was due to increased innovation, i.e. a notable externalisation of information technology, an increase in the attractiveness of working in science, and increased linkages. Linkages should be understood as cooperation between innovative firms, sustainable research connections between the private and public sectors, and the mobility of human resources between technology firms. The other examined country in the group of innovation leaders was Denmark. Its dimensions of innovativeness were summarised in Table 2.

Table 2. Key parameters for Denmark's innovative development in 2023

Indicator	Ratio to EU average
Human resources	176.7
Attractive research systems	189.5
Digitalisation	145.6
Finance and support	111.9
Firm investments	114.4
Use of information technologies	149.8
Innovators	117.2
Linkages	216.2
Intellectual assets	136.9
Employment impacts	107.9
Sales impacts	107.7

Table 2. Continued

Indicator	Ratio to EU average
Environmental sustainability	129.3
Summary innovation index	137.6

Source: developed by the author based on European Innovation Scoreboard (2023)

As can be seen, the final innovation rate in 2023 was one-third higher than the EU average and one of the highest on the continent. It was largely due to a significant increase in venture capital investment, increased digitalisation and linkages between knowledge-intensive areas of the economy. Germany's performance as a country in the second subgroup of innovation – strong innovators – was slightly below the leaders but was quite high (Table 3).

Table 3. Key parameters for Germany's innovative development in 2023

Indicator	Ratio to EU average
Human resources	99.8
Attractive research systems	109
Digitalisation	86.5
Finance and support	91.8
Firm investments	140.4
Use of information technologies	120.9
Innovators	141.1
Linkages	141.9
Intellectual assets	122
Employment impacts	128.4
Sales impacts	117.5
Environmental sustainability	121.2
Summary innovation index	117.8

Source: developed by the author based on European Innovation Scoreboard (2023)

Here, one of the strongest areas of development was the work of small and medium-sized enterprises, which take responsibility for innovations at the level of small private enterprises. Business investment in innovation by large non-state companies had a significant impact. The data for another representative of the group of strong innovators – France – were presented in Table 4.

Table 4. Key parameters for France's innovative development in 2023

Indicator	Ratio to EU average
Human resources	126.3
Attractive research systems	117.1
Digitalisation	112.3
Finance and support	132.7
Firm investments	89.7
Use of information technologies	73.8
Innovators	104.5
Linkages	120.9
Intellectual assets	80.6
Employment impacts	110.1
Sales impacts	81.7
Environmental sustainability	118.3
Summary innovation index	105.3

Source: developed by the author based on European Innovation Scoreboard (2023)

The strength of the French innovation policy was the visible finance and support and proper attention to the development of human resources. Therewith, the final indicators do not demonstrate breakthrough solutions and were at the level of the average arithmetic data of the European Union. The Czech Republic, despite the background of the East European socialist bloc, was able to join the ranks of developed economies quite quickly and establish its innovation policy. The main indicators of this activity for 2023 were summarised in Table 5.

Table 5. Key parameters of the Czech Republic's innovative development in 2023

Indicator	Ratio to EU average
Human resources	82.7
Attractive research systems	82.6
Digitalisation	76.7
Finance and support	82.1
Firm investments	113.2
Use of information technologies	100.4
Innovators	138.2
Linkages	94.1
Intellectual assets	63.1
Employment impacts	106.1
Sales impacts	103.1
Environmental sustainability	99
Summary innovation index	94.7

Source: developed by the author based on European Innovation Scoreboard (2023)

Despite a general level of innovation that was below the EU average, the Czech Republic had managed to take its rightful place in the group of moderate innovators due to the development and implementation of innovations in small and medium-sized enterprises. In addition, the state's ability and willingness to utilise borrowed and acquired information technology had given the innovative trend in the national economy the necessary impetus. The second representative of the group of moderate innovators was Italy. Despite a long tradition of enlightenment and innovation, the indicators of innovation development at this stage were relatively low and were presented in Table 6.

Table 6. Key parameters of Italy's innovative development in 2023

Indicator	Ratio to EU average
Human resources	62.1
Attractive research systems	106.2
Digitalisation	77.9
Finance and support	66.8
Firm investments	72.3
Use of information technologies	79.5
Innovators	115.2
Linkages	92
Intellectual assets	107.6
Employment impacts	107
Sales impacts	92.8
Environmental sustainability	113.4
Summary innovation index	90.3

Source: developed by the author based on European Innovation Scoreboard (2023)

As can be seen from the table, the country's potential was growing, largely due to government policies to stimulate the scientific sphere and its intellectual assets. High indicators of environmental sustainability, including resource efficiency, reduction of harmful emissions into the atmosphere and development of environmental technologies, deserve special attention. In particular, the data for Poland were summarised in Table 7.

Table 7. Key parameters of Poland's innovative development in 2023

Indicator	Ratio to EU average
Human resources	58.3
Attractive research systems	46.2
Digitalisation	81.1
Finance and support	61.2
Firm investments	59.3
Use of information technologies	90.3
Innovators	41.4
Linkages	73.7
Intellectual assets	84.2
Employment impacts	50.8
Sales impacts	68.2
Environmental sustainability	43.8
Summary innovation index	62.8

Source: developed by the author based on European Innovation Scoreboard (2023)

Despite the relatively low performance in almost all categories of innovation activity, the growth of digitalisation of the country and its population can be highlighted, as intellectual assets, which include various forms of intellectual property rights established in the process of innovation, including patent applications and trademark applications. On these parameters, the country was almost approaching the European average. Another country in the group of potential innovators was Bulgaria. Its indicators were presented in Table 8.

Table 8. Key parameters of Bulgaria's innovative development in 2023

Indicator	Ratio to EU average
Human resources	32.7
Attractive research systems	26.6
Digitalisation	49.8
Finance and support	22.1
Firm investments	35
Use of information technologies	48.1
Innovators	56
Linkages	35.4
Intellectual assets	92.5
Employment impacts	56.7
Sales impacts	59.7
Environmental sustainability	46.2
Summary innovation index	46.7

Source: developed by the author based on European Innovation Scoreboard (2023

At this stage, Bulgaria was in the rear-guard of European economies, and its total innovation score was not even half of the EU average. Therewith, a relatively high level of sales impact can be recognised, including exports of medium- and high-tech products, exports of knowledge-intensive services and sales of the results of the introduction of innovative products. In addition to the countries of the European Union, it was essential to explore the innovation performance of its neighbours to provide additional external criteria for assessing performance on the one hand and, on the other hand, to monitor the innovation potential of the EU's trading partners in advance. The UK, having left the EU, remains one of the most important economies on the continent with a large innovation potential. Its performance for 2023 was summarised in Table 9.

Table 9. Key parameters of the UK's innovation development in 2023

Indicator	Ratio to EU average
Human resources	161.5
Attractive research systems	170.6
Digitalisation	39.1
Finance and support	122.6
Firm investments	76.2
Use of information technologies	120.2
Innovators	48.1
Linkages	206.5
Intellectual assets	70.4
Employment impacts	147.3
Sales impacts	106.8
Environmental sustainability	116.1
Summary innovation index	114.8

Source: developed by the author based on European Innovation Scoreboard (2023)

In general, the innovation rate of almost 120% corresponds, according to the EU classification, to the group of "strong innovators". The indicators that allow deriving such an impressive coefficient deserve particular attention – they were linkages, the attractive research systems in the state, and a high assessment of human resources. In the context of the geopolitical situation, it was particularly important to assess the innovative activity of Turkey, which historically had been a "bridge" between Europe and Asia. According to the dynamics of development and introduction of modern technological innovations by this state, it was possible to develop forecasts regarding the innovation potential of both Central Asian and Transcaucasian regions. Turkey's coefficients for 2023 can be found in Table 10.

Table 10. Key parameters of Turkey's innovative development in 2023

Indicator	Ratio to EU average
Human resources	48.5
Attractive research systems	45.6
Digitalisation	36.6
Finance and support	68.6
Firm investments	46.8
Use of information technologies	32.6
Innovators	58.4
Linkages	64.7
Intellectual assets	27.1
Employment impacts	23.1
Sales impacts	65.9

Table 10. Continued

Indicator	Ratio to EU average
Environmental sustainability	44.1
Summary innovation index	47.6

Source: developed by the author based on European Innovation Scoreboard (2023)

The indicators at this stage were relatively low and were less than half of the average European innovation rate. Attention should be devoted to such indicators as the attraction of innovative technologies and the impact on employment – the figures for these indicators were extremely low, which may indicate the potential for the development of these areas. In addition to assessments of innovation activity as of 2023, "at the moment", it was equally important to understand the dynamics of the process. Having the trend of indicators in comparable values, it was possible to characterise the development of the national investment policy and get an idea of its near future. Due to the website of the European Innovation Scoreboard, it was possible to obtain data from 2016 onwards (Table 11).

Table 11. Dynamics of the innovation development index

Year	2016	2017	2018	2019	2020	2021	2022	2023
Belgium	122.3	123.7	125.9	129.3	127.6	136	136.9	136.4
Denmark	133.3	134.5	134.2	137.8	140.1	144.5	146.5	149.2
Germany	120.2	120.4	121.1	121.6	122.1	127.1	129	127.8
France	115.8	115.6	116.4	114.2	114.7	113.1	115.5	114.2
Czech Republic	81.7	81.7	82.1	83.2	85.7	89.1	92.3	102.7
Italy	82.4	83.6	84.4	89.9	92.9	102	103.6	98
Poland	54.8	56.4	56.5	58.9	58.3	61	62.9	68.1
Bulgaria	46.3	45.9	44.8	46.3	46.9	45.1	44.6	50.6
UK	123.3	126.9	128.2	128.5	130.3	124.7	127.1	124.5
Turkey	51.2	52.4	54.5	60.5	61.5	51	50.9	51.6

Source: developed by the author based on European Innovation Scoreboard (2023)

As can be seen from the data, for Belgium, innovation had a noticeable constant growth except for a slight decline in 2016. According to the table, after five years of relative stability, there was an explosive surge in innovation performance in 2021 and the positive trend continued in the following years in Denmark. Germany saw a major jump in the index in 2021 after several years of relative stability. Therewith, this country, unlike the innovation leaders Belgium and Denmark in 2023, failed to maintain the trend and experienced a decline in the final index. The picture of innovation in France differs significantly from that of previous national economies. After the peak in 2018, the indices declined. The small "rebound" in 2022 was too insignificant to make a significant difference. The Czech economy, although lagging behind the absolute indicators of "Old Europe", demonstrates constant and steady growth in relative terms. The same applies to innovation policy.

Italy's innovation performance was in line with the EU average for the 2016 sample. Having received small impulses in 2019 and 2021, the rest of Italy's innovation activity had been stagnant, and after eight years, the innovation index had only reached the EU average of 2016. From the group of the weakest countries in terms of investment, Poland was distinguished by its relatively strong dynamics and potential. As can be seen from the Table 11, the Poland's innovation activity sometimes demonstrates minimal growth values, nevertheless, the trend was positive throughout the entire period of observation. It was not the case for Bulgaria – the country's innovation index was in chaotic movement and after periods of upswing there were sharp declines in 2018 and 2021. Further monitoring of the innovation indices was needed to understand the subsequent dynamics.

Of the non-EU European countries, the UK has the largest economy. The Table 11 demonstrates a strong growth of the index until 2020 and a sharp decline in 2021. Therewith, notably, despite such shocks, the UK's innovation index was still well above the EU average. Turkey, as a logistics hub between Europe and Asia, is important in terms of innovation policy development. Based on the data in the Table 11, it can be argued that innovation development in Turkey was practically non-existent – the country was still at the level of 50% of the EU innovation potential of 2016. Moreover, this indicator was virtually unchanged from year to year, which means that a significant external impetus was required to turn the situation around.

Thus, 12 categories of innovation indicators for 2023 and the dynamics of aggregate indices of a number of countries for 8 years were analysed. Therewith, for the fullest possible understanding of the further development of innovation in the European Union, it was necessary to determine the relationship between innovation indicators and the country's GDP. Table 12 summarises these indicators for a number of examined countries in 2023, the latest year for which the World Bank had published official information. Since there was a notable variation in the correlation between the level of innovation and GDP, to determine the mathematical relationship between the two, a regression analysis of the data was conducted (Table 13).

Table 12. Key indicators of the countries examined

Country	Innovation Index-2023	GDP-2023, million $
Belgium	136.4	644,782
Denmark	149.2	407,091
Germany	127.8	4,525,703
France	114.2	3,051,831
Czech Republic	102.7	343,207
Italy	98	2,300,941
Bulgaria	50.6	102,407
Poland	68.1	809,200
UK	68.1	3,380,854
Turkey	51.6	1,118,252

Source: developed by the author based on GDP (current US$) (2023)

Table 13. Regression statistic

Multiple *R*	0.145238568
R-square	0.021094241
Standardised *R*-squared	-0.101268978
Standard error	1,614,366.766
Observations	10
Y-intersection	1,062,578.9067
Variable *X*1	6,267.175889

Source: developed by the author

These results indicate a weak correlation between the 2023 Innovation Index and the GDP of the countries. The *R*-square value suggests that only about 2.1% of the variation in GDP was explained by the level of innovation development. With a noticeable degree of error, the correlation between the innovation index and GDP can be determined by the formula (1):

$$GDP = 1{,}062{,}578 + 6{,}267 \times I_i, \quad (1)$$

where I_i – innovation index. Thus, the obtained results identified innovation leaders by key parameters of innovation activity and determined the dynamics of innovation policy development in several European countries. A regression analysis of the relationship between GDP and innovation was conducted, which did not identify a strong correlation between these indicators.

DISCUSSION

The subject of innovation development as the most important factor in stimulating national economies and improving civilisation, in general, attracts the deserved attention of many researchers. The issue of innovation had become especially relevant with the emergence of the Internet and the subsequent digital technological breakthrough. K. Mtar & W. Belazreg (2021), exploring the causal link between innovation, financial development and economic growth in the OECD countries, found that there was a unidirectional causal connection between the elements examined. The authors concluded that further regulation of financial systems and the quality of finance were critical to stimulating economic development, and national governments can play an important role in developing legislative frameworks that favour the development of innovation financing through patent guarantees. In addition, M. Capriati (2022) identified a complementary connection between innovation and human capital development, and innovation and a country's GDP. The researcher concluded that it was crucial to define human development as the ultimate purpose of innovation policy and that it was necessary to develop a macroeconomy designed to fully implement the potential of citizens. This research confirms the correlation between innovation and the economic development of a state – the higher the standard of living in a country, the higher its innovation rating.

I.A. Bathuure (2021) determined in his work the impact of social innovation on economic growth in the example of 147 countries proved that investments in digital communication technologies should be a priority, as they significantly reduce the cost of establishing and maintaining personal connections of employees, which positively affects labour productivity. In addition, innovation plays an important role in the global project of sustainable development. R.Y. Castillo-Acobo *et al.* (2023) explored the impact of innovation and willingness to transform closed-loop economies into environmentally sustainable models. In the process, the authors obtained evidence of a positive relationship between innovation adoption and sustainable development. A similar aspect of innovation was explored by J. Kučera & M. Fiľa (2022) and K. Belanova (2024). P. Nunes & K. Sytnychenko (2024) and R.R.N. Ghormare *et al*. (2024) identified the main components of the circular economy, identified the impact of these variables on the economic growth of the European Union countries and proved that all three components of sustainable development – environmental, social and economic – were significant for GDP growth. Therewith, as the results of this work confirm, there was no straight correlation between GDP volume and innovation index, and countries with smaller economies (Belgium, Denmark) overtake such European economic giants as Germany or the United Kingdom in terms of innovation development.

R. Bago *et al.* (2023) were able to identify the most relevant innovation areas for investment activities. By assessing the correlation between the volume of exports of high-tech products and the volume of net portfolio investment, they managed to rank 130 countries examined by four categories of efficiency of investment in innovative developments. This research confirms the attractiveness of investment areas such as digitalisation and human capital development. To explore more fully the impact on human capital development of such an aspect of innovation as modern university education,

T. Agasisti & A. Bertoletti (2022) conducted a longitudinal study of European regions between 2000 and 2017. The duration of the experiment allowed maximising the impact of innovation and almost eliminating the factor of randomness. The result was an unambiguous conclusion that innovation in R&D activities was an important driver of GDP per capita growth in the region, regardless of the form of ownership of the educational institution. By analysing the level of individual firms, E. Chalioti *et al.* (2020) found that as competition between exporters of a non-innovative product becomes more intense, an innovative firm export more compared to its non-innovative competitors in more distant markets and confirmed this hypothesis empirically using the example of Greek exporting firms. Thus, it can be concluded that reorientation towards operating with innovative products was a profitable alternative to operating in an oversaturated "conventional" product market. Indirect confirmation of this conclusion was obtained in the present research, where it was demonstrated that an increase in the Sales Impact Index tended to correspond to an increase in the Generalised Innovation Activity Index.

Either way, a modern enterprise can use changes in the innovation market environment as an opportunity to establish new products and services that constitute a competitive advantage defined by the business strategy adopted. S. Pangsy-Kania *et al.* (2023) explored the relationship between business strategies used in industrial enterprises and their effects in the form of different types of innovations. Based on statistical data for several EU countries, a cluster analysis was conducted and the hypothesis was confirmed that the importance of business strategies for innovative companies varies from country to country and combinations of different innovation strategies were the most effective. Another important aspect of innovation development was the ability of authors of an invention or discovery to protect their intellectual property. The lack of effective patenting and royalty mechanisms can significantly reduce or even stop R&D altogether. It was particularly true for companies in the private sector. S. Kwon (2020) examined how a firm's acquisition of external patents affects the innovation activities of competing firms. By analysing the literature on patent delays and examples of firms' strategic use of patents, the researcher confirmed the hypothesis that the purchase of an external patent constrains the development of relevant technologies within a competitive environment.

Consequently, a balance between intellectual property protection and the ability of the rest of the market to legally utilise innovative achievements was necessary for the development of innovation. D. Hegde *et al.* (2023) examined a large-scale natural experiment – the passage of the American Inventors Protection Act of 1999 – which accelerated the public disclosure of most U.S. patents by two years. After the Act went into effect, U.S. patents were cited more frequently and more quickly, fuelling the diffusion and dominance of U.S. technologies against lagging European patents whose disclosure timelines were not changed. Thus, the patent activity of a country was a marker of the activity of its investment activity. For a more complete assessment of innovation efficiency, L. Ponta *et al.* (2021) proposed to introduce a special patent index IPI, which allows quantitatively summarising various aspects of innovation activity of firms. In their work, the authors, using three different machine learning algorithms, identified five key aspects of IPI – efficiency, time, diversification, quality and internationalisation – and proved that this method was effective, easy to use and indispensable in planning innovation potential.

M. Dritsaki & S. Dritsaki (2023) and A.F. Bate *et al.* (2023) examined the relationship between R&D expenditure and the global innovation index across countries. The results of the research demonstrated a long-term positive significant relationship between R&D investment and the innovation index, whereas in the short term, the correlation was negative. Similar trends in the European investment market were observed in this research. The experience of the above authors helped to define the background of investment activity and identify its specific features in the context of real markets, primarily European. Comparing the results of this work with the experience of other studies, it can be stated that there was no stable regression relationship between the innovative activity of the state and the size of its GDP.

CONCLUSIONS

The European Union's dedication to promoting innovation was reaffirmed by the European Innovation Scoreboard 2023, which also noted a consistent improvement in innovation performance over the previous eight years. Overall, the EU's innovation growth since 2016 was about 8.5%, with most Member States exhibiting encouraging trends. To guarantee balanced development, additional national and regional policy measures were required, as the continent's progress was still uneven. The examination of important innovation metrics shows that Belgium and Denmark have solidified their positions as leaders, outperforming the EU average in several areas, most notably in the areas of digitalisation, research system attractiveness, and human capital development. Despite their relatively modest growth rates, Germany and France were still in a good position. Though at a slower rate, up-and-coming innovators like Poland and the Czech Republic have shown encouraging trends. On the other hand, with only modest gains seen in their respective innovation indexes, Bulgaria and Turkey continue to rank among the least inventive economies in the area.

Although there was a broad association, regression study of the relationship between GDP and innovation performance showed that it was not strictly linear. In terms of innovation production, certain smaller economies – like Belgium and Denmark – that had robust innovation policies perform better than larger ones like Germany and the UK. This implied that, regardless of GDP size, focused innovation policies, calculated R&D expenditures, and improved public-private sector collaboration were essential for promoting innovation. The results highlighted the need for more public and private investment in R&D, clear funding procedures, and improved support systems for start-ups and tech-driven businesses from a policy standpoint. To further reduce the innovation gap within the EU, it will be crucial to establish regional innovation hubs and promote cross-border cooperation. Furthermore, in order to guarantee a sustainable

knowledge-based economy, methods for retaining talent must be given top priority. Finding recurring patterns in the growth of innovations and emphasising important areas for further investment were the research's practical implications. Further research is required to examine the long-term effects of emerging technologies, the role of artificial intelligence in innovation ecosystems, and the efficacy of governmental innovation policies in various economic contexts, even though the study offers insights into the current state of innovation in Europe.

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CONFLICT OF INTEREST

None.

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Аналіз ефективності інновацій в контексті економічного розвитку

Анотація. Метою цього дослідження було проаналізувати ключові характеристики інновацій у вибраних європейських країнах і, на основі цього аналізу, визначити кореляцію між зростанням інвестицій в інноваційні рішення та динамікою економічного розвитку держав. У межах дослідження були розглянуті такі показники інноваційних процесів, як обсяг людського капіталу, кількість наукових публікацій, рівень цифровізації, державні та приватні інвестиції в інновації, інтелектуальні активи та експорт наукомісткої продукції у кількох європейських країнах. Було проведено регресійний аналіз для визначення закономірностей розвитку національних економік. Дослідження охоплює динаміку інноваційної активності в Європі у період з 2016 по 2023 роки, що дозволило визначити ключові вектори розвитку окремих країн і встановити залежність економічного зростання від фінансових інвестицій у нові технології та швидкості їх впровадження. Результати показали, що Бельгія та Данія демонструють найвищий рівень інноваційної активності, значно перевищуючи середні показники ЄС, зокрема за рівнем цифровізації, розвитку людського капіталу та привабливості наукових досліджень. Німеччина та Франція демонструють стабільне, але помірне зростання інноваційних показників, тоді як Польща та Чехія мають позитивні, але більш повільні тенденції. Водночас Болгарія та Туреччина опинилися серед найменш інноваційних економік регіону. Регресійний аналіз взаємозв'язку між ВВП та індексом інновацій показав, що ця кореляція не є строго лінійною. Деякі менші економіки з ефективною інноваційною політикою демонструють вищий рівень розвитку інновацій, ніж більші країни. Отримані результати підкреслюють необхідність збільшення як державних, так і приватних інвестицій у сферу R&D, оптимізації механізмів фінансування та зміцнення державно-приватного партнерства для підтримки інновацій. Практичне значення дослідження полягає у визначенні прогнозованих тенденцій інноваційної активності, виділенні найбільш перспективних напрямів для майбутніх інвестицій та визначенні ключових сфер застосування новітніх технологій

Ключові слова: національні економіки; окремі підприємства; ефективність; підвищення конкурентоспроможності; інвестиції в майбутнє

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The role of public investment in innovative projects during martial law

Abstract. The purpose of the study was to analyse the impact of martial law on public investment in innovation projects and to identify ways to adapt them to the new economic environment. The study analysed changes in financial and economic policy during martial law, assessed the priorities of public investment in innovation, and investigated the impact of regulatory measures on the development of technology projects. The martial law in Ukraine has significantly changed the economic priorities of the state, affecting the mechanisms for financing innovation projects. The analysis showed that a significant portion of public resources was redirected to defence needs, with defence funding amounting to UAH 350 billion in 2022 and expected to reach UAH 550 billion in 2024. This has also contributed to the development of dual-use technologies. The introduction of tax incentives and grant programmes has supported businesses operating

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in strategically important sectors, including cybersecurity, healthcare, and energy. Public investment in innovation in 2022 was only UAH 5.8 billion, but in 2024, this figure increased to UAH 7 billion, which became a key tool to support the national economy in the face of limited access to private capital. The creation of strategic funds made it possible to allocate funds for the development of critical innovative solutions that ensure defence capability and economic stability. An analysis of legislative changes has shown that the government has simplified the procedures for financing innovative projects and encourages the export of technological products. Despite serious challenges, the country retains the potential for innovative development through the adaptation of financial instruments and the active use of public-private partnership mechanisms. The study identified effective approaches to financing innovative projects under martial law, which contributes to the development of a strategy for economic sustainability and technological development

Keywords: defence capability; tax incentives; grant programmes; cybersecurity; energy; economic resilience

INTRODUCTION

The martial law in Ukraine has led to new economic challenges that have affected financial processes, investment mechanisms and strategic priorities of the state. Changes in the budget structure and the reallocation of resources to defence and security needs have significantly narrowed the opportunities for traditional financing of innovative projects. At the same time, the growing importance of dual-use technologies and the development of strategically important sectors of the economy, including cybersecurity, healthcare, and energy, require new approaches to public investment. In such circumstances, public funding becomes crucial for maintaining economic stability and promoting the country's technological development. An analysis of financial instruments and tax incentives to support innovation, as well as the adaptation of legislation to current realities, will help determine the prospects for the development of innovation even in times of war.

The issue of the impact of martial law on investment in innovative projects is important for understanding economic processes in a crisis. E.S. De Dios *et al.* (2021) noted that martial law forced the Philippines to redirect resources to defence, which limited the ability to finance innovative projects. At the same time, it has stimulated the development of vital technologies, particularly in the defence and security sectors. J. Juliana *et al.* (2022) emphasised that the introduction of tax incentives was necessary to stimulate private investment in high-tech and defence industries during martial law. This helped to ensure economic sustainability and development of strategic sectors, even in the face of limited access to finance. S. Choi *et al.* (2021) highlighted the role of government grants as an effective tool to support innovative start-ups in times of economic instability. They also pointed out that government support helped to overcome the shortage of investment resources for technological development. Researchers J. Shkabatur *et al.* (2021) noted that foreign investment inflows played a crucial role in the development of innovative projects in strategic sectors, including energy and defence. This required the development of special government support programmes that created attractive conditions for investors. Y. Zeng & T. Peterson (2024) emphasised the importance of government subsidies and soft loans for companies developing dual-use technologies. This made it possible to support innovative projects even in conditions of limited budget and instability.

V. Anghel & J. Džankić (2023) studied the adaptation of public investment in the context of military conflict and justified the need to create special investment funds for the development of strategic technologies. They believed that these funds should have been focused on supporting enterprises that were engaged in critical developments for the state. Y. Chen *et al.* (2022) emphasised that the role of national governance is critical to ensure the stability of investment in times of crisis. This is especially important for ensuring economic resilience in times of war, when risks and challenges are increasing. G. Ampratwum *et al.* (2022) analysed the prospects of public-private partnerships as a tool for minimising financial risks in the implementation of innovative projects. They believed that such partnerships could become the basis for sustainable financing of technology initiatives. P. Kulikov *et al.* (2022) noted that to maintain interest in innovative projects during the war, it was necessary to develop new financial mechanisms that reduced investment risks. They proposed the creation of special support programmes for enterprises operating in critical industries. Z. Sinaj *et al.* (2024) emphasised the need to develop strategic investment programmes aimed not only at supporting innovation, but also at strengthening the country's technological independence. They should be based on long-term priorities for the development of the national economy in the context of military conflict.

Despite the existing research, there are gaps that require further study. In particular, the specific mechanisms of public-private partnerships under martial law, as well as a comprehensive analysis of the impact of changes in tax policy on attracting investment in technology sectors, have not been sufficiently studied. Another critical area is to assess the effectiveness of the created investment funds and their impact on the development of innovations in critical sectors. The purpose of the study was to comprehensively analyse the impact of martial law on public investment in innovative projects and develop proposals for their reorientation to address pressing economic issues in the new environment. Research objectives are: to investigate the impact of tax benefits and government grants on stimulating investment in innovative projects; to analyse the effectiveness of public-private partnerships as a mechanism for minimising financial risks during the period of military operations; to assess the feasibility of creating special funds to support strategic technologies in times of crisis.

MATERIALS AND METHODS

The study analysed changes in the economic environment in 2021-2024 in Ukraine (World Economic Forum, 2024), driven by the increase in public spending on defence and security, as well as the redistribution of the budget to

support key industries. The first step was to study the changes in economic conditions caused by the need to increase public spending on defence and security and to reallocate the budget to support key industries. This included an analysis of changes in tax incentives for strategically important sectors, such as defence technology and energy security, and a study of how these changes affected the attraction of private capital to innovative projects. An important aspect was to assess how the increased economic and political risks associated with the war could affect the country's investment attractiveness and the willingness of businesses to participate in such projects.

The second area of the study was to identify priorities for public investment in 2021-2024 (Innovative activity of industrial enterprises, 2018). The study analysed which industries receive the most support from the state under martial law, including funding for defence technologies, cybersecurity, and energy independence. At the same time, the creation of special strategic funds for the development of innovative projects to maintain economic stability in a crisis and promote technological development in important areas was studied. Particular attention was paid to supporting scientific and technological research, particularly in key areas such as medicine and logistics, which are critical to national security.

The next step was to explore the possibilities of developing public-private partnerships to increase the efficiency of public funds. It was analysed how co-financing of innovative projects could reduce the budgetary burden, and how involvement of the private sector in the development of new technologies could help to speed up their implementation and increase their economic efficiency. An important aspect was also the simplification of conditions for launching innovative start-ups, which can stimulate entrepreneurial activity in this difficult period. The study analysed the changes in the economic situation in Ukraine, in particular the increase in public spending on defence and security, which leads to a redistribution of budgetary resources and affects the financing of other sectors. The transformation of the financial and tax environment, including the introduction of privileges and subsidies for strategically important industries and the creation of grant programmes to support innovation, is also considered. Particular attention is paid to the impact of martial law on investment in innovative projects, including risks to attracting private capital and opportunities for developing public-private partnerships.

The last important aspect was the study of changes in legislation to create favourable conditions for innovation under martial law, including simplification of financing and registration of innovative enterprises, as well as stimulation of foreign investment. In particular, the measures introduced in April 2022 were analysed (Nosenko *et al.*, 2023). This included the reduction of the single tax rate, the temporary abolition of mandatory payments for individual entrepreneurs, the introduction of a zero-excise tax on fuel and the reduction of the value added tax (VAT) rate, which helped to stabilise the market and ensure the supply of essential goods.

RESULTS

Changes in the economic situation during martial law

Martial law usually has a significant impact on a country's economy, changing its structure and functioning in various areas. In Ukraine, starting in 2022, the economic situation has undergone significant changes due to military operations and the need to reorient resources to ensure national security. In this context, there are three main aspects of changes in the Ukrainian economy: increased defence and security spending, reallocation of the state budget to support critical industries, and the impact of increased risks on private capital attraction (Table 1).

Table 1. Changes in the economic situation in Ukraine

Indicator	2021	2022	2023	2024
Economic growth (GDP, %)	3.4	–30.4	–4	1.5
Investment attractiveness	56	42	44	48
Exports of goods and services (billion USD)	49.3	25.5	30.2	34
Unemployment (%)	9	13.5	11	9
National currency exchange rate (UAH/USD)	27.1	37.3	39	38.5
Inflation (%)	10	22.3	19.7	15
External debt (USD billion)	126	150	170	180

Source: created by the authors based on World Economic Forum (2024)

One of the most important consequences of martial law is a significant increase in defence and security spending. In times of war, the state is forced to significantly increase funding for the army, law enforcement agencies and other bodies that ensure national security. This includes spending on the purchase of weapons, equipment, logistics, and financing the needs of military personnel and volunteer groups. These expenditures can have both positive and negative effects on the economy. On the one hand, they stimulate certain industries, in particular, the production of defence equipment, weapons, and ammunition. On the other hand, the reorientation of financial resources towards defence often leads to a reduction in funding for other important sectors, such as education, healthcare, and social protection (Becker & Dunne, 2021).

During martial law, the structure of public spending changes significantly. The budget, which could previously have been focused on social benefits or infrastructure development, is redirected to finance industries that are strategically important to the country. One of these is the energy sector, which ensures the operation of the entire infrastructure and the maintenance of production facilities. Particular attention is paid to the agricultural sector, which is important for the country's food security, as well as to the transport infrastructure, which ensures the supply of essential goods. Budget reallocation may lead to a

reduction in funding for sectors that are not critical in a time of war. For example, capital investment in infrastructure, research, and other long-term projects may be suspended or reduced, which could affect the sustainability of economic development after the war ends in the long run. One of the main challenges for the economy during martial law is the increase in risks associated with investment activities. Martial law is accompanied by increased uncertainty and risks, which significantly reduces the country's attractiveness to foreign investors. Increased geopolitical and economic risks, including a decline in confidence in the stability of the legal system and financial infrastructure, make investment in the country less profitable. Investors often decide not to invest in countries with high political and economic risks, even if the market remains large and promising. As a result, the domestic market is experiencing a shortage of investment that could stimulate innovation, business development, and support for small and medium-sized enterprises. At the macro level, the government may try to compensate for the lack of private investment by attracting international aid and loans, which could lead to an increase in external debt (Sun *et al.*, 2023).

All three aspects-increased defence and security spending, reallocation of the state budget to support critical industries, and the impact of increased risks on private capital attraction-indicate that martial law is changing Ukraine's economic landscape. While these changes are necessary to ensure national security, they also have serious economic consequences. The redirection of funding to defence and critical industries often results in fewer resources available for the development of other sectors of the economy, which can have lasting consequences for the country's stability and economic growth. At the same time, increased risks for private capital limit the opportunities for attracting investment, which significantly affects economic recovery and modernisation.

Changes in financial and tax conditions

Martial law, like any emergency situation, requires prompt decisions to ensure economic stability. In Ukraine, due to the war, changes in the financial and tax environment were introduced to support key sectors of the economy and stimulate innovation. Particularly important are measures such as the introduction of tax incentives for strategically important industries, the creation of grant programmes to support innovative developments, and the introduction of subsidies for enterprises engaged in dual-use technologies (Table 2).

Table 2. Changes in financial and tax conditions in Ukraine

Indicator	2021	2022	2023	2024
Income tax rate (%)	18	15	15	18
Moratorium on inspections	Inspections were carried out	Moratorium on inspections	Moratorium on inspections	The moratorium remains
Tax benefits	Missing	Benefits for farmers, tax deferral	Continuation of benefits for small businesses	Limited benefits for business recovery
Land tax rates (UAH/ha)	3,600	1,800	1,800	2,000
Tax revenues (bn UAH)	454.1	325.5	315.7	350
Financing of defence needs (bn UAH)	130	350	500	550
Real estate tax (UAH/m^2)	0.50	0.10	0.10	0.20
VAT rate (%, average rate)	20	10	10	20

Source: created by the authors based on N. Bak & A. Kharovska (2023)

One of the first steps taken to adapt the economy to martial law was the introduction of tax breaks for strategically important industries. In a time of war, certain sectors of the economy, such as energy, agriculture and defence, are of particular importance. To support these industries, the Ukrainian government has proposed tax cuts and temporary exemptions to reduce the financial burden on businesses operating in these critical sectors. In particular, companies engaged in the production of military equipment and ammunition have been granted reduced corporate tax rates. This will provide them with the necessary financial resources to fulfil government orders and develop new technologies. In addition, farmers have been granted tax holidays, which has helped to maintain production capacity in the agricultural sector, which is important for the country's food security (Markowski *et al.*, 2021). These measures also help maintain economic activity during the war and are aimed at preserving jobs. However, their impact on the country's budget in the future may be difficult to predict, as a decline in tax revenues in the short term may affect the financing of other important social programmes. A key element of economic adaptation during martial law is to support innovation and scientific and technological developments. One of the main strategies has been to create grant programmes to support research and development that not only helps the country during the war, but also contributes to its recovery after the conflict.

The grants are provided to small and medium-sized enterprises, start-ups and research institutes working in areas such as information technology, energy, healthcare, and defence technologies. This stimulates the development of new technologies that can be used for both military and civilian purposes (Peng & Tao, 2022). Grant programmes are of particular importance in times of war, as supporting innovation can ensure economic growth in the future by stimulating the development of high-tech sectors that not only contribute to national security but can also help Ukraine rebuild its economy after the war. In particular, start-up support programmes in the field of dual-use technologies can become the basis for developing new export opportunities and attracting investment after the war.

Dual-use technologies are developments that can be used in both the military and civilian sectors. Under martial law, this area of activity becomes particularly

important, as companies operating in this sector can provide the country with the necessary technologies for defence and contribute to economic recovery after the war. To support such enterprises, the government has introduced a system of subsidies that provides partial funding for research and development costs, as well as for the purchase of necessary equipment and technologies. This allows enterprises to adapt their production capacities to wartime requirements, in particular for the production of dual-use products for both the army and the civilian sector. Subsidies for enterprises engaged in dual-use technologies not only provide operational support in times of war, but also lay the foundation for economic growth in the long term. As many of these technologies can be adapted for peaceful purposes, they have a high potential for export, which will help Ukraine increase foreign exchange earnings and strengthen its competitiveness in global markets (Efendi *et al.*, 2023).

Changes in financial and tax conditions during martial law in Ukraine are important tools to support strategically important industries, stimulate innovation, and ensure technological independence. In the future, the implementation of such initiatives could be a key factor in maintaining economic stability in the short term and restoring the country's competitiveness in the future (Teremetskyi *et al.*, 2024). In particular, tax holidays for small and medium-sized businesses in critical sectors of the economy, exemptions from import duties and VAT on equipment for the production of defence products, grant programmes such as eRobota supporting start-ups in the technology and agriculture sectors, and state subsidies for the introduction of energy-efficient technologies in industry have been introduced. These measures help to adapt the economy to wartime conditions and create the basis for recovery and development after the war.

Priorities of public investments

Martial law is not only a period for maintaining stability and ensuring national security, but also an important stage in determining the priorities of public investment. In the context of current geopolitical challenges, economic policy should be aimed at ensuring strategic autonomy and development of key sectors that determine the country's future. In Ukraine, during the war, the main areas of investment were the financing of defence technologies, cybersecurity, energy independence, the creation of strategic funds for the development of innovative projects, and support for scientific and technical research in the fields of medicine and logistics (Table 3).

Table 3. Impact of martial law on investment in innovative projects in Ukraine

Indicator	2021	2022	2023	2024
State investment in innovation (bn UAH)	15.2	5.8	5	7
Foreign investment (USD billion)	4.5	1.2	0.8	1.5
Startup financing (bn UAH)	3.1	0.8	1	1.5
Investments in the IT sector (bn UAH)	4.5	2	1.5	3
Industries affected	IT, energy, agriculture	IT, energy, agri-food sector	IT, energy, agri-food sector, infrastructure	IT, energy, agri-food sector, infrastructure restoration

Source: created by the authors based on Innovative activity of industrial enterprises (2018)

In times of war, the main priorities for public investment are defence technology, cybersecurity, and energy independence. Being at war, Ukraine has to significantly increase investments in its defence capabilities. This includes not only the purchase of the latest weapons and equipment, but also the development of technologies that ensure a high level of defence capability. Cybersecurity is of particular importance in the face of modern threats. In addition to physical attacks, the aggressor is trying to carry out cyber-attacks on critical infrastructure, banking systems and government agencies. Investments in cyber defence are becoming a key factor in ensuring the continuity of state institutions and the economy during wartime. To this end, government resources are being channelled to develop encryption technologies, protect information systems and train personnel to effectively counter cyberattacks.

Energy independence is also an important priority, as Ukraine needs a stable energy supply, even during shelling and other military operations. Investments in renewable energy sources, construction of new infrastructure facilities, and modernisation of existing energy systems help to reduce dependence on external suppliers and increase the resilience of the energy infrastructure in times of war (Ige *et al.*, 2024). Creating strategic funds to support innovative projects is an important area of public investment. Martial law requires not only defence mobilisation of resources, but also the creation of conditions for the development of new technologies that can be used in both military and civilian sectors. To do this, it is necessary to attract investments in research, start-ups and innovative companies that can form the basis for economic recovery after the conflict ends.

Investments in start-ups that deal with dual-use technologies, digital development, energy, and infrastructure allow the country to retain its intellectual potential and promote economic growth even during a time of war. Establishing government funds that provide non-repayable or low-interest financing is an important tool to support innovative enterprises working to bring new products or technologies to market (Riebe *et al.*, 2024). It also creates additional opportunities for the development of research institutions that provide the country with innovative solutions in various sectors, from defence to healthcare and agriculture. Scientific and technical research in the fields of medicine and logistics is also gaining importance under martial law. The COVID-19 pandemic has demonstrated how critical effective medical technologies and healthcare systems are, but the war has highlighted an even greater need for innovative solutions to provide medical care, treat the wounded, and maintain public health (Wang *et al.*, 2021).

Investments in the development of medical technologies – from the introduction of new treatments to the

development of tools for the diagnosis and treatment of severe injuries – are extremely important for the country. This ensures a high level of medical care for both military personnel and civilians, especially in resource-limited environments. Supporting research projects in the field of logistics is also of great importance. In times of war, efficient logistics is key to ensuring the supply of food, medicine, weapons, and other essential resources. Creating innovative solutions for transport, warehousing, and supply helps to reduce costs and increase the efficiency of public and private companies involved in logistics.

The priorities for public investment under martial law determine Ukraine's future in several important areas. Funding for defence technology, cybersecurity, and energy independence is essential to ensure national security and resilience. The creation of strategic funds to support innovative projects and scientific and technical research in medicine and logistics helps preserve the country's potential to recover from the war and maintain the efficient functioning of the economy even during the war. All these priorities are key to Ukraine's future development and its ability to adapt to new economic and technological realities.

Development of public-private partnership

Public-private partnerships (PPPs) are an important tool for ensuring sustainable economic development, particularly in times of crisis or martial law. In Ukraine, given the difficult economic and political situation, expanding and intensifying this partnership can be an effective mechanism for attracting investment, developing innovation, and implementing important projects. One example of a successful PPP is the implementation of a road infrastructure modernisation project involving private investors, which allows raising capital to rebuild roads and bridges at the local level, creating new jobs and contributing to the development of regional economies. In addition, the introduction of a PPP programme in the energy sector allows private companies to be involved in the reconstruction of thermal power plants, which helps to reduce energy dependence and ensure a stable supply of energy locally (Fay *et al.*, 2021). Co-financing of projects reduces the budgetary burden, engages private companies in the development of new technologies, and simplifies the conditions for launching innovative start-ups.

One of the key advantages of public-private partnerships is the ability to attract private investment to finance public projects. In the context of tight state budgets and ever-increasing financial obligations, co-financing reduces the burden on public funds and reduces risks to budgetary stability. Projects in the infrastructure, energy, healthcare, and education sectors require significant investments that often exceed budget capacity. In this context, PPPs allow private companies to take on part of the costs, which makes it possible to implement important social and economic initiatives without significantly increasing public debt. The role of PPPs is particularly important in the restoration and modernisation of infrastructure damaged during the war. Co-financing allows private capital to be used to rebuild infrastructure such as bridges, roads, hospitals and educational facilities, ensuring that they can be restored more efficiently and quickly. In addition, private companies can provide the necessary technological support, innovation, and project management to improve the quality and timing of work. The public sector is often limited in its ability to develop new technologies due to a lack of resources or high levels of bureaucracy. Private companies, on the other hand, often have considerable capacity for innovation, but may lack access to large-scale markets or funding to develop and deploy their technologies.

Joint investments between the public and private sectors can significantly accelerate the adoption of new technologies, which can contribute to technological progress in critical areas such as defence, energy, healthcare, and agriculture. The public-private partnership format makes it possible to attract private investors to develop dual-use technologies that can be used for both civilian and military purposes (Pandey *et al.*, 2021). Involving private business in technology development allows the country to use its experience, investment, and expertise to create solutions that meet modern requirements. It also contributes to the accelerated introduction of new technologies, such as artificial intelligence, innovations in the energy and environmental sectors, which have the potential to significantly improve the efficiency of the Ukrainian economy after the war.

One of the key aspects of developing public-private partnerships is to support start-ups and small businesses involved in innovative technologies. Ukraine has significant potential in areas such as information technology, agronomy, renewable energy and biotechnology, which is also confirmed by other researchers (Bokovets *et al.*, 2024). However, a favourable business environment needs to be created for start-ups to develop, including reduced bureaucratic obstacles, tax incentives, access to finance and government support programmes. Simplifying the conditions for start-ups can include lowering tax rates, creating special innovation zones, and launching mentoring and financing programmes. Such initiatives may include grants and soft loans, assistance in entering foreign markets, support for research, and training programmes for entrepreneurs. Joint projects between the state and the private sector aimed at innovative development can be an important driver for creating new jobs, technological solutions, and contribute to the country's economic growth (Stahl *et al.*, 2023).

The development of public-private partnerships in Ukraine is a key step towards ensuring stable economic development, including in the context of martial law. Co-financing of projects reduces the burden on the state budget, involvement of private companies in the development of the latest technologies stimulates technological progress, and simplification of conditions for start-ups opens up new opportunities for innovative solutions. All these measures will not only contribute to an effective response to current challenges, but also to ensuring the country's recovery and further growth in the future. Public-private partnerships are a powerful tool for creating conditions for sustainable development and technological progress in any national context.

Adaptation of legislation

Adapting legislation during martial law is an important factor in ensuring economic stability and promoting the country's innovative development. In April 2022, the government introduced a number of tax changes aimed at supporting the economy under martial law. In particular, the single tax rate was reduced from 5% to 2% for taxpayers

of the first and second groups. This change significantly reduced the tax burden on small businesses and individual entrepreneurs, allowing more than 185,000 companies and 40,000 individual entrepreneurs to continue operating in the difficult environment. Mandatory payments for this category of taxpayers were also temporarily cancelled, providing them with financial support in the face of economic instability. Another important initiative was the introduction of a zero-excise tax rate on petrol, diesel fuel and liquefied gas, which helped to reduce fuel costs and stabilise the supply of goods essential to the country's vital functions. The reduction of the VAT rate from 20% to 7% on a number of goods also helped to reduce the cost of essential goods. These steps helped to stabilise the market situation, improve the availability of basic goods and services for the population and ensure uninterrupted supply of vital resources during the crisis. In addition, the creation of special economic zones, where investors can benefit from tax incentives and other advantages, is an important step to attract foreign capital and stimulate the development of new high-tech industries. This process includes simplifying procedures for financing and registering innovative companies, creating special regimes for exporting technological products, and encouraging foreign investment through legislative reforms.

One of the main obstacles to the development of new technology companies in Ukraine is the complex bureaucratic procedures that require significant time and money. To support innovation and ensure the effective development of start-ups, it is necessary to amend the legislation governing the financing and registration of innovative enterprises. Simplification of these procedures involves the introduction of electronic platforms for business registration, reducing the number of required permits and shortening the time for obtaining licences or other permits. This will reduce the costs of starting new businesses and make financial resources more accessible to small and medium-sized innovative companies. In addition, the government could offer preferential terms for entrepreneurs planning to start businesses in areas important for the country's economic recovery, such as information technology, energy, agriculture, and research and development.

Simplifying procedures for registration and financing will help create a favourable environment for business start-ups, attracting not only domestic entrepreneurs but also foreign investors. This is especially important during martial law, when the country needs to quickly restore its economic potential and create new jobs (Das & Das, 2021). One of the main areas of development of the innovation economy is to support the export of technological products. Ukraine has significant potential in areas such as software development, energy technologies, biotechnology, and engineering. In order to support these industries and facilitate their expansion on international markets, special legislative regimes for exports of technology products should be introduced.

In particular, preferential tax rates or even exemptions from certain taxes could be provided for companies exporting innovative products abroad. This will allow Ukrainian companies to be more competitive in international markets and attract foreign exchange earnings to the country's economy. In addition, the introduction of special regimes for technology exports will help reduce trade barriers and facilitate access to international contracts and agreements (Fang *et al.*, 2023). The introduction of such special regimes could become an important step in the strategic development of Ukraine's economy, as it would allow attracting additional resources to expand production, improve technologies, and enter new markets for Ukrainian innovative companies. Attracting foreign investment requires profound legislative reforms that will ensure transparency, stability, and predictability of the economic environment. One of the main tasks is to create legal guarantees for foreign investors so that they can feel confident in a country at war and with significant risks.

Key steps in this direction include reforming tax legislation, introducing benefits for investors, protecting their rights and property, and simplifying procedures for investing in various sectors of the economy, including high-tech projects. One important tool to stimulate foreign investment could be the creation of free economic zones, where investors can take advantage of additional tax benefits and other advantages (Zakari & Khan, 2021). Reforms aimed at improving the investment climate will help attract capital to finance innovative projects, rebuild infrastructure, and develop new technologies. This, in turn, will help Ukraine to improve its economic potential, ensure high employment, and promote social recovery.

Adapting legislation is a key step to ensure stability and economic development under martial law. Simplifying procedures for financing and registering innovative enterprises, introducing special regimes for exporting technological products and encouraging foreign investment will create favourable conditions for the development of new businesses, increasing competition in international markets and attracting resources for innovative progress. The legal changes will not only support national enterprises but also strengthen ties with international investors, which will contribute to the recovery and development of the Ukrainian economy both during and after the war.

DISCUSSION

During martial law, the economic situation in the country underwent significant changes that affected all areas of government policy, including the financing of innovative projects. Increased spending on defence and security has led to a significant reduction in resources for other sectors of the economy. However, the reallocation of the budget to support critical sectors such as energy, transport, and healthcare has highlighted the importance of investing in the country's resilience and stability. The preservation and development of infrastructure of strategic importance has become a priority. This situation has led to increased risks for attracting private capital, as investors are generally reluctant to invest in countries with a high level of uncertainty, making it difficult to finance innovative projects.

This problem was also studied by M. Maher & Y. Zhao (2021), where the results confirmed that political instability and high military spending in Egypt have a significant impact on the country's economic growth. Applying the ARDL approach to analyse this impact allowed to clearly identify how such factors slow down economic development by reducing government revenues and affecting fiscal policy. As a result, the state budget is under pressure,

as a significant portion of resources is directed to support the army, which limits investment in other key sectors of the economy.

The study by F. Dorn *et al.* (2024) also showed that European countries in 2024 face the need to increase defence spending as growing global threats require increased security. However, economic difficulties such as inflation and financial instability limit the scope for such spending. Reallocating spending to critical sectors is becoming an important element of the strategy, as countries must balance security with other needs while ensuring that financial resources are used efficiently. It is important to note that political instability and increased defence spending can have long-term negative consequences for the economy, as reallocation of resources to the military is often at the expense of investments in infrastructure, education, and healthcare (Kostyk & Ovsiienko, 2023). This creates a vicious circle where economic growth slows down, which in turn worsens the country's financial situation, reducing its ability to innovate and recover. Such factors can make it much more difficult to overcome economic difficulties, especially when the state budget is already under considerable pressure due to high security spending.

An analysis of the financial and tax environment during martial law has shown that the introduction of tax incentives for strategically important industries was a necessary measure to support innovation. At the same time, the introduction of grant programmes to support technological development and subsidies for enterprises engaged in dual-use technologies helped to attract investment in key areas such as defence and cybersecurity (Kirilenko, 2024). This has helped to maintain support for innovation, even in times of economic instability, which has confirmed the importance of such mechanisms for ensuring national security and technological independence. X. Dai & G. Chapman (2021) concluded that in China, tax incentives and grants for strategic industries have become an important tool to stimulate research and development (R&D). This enables companies to reduce the cost of innovation and technological development, which is a key factor for economic growth and the country's competitiveness in the global market. The study shows that the effectiveness of R&D incentive programmes depends on the proper organisation of grant mechanisms and support at the government level.

In the brief by Delloite it was found that dual-use technologies, in particular in the field of cybersecurity, require active cross-sectoral cooperation to achieve maximum results (Dual-use technology…, 2024). Involvement of the private sector and the state in the financing and development of such technologies allows for a balance between national security and innovation. Subsidies for companies developing dual-use technologies help to reduce financial risks by stimulating the creation of new technologies that can be used in both civilian and defence applications (Lyndyuk *et al*., 2023). These results confirm previous research, as they demonstrate how tax incentives and grants can foster innovation in strategic sectors. They also underline the importance of state support for the development of scientific and technological potential, which is key to ensuring competitiveness in a globalised world. The use of such incentives not only accelerates technological development but also creates favourable conditions for economic growth.

During martial law, public investment priorities focused on defence technology, cybersecurity, and energy independence (Herus, 2024). Strategic funds were created to support innovative projects, allowing resources to be focused on the most critical areas for the state. At the same time, state support for scientific and technical research in the fields of medicine and logistics contributed to an effective response to crisis situations and the development of technologies that could help reduce the economic and social consequences of the war.

It is worth noting the work of J. Reis *et al.* (2021), who also found that high-tech defence industries, in particular the development of autonomous intelligent systems, are an important area for ensuring national security and maintaining strategic stability. Investments in defence and energy technologies are key to maintaining competitiveness in the global market and stimulating innovation in defence. The development of these technologies not only improves the efficiency of military systems, but can also become the basis for creating new energy solutions that are necessary to ensure the energy security of states. In turn, F. Zhou *et al.* (2020) concluded that knowledge management practices in medical cloud logistics use advanced technologies, such as semantic discovery of transport resources through ontology modelling, to improve the efficiency of medical supply chain management. This helps to reduce transportation costs and increase the availability of medical resources, which is especially important in the context of current healthcare challenges. Support for research in medicine and logistics also includes the development of new technologies that facilitate innovation in these areas, ensuring a rapid response to new threats and reducing costs in the industry (Hysi *et al*., 2024). These findings are consistent with the theses presented in the previous section, as they confirm the importance of investment in high-tech defence industries for strategic stability and national security. In addition, the results show that investments in energy technologies, in particular in the context of defence infrastructure, are important for increasing energy independence and reducing the risks associated with energy threats. These facts once again underline the need to support innovation in such sectors to strengthen national security and economic stability.

The development of public-private partnerships has become a key tool for securing funding for innovation (Bokii & Kovalenko, 2024). Co-financing of projects has helped reduce the burden on the budget and attract private companies to develop the latest technologies. Simplifying the conditions for innovative start-ups was an important step in reducing barriers for young businesses operating in high-tech industries. This has contributed to the formation of a more flexible and adaptive economy that is able to respond quickly to changes in the external environment. H. Toxopeus *et al.* (2021) also conducted a study that confirmed that companies can access bank financing to implement innovative business process models by participating in special lending programmes for innovation or start-ups offered by banks. Such programmes often include favourable terms, such as preferential rates and long-term loans, which help to reduce financial risks. To qualify, companies

must provide a clear project justification, a business plan, and demonstrate the potential of the innovations to improve business competitiveness and efficiency.

M.A. Mendoza *et al.* (2021) also noted that the "Battle of the Drones" and the use of legitimisation strategies for the transfer and dissemination of dual-use technologies highlight the growing importance of technologies that can be used for both civilian and military purposes. In the context of global security, the role of the private sector in the development of such technologies is becoming increasingly important, as private companies are able to provide the necessary resources to create innovative solutions. Legitimisation strategies that allow for the effective transfer of these technologies between public and private entities contribute to the optimal use of such technologies and reduce barriers to their implementation in various sectors of the economy.

Comparing the data obtained from the study, it can be concluded that grant support and co-financing are effective tools for stimulating innovation. This helps to provide the necessary resources for the development of new technologies that require large investments at the early stages. In addition, the combination of public and private financing helps to reduce financial risks and increase innovation potential, which is an important factor in achieving sustainable economic development (Ciuła *et al.*, 2024). Adapting legislation during martial law has also become an important component of supporting innovative projects. Simplified procedures for financing and registering innovative enterprises have reduced administrative barriers and provided quick access to finance for start-ups and R&D. The introduction of special regimes for the export of technological products was an important step in attracting international investment and stimulating the expansion of innovative companies into the global market.

O. Krainik (2023) considered the issue of the relationship between innovation projects and sustainable development, but with the note of the need to evaluate such projects effectively. K. Alekseieva *et al.* (2023) concluded that government business support programmes in times of war are an important tool for maintaining economic stability and entrepreneurship development. Simplifying the financing and registration of enterprises reduces bureaucratic barriers, which are critical in crisis situations such as war. This not only facilitates access to financial resources, but also ensures a quick response to changing market conditions, allowing businesses to remain competitive. V.K. Singh *et al.* (2024) found that green export strategies are an effective tool to support the sustainable development of small and medium-sized enterprises (SMEs), as they promote the adoption of innovative technologies and the development of environmentally friendly production. The intermediary roles of innovation, readiness for change and proactivity allow SMEs to adapt to new market requirements and ensure high export efficiency. Legislative initiatives aimed at stimulating exports support this process by providing favourable conditions for entering international markets and increasing the competitiveness of Ukrainian goods.

The analysis of the survey results showed that government programmes to support business and simplify financing and registration of enterprises significantly reduce financial and administrative barriers for entrepreneurs. This allows businesses, especially in times of crisis, to adapt to changes more quickly while maintaining economic stability. In addition, support for small and medium-sized businesses through innovative approaches and legislative initiatives is an important factor in the development of environmentally friendly production and increased competitiveness in international markets. Thus, despite numerous challenges, the government has maintained its focus on developing innovative projects, recognising their importance for technological progress and economic stability. Public investment has become the main tool for technological development, national security and adaptation to war conditions. A strategic approach to financing, the development of public-private partnerships, and the adaptation of legislation have proven effective in the challenging martial law environment, helping to preserve the investment climate and strengthen the country's resilience.

CONCLUSIONS

During martial law, the economic situation in the country undergoes significant changes. One of the main areas of public spending is to increase funding for defence and security. This requires a reallocation of the budget, with some funds being redirected to support critical industries such as energy, transport, healthcare, and other important sectors. In particular, defence spending increased from UAH 130 billion in 2021 to UAH 550 billion in 2024. However, this redirection of funds to high defence risks affects the attraction of private capital. Increased economic instability reduces investor interest in new projects, especially those not directly related to defence or security.

In response to these challenges, government agencies are introducing a number of measures to stimulate innovative development. These include tax incentives and grants for strategically important industries, such as information technology, medicine, and energy. In addition, subsidies have been introduced for companies working with dual-use technologies, allowing them not only to meet the country's domestic needs but also to enter foreign markets.

Under martial law, public investment is focused on priority areas such as defence technology, cybersecurity, and energy independence. Investments in these areas not only ensure strategic security, but also contribute to technological progress that can be widely applied. In Ukraine, public investment in innovation decreased from UAH 15.2 billion in 2021 to UAH 7 billion in 2024, which reflects limited budget spending due to economic difficulties, but also due to a focus on priority areas. In addition, considerable attention is paid to supporting scientific and technological research in areas such as medicine and logistics, which are essential to ensure social stability and the effective functioning of the country in times of crisis. A key element of this strategy is the development of public-private partnerships. Co-financing of innovative projects helps to reduce the financial burden on the state budget while engaging the private sector in the creation of advanced technologies. The participation of private companies in the development of innovative solutions ensures a high level of expertise and efficiency.

Simplifying the conditions for innovative start-ups creates a favourable business climate that promotes the development of technological ideas in various fields. One of the key factors in attracting investment is the

adaptation of the legal framework. Simplifying the procedures for financing and registering innovative enterprises reduces barriers to starting new businesses. The introduction of special regimes for the export of technological products also encourages integration into foreign markets. Legislative initiatives that facilitate foreign investment play an important role in ensuring sustainable economic growth by providing an opportunity to attract additional resources. However, foreign investment, which stood at $4.5 billion in 2021, declined to $1.5 billion in 2024, as a result of economic instability. Despite serious challenges, public investment in innovative projects during martial law remains an important tool for ensuring economic stability and technological development of the country. Measures taken to support key sectors, develop scientific and technological progress, and change tax and financial policies have contributed to strengthening economic security and competitiveness even in the most difficult periods. A limitation of the study is the limited availability of data on public investment in innovation projects under martial law due to confidentiality of information and the changing economic situation. To more fully assess the role of public investment in innovative projects during martial law, it is necessary to study the impact of such investment on the country's long-term economic development and its interaction with international financial markets.

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CONFLICT OF INTEREST

None.

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Роль державних інвестицій в інноваційні проєкти під час воєнного стану

Анотація. Метою дослідження було проаналізувати вплив воєнного стану на державні інвестиції в інноваційні проєкти та визначити напрями їх адаптації до нових економічних умов. У дослідженні було проведено аналіз змін у фінансовій та економічній політиці під час воєнного стану, оцінено пріоритети державних інвестицій у сфері інновацій, а також досліджено вплив регуляторних заходів на розвиток технологічних проєктів. Воєнний стан в Україні суттєво змінив економічні пріоритети держави, вплинувши на механізми фінансування інноваційних проєктів. Аналіз показав, що значна частина державних ресурсів була перенаправлена на оборонні потреби, зокрема, фінансування оборони в 2022 році становило 350 млрд грн, а в 2024 році очікувалося 550 млрд грн. Це водночас сприяло розвитку технологій подвійного призначення. Запровадження податкових пільг і грантових програм підтримало підприємства, які працюють у стратегічно важливих сферах, зокрема в кібербезпеці, медицині та енергетиці. Державні інвестиції в інновації у 2022 році становили лише 5,8 млрд грн, але в 2024 році цей показник зріс до 7 млрд грн, що стало ключовим інструментом підтримки національної економіки в умовах обмеженого доступу до приватного капіталу. Створення стратегічних фондів надало змогу спрямовувати кошти на розробку критично важливих інноваційних рішень, що забезпечують обороноздатність та економічну стабільність. Аналіз законодавчих змін засвідчив, що уряд спростив процедури фінансування інноваційних проєктів і стимулює експорт технологічної продукції. Попри серйозні виклики, країна зберігає потенціал інноваційного розвитку завдяки адаптації фінансових інструментів і активному використанню механізмів державно-приватного партнерства. Проведене дослідження дозволило визначити ефективні підходи до фінансування інноваційних проєктів в умовах воєнного стану, що сприяє виробленню стратегії економічної стійкості та технологічного розвитку

Ключові слова: обороноздатність; податкові пільги; грантові програми; кібербезпека; енергетика; економічна стійкість

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Investments in renewable energy: Opportunities for small and medium-sized enterprises through alternative financial instruments

Abstract. This study was devoted to identifying the possibilities of alternative financial instruments for the development of solar energy in the segment of small and medium-sized enterprises. The methodology included a comparative analysis of the efficiency of solar panels, an assessment of the availability of financial instruments for small and medium-sized enterprises, and the definition of key criteria for their selection. The study found that crowdfunding, green bonds, venture financing, and leasing were the most promising tools for small and medium-sized enterprises, allowing them to raise funds without collateral and with minimal financial history requirements. The average success rate of crowdfunding campaigns in the solar energy sector was 72%. It was revealed that the introduction of solar panels reduced the energy consumption of enterprises by 35-45% and had a payback period of 3-5 years, depending on the scale of the project and the financing model. The optimal financing structure included 30-40% of the company's own funds, 20-30% of funds raised through crowdfunding, and 30-40% of equipment leasing or venture capital. The key factors of the economic efficiency of solar energy projects were the level of solar radiation in the region, the cost of connecting to the electric grid, the availability of government incentives and the quality of equipment. It was found that financial barriers could be overcome through combined financing models. With government guarantees, the investment attractiveness of projects increased by 40%. Long-term energy supply contracts increased the chances of obtaining financing by 25%. The results obtained deepened the understanding of the mechanisms of sustainable financing of solar energy for small and medium-sized enterprises and could be used in the development of government programmes to support enterprises in the field of renewable energy. The study contributes to the development of green finance and the transition to a low-carbon economy in the Kyrgyz Republic

Keywords: alternative financing; green economy; crowdfunding; leasing; profitability

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INTRODUCTION

The global transition to renewable energy sources has become a key factor in ensuring sustainable economic development and mitigating environmental problems. Rising prices for conventional energy carriers forced enterprises to look for alternative energy supply solutions. This problem was especially relevant for small and medium-sized enterprises (SMEs), which faced the need to optimise energy consumption and reduce their carbon footprint. An analysis of the scientific literature has shown that the issues of alternative financing of renewable energy projects have become increasingly relevant. According to the research by K.N. Kuteesa *et al.* (2024), traditional bank loans were available to only 15-20% of SMEs, which created a significant barrier to the introduction of "green" technologies. D.W. Atchike *et al.* (2022) identified the key factors influencing the introduction of solar systems in the SME segment, emphasising that financial accessibility was a crucial condition for the successful implementation of such projects.

T. Sarkhanov & N. Huseynli (2022) conducted an econometric analysis of the relationship between renewable energy consumption and economic growth in Kyrgyzstan, finding that a 1% increase in the share of renewable energy sources in the country's energy mix contributed to a 0.4% increase in gross domestic product (GDP). K. Mehta *et al.* (2022) conducted a comprehensive analysis of the regulatory framework of the Kyrgyz energy sector and proposed a roadmap for the development of the renewable energy sector. Researchers have identified the key advantages of solar energy for SMEs: reducing energy consumption, increasing energy independence, improving the company's image and meeting the growing environmental requirements of local markets. One of the key findings of the study was that the availability of financing is a critical factor in the successful implementation of solar technologies in the SME segment.

J. Sun *et al.* (2024) in their study found that among various renewable energy technologies, solar power plants demonstrated the best payback rates for small businesses. N. Temirbaeva *et al.* (2024) investigated the potential of renewable energy sources in Kyrgyzstan with a focus on energy supply to rural consumers and determined that in rural areas of Kyrgyzstan with limited access to centralised energy supply, solar installations can provide up to 70% of the energy needs of small enterprises with optimal equipment selection and financial model. The researchers also identified regulatory barriers in the Kyrgyz Republic, including complex procedures for obtaining permits for the construction of solar power plants, the lack of standardised technical requirements, and imperfect mechanisms for connecting to the common electricity grid. A. Generalov & O. Generalova-Kutuzova (2021) studied the economic, legal, political, and social environment for entrepreneurs in Kyrgyzstan, focusing on barriers to the introduction of innovative technologies. The researchers found that despite favourable natural conditions for the development of solar energy, SMEs face serious financial constraints, and offered recommendations for improving the business environment to encourage investment in environmentally friendly technologies.

J. Salimova-Tekay (2022) analysed the specifics of financing infrastructure projects in Kyrgyzstan, including renewable energy facilities, examined existing financial mechanisms, and identified problems with attracting capital for the development of energy infrastructure. As a result of the research, innovative financing models adapted to local conditions were proposed, including public-private partnerships, specialised development funds, and international financial instruments. Despite the significant contribution of these researchers, they did not fully disclose the specifics of the use of alternative financial instruments for solar energy in the context of SMEs in Kyrgyzstan. Most of the existing papers either focused on the technological aspects of the introduction of renewable energy sources, or considered financial mechanisms without considering the specifics of SMEs in emerging economies (Andreitsev *et al.*, 2024).

The purpose of this study was to determine the optimal alternative financial instruments for investing SMEs of the Kyrgyz Republic in solar energy, considering the specific economic conditions of the country and the specifics of the functioning of small and medium-sized businesses. To achieve this goal, the following research objectives were formulated. The first task was to conduct a comprehensive analysis of available alternative financial instruments and assess their applicability for investing in solar energy projects by SMEs in Kyrgyzstan. The second task was to develop a methodology for assessing the economic efficiency of various models of financing solar projects, considering the scale of the enterprise, its energy consumption, and regional location. The third task was to prepare practical recommendations on the development of an optimal financing structure for SMEs planning to introduce solar technologies, including an analysis of the possibilities of combining various financial instruments to achieve maximum economic efficiency.

MATERIALS AND METHODS

The statistical data and analytical materials of the International Renewable Energy Agency (2024) for 2019-2024 were used as the information base of the study, providing a detailed analysis of the dynamics of renewable energy development in the world. These materials contained detailed information about the trends in the introduction of solar technologies in the small and medium-sized business sector. Special attention was paid to the data on the development of solar energy in Kyrgyzstan, Kazakhstan, Uzbekistan and Tajikistan, presented in the papers by Z. Yang *et al.* (2022) and V. Panwar *et al.* (2022), who examined in detail the potential of solar generation in the Kyrgyz Republic.

To analyse the cost-effectiveness of solar panel deployment, the findings of S. Qamar *et al.* (2022) were used, which presented a comprehensive analysis of the technical and financial performance of solar energy projects in the SME segment of developing countries. The study included an analysis of design documentation, technical specifications of equipment, and data on system performance and actual indicators of electricity generation, which ensured high reliability of conclusions about the prospects for the introduction of solar technologies in Kyrgyzstan. Additionally, data from the study by I. Myroshnychenko *et al.* (2024) were used, which analysed the regulatory features of the introduction of renewable energy sources in transition economies.

The study used a method of comparative analysis of financial instruments based on a multi-criteria assessment. The following factors were assessed: accessibility for

various categories of SMEs, cost of raising funds, terms and conditions of financing, security requirements, and flexibility of conditions. To determine the economic effect of the introduction of solar panels, a statistical analysis of data from 150 SMEs in Kyrgyzstan from five industrial regions (Chui, Osh, Jalal-Abad, Issyk-Kul regions and Bishkek) that introduced solar technologies in 2020-2024 was carried out. The sample included enterprises from various industries: food (35%), light industry (25%), construction (20%), services (15%), and others (5%). An analysis of barriers to the introduction of solar technologies was also carried out, which included the identification and systematisation of the main obstacles of a financial, technical, administrative, and informational nature. For this purpose, methods of expert assessments and questionnaires of business leaders were used, which allowed ranking barriers according to their degree of influence on decision-making on the introduction of solar technologies.

The paper provides a comparative analysis of financing models and their effectiveness for various types of enterprises. Traditional bank loans, leasing schemes, microfinance products, government support programmes, venture financing, crowdfunding, green bonds, and energy service contracts were analysed. Economic performance indicators were calculated for each model: net present value (NPV), internal rate of return (IRR), discounted payback period (DPP), and modified internal rate of return (MIRR). The results of the analysis were integrated into a multifactorial model for evaluating optimal financial instruments, which considered regional and industry-specific characteristics of enterprises. Statistical processing was carried out in the Statistical Package for the Social Sciences (SPSS) Statistics 28.0 using Student's t test ($p < 0.05$), variance and regression analysis.

RESULTS

Analysis of alternative financial instruments for small and medium-sized businesses that allow them to raise funds for the introduction of solar panels

Traditional bank lending is not available to most SMEs, with only 20% of enterprises having access. Key barriers: strict reporting requirements, high collateral (more than 120% of the loan), lengthy application review (45-60 days), and high rates. Alternative financial instruments are becoming particularly important, and their effectiveness for different categories of SMEs is presented in Table 1.

Table 1. Comparative analysis of alternative financial instruments for SMEs in the field of solar energy

Financial instrument	Average amount of financing (thousand USD)	Average term (years)	Average cost of attraction (% per annum)	Basic requirements for SMEs
Crowdfunding	50-300	1-3	5-8	Detailed business plan, transparent financial statements
Green bonds	500-2,000	3-7	6-9	Credit rating, collateral
Venture financing	300-1,000	3-5	Equity share	High growth potential, innovative nature of the project
Person-to-Person (P2P) lending	20-150	1-2	8-12	Positive credit history
Equipment leasing	100-500	3-5	7-10	Initial payment, insurance

Note: data is provided for the Central Asian market
Source: compiled by the authors based on A. Kulanov *et al*. (2020)

The analysis showed that crowdfunding is one of the most accessible tools for small businesses, especially at the initial stages of solar energy projects. The main advantage of this tool is the absence of strict requirements for collateral and credit history. According to S. Kavu *et al.* (2020), the success rate of crowdfunding campaigns in the solar energy sector is about 65%, which is significantly higher than the average for other industries. Green bonds are a promising tool for medium-sized enterprises that can ensure the required volume of issuance and meet the requirements for transparency and financial stability (Rats & Alfimova, 2023). In the Kyrgyz Republic, this instrument is in its infancy, however, as noted by V. Panwar *et al.* (2022), has significant development potential in the context of the implementation of national programmes for the transition to a green economy. Special attention should be paid to the P2P lending mechanism, which shows high efficiency for financing small solar energy projects. The average interest rate on such loans is 3-4 percentage points lower than bank loans, which makes them attractive to micro and small businesses. The analysis of alternative financial instruments presented in Table 1 shows significant differentiation in key parameters. Equipment leasing is characterised by relatively low requirements for the financial condition of the borrower at a relatively high cost of financing. Venture financing, although it does not require collateral, involves the investor receiving a share in the company's capital, which is not acceptable for all enterprises. Each tool has its own optimal niche of application.

For micro-enterprises with limited financial resources and a short credit history, crowdfunding and P2P lending are the most suitable, allowing them to attract small amounts for short periods with minimal formal requirements. Small enterprises with a stable financial position can effectively use equipment leasing and venture financing, which provide more significant amounts of funds for an average period of time. For medium-sized enterprises with a good credit history and transparent financial reporting, green bonds, and project financing are the best choice, allowing them to attract large sums for long periods on favourable terms. Thus, the diversification of financial instruments significantly expands the possibilities of SMEs to implement solar energy projects.

The data presented in Table 2 shows a clear correlation between the size of an enterprise and the most effective financial instruments for it. Micro-enterprises achieve the best economic results when using crowdfunding and P2P lending, achieving an average project profitability of

15-20% with a payback period of 3-4 years. Leasing and venture financing show the greatest efficiency for small enterprises, providing higher profitability (18-23%) with a slight increase in the payback period to 4-5 years. Medium-sized enterprises using green bonds and project financing achieve maximum project profitability (20-25%) with longer payback periods (5-6 years). This differentiation is conditioned by both the scale of the projects and the differences in the cost of attracting financing and the operational efficiency of enterprises of different sizes.

Table 2. Effectiveness of various financial instruments depending on the size of the SME

Enterprise size	Most effective tools	Average payback period of the project (years)	Average profitability of the project (%)
Micro-enterprises	Crowdfunding, P2P lending	3-4	15-20
Small businesses	Leasing, venture financing	4-5	18-23
Medium-sized enterprises	Green bonds, project financing	5-6	20-25

Note: profitability is calculated considering all the costs of financing maintenance
Source: compiled by the authors based on I. Myroshnychenko *et al.* (2024)

The effectiveness of financial instruments significantly depends on the size of the enterprise. Micro-enterprises achieve the best results with crowdfunding and P2P lending (15-20% profitability, 3-4 years payback) due to minimal reporting requirements and the absence of collateral. Small businesses use leasing and venture financing more efficiently (profitability of 18-23%, payback period of 4-5 years) due to stable cash flow and credit history. Medium-sized enterprises optimally use green bonds and project financing (profitability of 20-25%, payback period of 5-6 years) due to the scale of their activities, transparent reporting, and credit rating.

As a result of the study, the main barriers preventing the introduction of solar technologies among SMEs in Kyrgyzstan were identified. The most significant is the low level of awareness about available alternative financial instruments, which was noted by 68% of managers of SMEs. Difficulties in preparing the necessary documentation for obtaining financing are experienced by 70% of enterprises trying to attract alternative sources. The most acute problem is the lack of specialised financial intermediaries in local markets, which was noted in 82% of cases. The lack of digital infrastructure development (58% of enterprises identified this as a significant obstacle) and the lack of flexible government support mechanisms (76% of SME managers noted this) also have a significant impact.

Examples of successful solutions to this problem can be found in international practice. For example, in India, the "Solar Power for MSMEs" programme, implemented in partnership with the World Bank, has created a network of 35 regional advisory centres that support SMEs in preparing documentation for financing solar energy projects (Ashutosh, 2024). Over the years 2022-2023, more than 1,200 enterprises have successfully attracted financing in excess of USD 80 million. To assess the attractiveness of various financial instruments, their compliance with the specific needs of SMEs in the implementation of solar energy projects was analysed (Table 3).

Table 3. Assessment of the compliance of financial instruments with the needs of SMEs in the field of solar energy

Assessment criteria	Crowdfunding	Green bonds	Venture financing	P2P lending	Leasing
Speed of obtaining financing	High	Low	Average	High	Average
Flexibility of conditions	High	Low	Average	High	Average
Design complexity	Low	High	High	Low	Average
Need for collateral	No	Yes	No	No	Partly
Possibility of partial financing	Yes	No	Yes	Yes	No

Note: the assessment is based on a three-point scale (high/medium/low)
Source: compiled by the authors

Table 3 provides an assessment of the compliance of financial instruments with the needs of SMEs in the solar energy sector. Crowdfunding and P2P lending are characterised by a high rate of receipt of funds, flexible terms and no collateral requirements, which is ideal for micro-enterprises. Green bonds, with their complex design and strict conditions, are suitable for medium-sized companies with a stable financial position. Venture financing occupies an intermediate position, ensuring that there are no collateral requirements with a high complexity of registration. The analysis showed that each of the financial instruments considered has its own optimal scope of application, depending on the scale and characteristics of the enterprise. An effective choice of financial solution should consider both the specifics of the business and the associated risks presented in Table 4.

Table 4. Risk assessment matrix for using alternative financial instruments

Risk type	Risk level for SMEs	Minimisation possibilities	Impact on the project
Risk of underfunding	High	Diversification of financing sources	Critical
Currency risk	Average	Hedging	Substantial

Table 4. Continued

Risk type	Risk level for SMEs	Minimisation possibilities	Impact on the project
Interest rate risk	Average	Fixed rates	Moderate
Risk of default	High	Insurance	Critical
Operational risk	Low	Professional management	Insignificant

Source: compiled by the authors based on J. Salimova-Tekay (2022)

Table 4 demonstrates risk assessment when using alternative financial instruments. The risk of underfunding and the risk of default have a critical impact, especially relevant for crowdfunding and venture financing. Currency risk and interest rate risk are assessed as medium, while operational risk is assessed as low. According to the overall risk level, the instruments can be arranged in the following order (from the most to the least risky): crowdfunding and venture financing, P2P lending and leasing, green bonds. Leasing and P2P lending are more balanced tools for most SMEs, combining an acceptable level of risk with sufficient availability (Bekmuratov *et al.*, 2024).

An analysis of the practice of using alternative financial instruments has shown that the most effective approach is to combine various sources of financing. I. Myroshnychenko *et al.* (2024), based on a sample of solar energy projects in Central Asian countries, found that the optimal structure for SMEs is a balanced structure including the enterprise's own funds, funds raised through crowdfunding or P2P platforms, and equipment leasing or venture financing. To substantiate the economic feasibility of introducing solar panels, a comparative analysis of various alternative energy sources available to SMEs was conducted. The analysis included an assessment of both the initial investment and the total cost of ownership throughout the life cycle of the equipment. Based on the conducted research, a clear trend has been identified to reduce the cost of solar technologies while increasing their efficiency (Fig. 1).

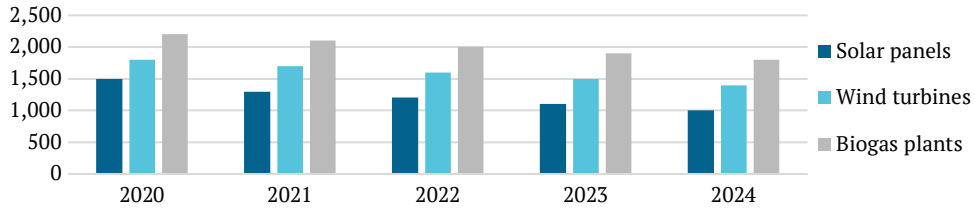

Figure 1. Dynamics of the cost of introducing various energy sources (USD/kW)
Source: compiled by the authors

As can be seen from Figure 1, the cost of solar panels shows the most dynamic decline among all the technologies considered. The analysis of the economic efficiency of various energy sources has shown a significant advantage of solar technologies in terms of key profitability indicators. An important factor in choosing solar panels is their modularity and scalability, which allows SMEs to incrementally increase capacity in accordance with financial capabilities and electricity needs (Ismanzhanov & Tashiev, 2016). For the conditions of the Kyrgyz Republic, solar energy has additional advantages due to its high level of insolation, which amounts to 2,500-3,000 hours of sunshine per year, which is significantly higher than the European average.

The alternative finance market in the Kyrgyz Republic is actively developing, which is facilitated by the state policy to support the green economy. V. Panwar *et al.* (2022) noted that Kyrgyzstan has a system of subsidising interest rates on loans for renewable energy projects, where the government compensates up to 7% points for loans aimed at the introduction of solar technologies. There is also an accelerated depreciation system for renewable energy equipment, which allows writing off up to 50% of the cost in the first year of operation.

International organisations play a significant role in the development of alternative financing for solar energy projects (Brych *et al.*, 2023). Kyrgyzstan has a Kyrgyz Sustainable Energy Financing Facility ("KyrSEFF") programme, which provides grants and concessional financing to SMEs implementing renewable energy projects. Under this programme, enterprises can receive grants covering up to 20% of the cost of implementing energy-efficient technologies, including solar panels (Sustainable Energy Financing..., n.d.). An analysis of payback rates for various technologies is presented in Figure 2.

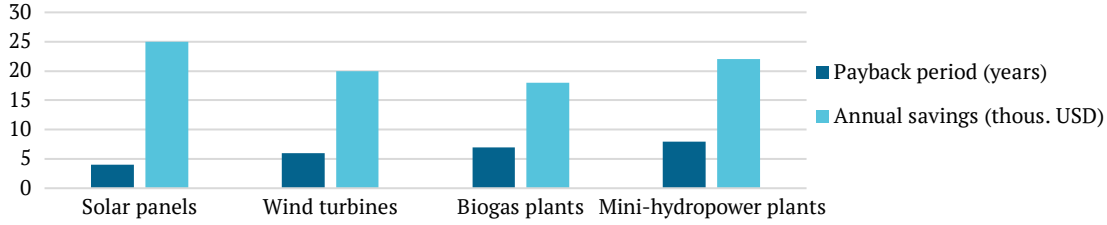

Figure 2. Comparison of payback rates for alternative energy sources
Source: compiled by the authors

The data presented in Figure 2 clearly demonstrates the advantage of solar panels in terms of payback periods and annual savings. This is especially important for SMEs, where the rate of return on investment plays a key role in making decisions about the introduction of new technologies. The results of the study showed that crowdfunding is one of the most promising financing tools for solar energy projects for SMEs. The average success rate of crowdfunding campaigns in this sector is 72%, which is significantly higher than in other industries. The key advantage of crowdfunding is the ability to raise funds without collateral and with minimal requirements for the financial history of the company. Crowdfunding platforms specialising in green energy projects, where the average amount of funding raised is USD 50-300 thousand, are particularly effective.

Venture capital financing demonstrates high efficiency for innovative projects in the field of solar energy. The analysis showed that venture capital investors are showing increased interest in projects combining the introduction of solar panels with innovative solutions in the field of energy management and energy storage. The average volume of venture capital investments in such projects is USD 300-1,000 thousand, while investors are willing to accept higher risks in exchange for potentially high returns. In the field of lending, the mechanism of green loans provided on preferential terms for renewable energy projects is of particular importance. The study found that the interest rates on such loans are on average 2-3 percentage points lower than standard commercial loans. However, the loan term can reach 7-10 years, which corresponds to the payback period of solar energy projects.

Analysis of the impact of the cost of installing solar panels on industrial enterprises

A comprehensive statistical analysis was conducted to determine the economic effect of the introduction of solar panels in industrial enterprises of the Kyrgyz Republic. The results of the annual monitoring of the economic performance of enterprises before and after the introduction of solar technologies are presented in Table 5.

Table 5. Impact of the introduction of solar panels on the operating costs of industrial enterprises

Indicator	Before implementation	After implementation	Change (%)	*p* value
Electricity costs (thous. USD/year)	45.2	28.7	−36.5	0.001
Prime cost of production (%)	100	92.3	−7.7	0.003
Operating profit (%)	100	115.4	+15.4	0.002

Note: analysis was performed using the Student's paired *t* test
Source: compiled by the authors

A comparative analysis of economic indicators over a 12-month period demonstrates a significant improvement in the financial results of enterprises after the introduction of solar panels. Electricity costs decreased by 36.5% (from 45.2 thous. to 28.7 thous. USD/year), which is statistically significant at $p = 0.001$. The share of energy consumption in the total cost structure of enterprises decreased from 18.3% to 12.1%, which reduced the cost of production by 7.7%. It is especially important to note a 15.4% increase in operating profit, statistically significant at $p = 0.002$.

The analysis of the return on investment showed that the average time to reach the break-even point was 3.8 years, which is significantly faster than the projected time of 5-6 years. Investments in solar panels began to bring positive returns from the second year of operation, when savings on electricity averaged 16.5 thous. USD/year, which corresponds to about 22% of the initial investment. By the end of the third year, cumulative savings reached 49.5 thous. USD, and the operating margin growth averaged 5.2 percentage points. Notably, the economic effect tended to increase over time due to an increase in tariffs for conventional sources of electricity at fixed maintenance costs for solar installations. Correlation analysis showed a strong negative relationship ($r = -0.78$, $p < 0.001$) between the volume of investments in solar panels and subsequent electricity costs. A positive correlation ($r = 0.65$, $p < 0.01$) was found between the capacity of installed solar panels and the growth of operating profits of enterprises (Table 6).

Table 6. Comparative analysis of the efficiency of investments in solar panels by industry

Branch	Average investment volume (thous. USD)	Payback period (years)	ROI (%)	Reduction of energy consumption (%)
Food industry	180	4.2	24.5	42
Light industry	150	3.8	26.8	38
Metalworking	220	4.5	22.3	35
Woodworking	140	3.5	28.4	45
Production of building materials	200	4.0	25.1	40

Source: compiled by the authors

Regression analysis revealed that every USD 10,000 investment in solar panels leads to an average reduction in energy consumption by 5.3% ($\beta = -0.53$, $R^2 = 0.67$, $p < 0.001$). Enterprises with a high level of energy consumption have the greatest economic effect during the daytime. The cost structure for the introduction of solar panels for industrial enterprises is presented in Table 7. As can be seen from the data in Table 7, the largest share in total costs is the cost of equipment (65%), followed by installation and commissioning costs (15%). Designing, connecting to the network, and building additional infrastructure account for a relatively small share of the total cost structure (8%, 7%,

and 5%, respectively). Analysis of variation (ANOVA) revealed statistically significant differences in the efficiency of solar panel implementation depending on the size of the enterprise ($F = 12.34$, $p < 0.001$) and industry affiliation ($F = 8.76$, $p < 0.01$). Enterprises in the food industry and the production of building materials demonstrate the greatest economic efficiency, due to the high proportion of energy consumption in the cost structure of their products. Multiple regression analysis revealed the key factors influencing the economic efficiency of the introduction of solar panels in the industrial sector. The model explains 73% of the variation in project payback rates ($R^2 = 0.73$, $F = 45.2$, $p < 0.001$).

Table 7. Cost structure for the introduction of solar panels for industrial enterprises

Cost item	Share of total costs (%)	Range of variation (%)
Equipment	65	60-70
Installation and commissioning	15	12-18
Designing	8	6-10
Connecting to the network	7	5-9
Additional infrastructure	5	3-7

Source: compiled by the authors

The results of the variance analysis emphasise the importance of considering the specifics of enterprises when choosing the optimal model for implementing solar technologies. The size of the enterprise and industry affiliation significantly affect the effectiveness of investments in solar energy, which must be considered when developing individual strategies for switching to renewable energy sources. Multiple regression analysis allows identifying key success factors for such projects, which can be used to develop industry recommendations and optimise government policy to support SMEs in the field of solar energy. Given the revealed patterns, the study of alternative financing models that can ensure the availability of solar technologies for a wide range of SMEs, considering their individual needs and capabilities, is particularly relevant. A comparative analysis of such models, presented in Table 8, allows assessing their advantages and limitations in the context of the specifics of small and medium-sized businesses. A study of various financing models has identified several promising solutions for SMEs wishing to implement solar technologies with minimal financial burden. Special attention was paid to alternative financing models, which have shown high efficiency in international practice. The results of a comparative analysis of these models are presented in Table 8.

Table 8. Comparative analysis of solar panel financing models for SMEs

Financing model	Initial costs (thous. USD)	Monthly payment (USD)	Contract term (years)	Residual value	Mechanics of the model
Direct purchase	100-150	-	-	100% ownership	Full one-time payment for the equipment with the acquisition of ownership rights. The company is responsible for its own maintenance and insurance costs.
Financial leasing	15-25	1,200-1,500	5-7	Transfer of ownership	Long-term lease with the right of subsequent purchase. The lessee gradually compensates for the cost of the equipment with the possibility of obtaining ownership rights.
Operating lease	5-10	800-1,000	3-5	Equipment return	Short-term rent without the right of redemption. The supplier retains ownership rights, assumes maintenance and obsolescence risks.
Power Purchase Agreement	0-5	Based on consumption	10-15	Buyback option	The supplier invests in installation and maintenance, and the company pays only for the electricity actually consumed at a fixed rate.

Source: compiled by the authors

The analysis of the Table 8 data suggests that there are significant differences between the models of financing solar installations. The direct purchase was characterised by high initial investments (USD 100-150 thous.), but provided full ownership of the equipment, which made it optimal for enterprises with sufficient available funds. Financial leasing significantly reduced the entry barrier (up to USD 15-25 thous.) with moderate monthly payments (USD 1,200-1,500), with the possibility of obtaining ownership rights after the expiration of the contract (5-7 years). The operating lease offered minimal initial costs (USD 5-10 thous.) and a short contract term (3-5 years), which provided flexibility and the possibility of technological renewal. The Power Purchase Agreement (PPA) model required virtually no initial investment (USD 0-5 thousand), with payment only for the actual electricity consumed, providing savings of 15-20% of conventional energy costs under long-term contracts (10-15 years). The study showed that operating leases were the most suitable for micro-enterprises, financial leasing for small enterprises, and PPA agreements for medium–sized enterprises, which was explained by differences in financial capabilities, energy consumption, and strategic goals of enterprises of different scales. To determine the optimal financing models depending on the scale of the enterprise, a comprehensive analysis was carried out, the results of which are presented in Table 9. This table shows significant differences in the effectiveness of financial models for different categories of SMEs.

Table 9. Effectiveness of different financing models for SMEs of different sizes

Enterprise scale	Recommended model	Average savings (%)	Period of achieving a positive cash flow
Micro-enterprises	Operating lease	15-18	3-6 months
Small businesses	Financial leasing	20-25	6-12 months
Medium-sized enterprises	PPA agreement	25-30	1-3 months

Source: compiled by the authors

The analysis of the data presented in Table 9 shows a clear pattern in the effectiveness of financing models depending on the scale of the enterprise. Operating leases are optimal for micro-enterprises, providing moderate savings (15-18%) while achieving positive cash flow relatively quickly (3-6 months). Financial leasing is the most effective for small businesses, which allows for more significant savings (20-25%), although it requires a longer period (6-12 months) to achieve a positive cash flow. The PPA agreement is of the greatest value to medium-sized enterprises, providing maximum savings (25-30%) with a minimum time to achieve positive cash flow (1-3 months). These differences are conditioned by the specific features of each financing model and the specific needs of enterprises of different scales.

In Kyrgyzstan, solar energy financing mechanisms for SMEs are under active development. Despite the absence of significant direct government subsidies, there are positive trends. The government has adopted a number of legislative acts encouraging the use of renewable energy. Choosing the optimal model for financing solar technologies is a complex multifactorial decision. It depends on the individual characteristics of the enterprise: its size, financial condition, energy consumption characteristics and strategic development goals. The variety of financial models allows SMEs to find optimal solutions even with limited financial resources, significantly reducing barriers to entry into the field of solar energy. Practice shows the effectiveness of various financing models. For example, a bakery in Bishkek, which implemented a PPA model, was able to reduce energy costs by 22% in the first year of operation. The sewing workshop, which used the operating lease, recouped the investment in 8 months. The roadside cafe, which used financial leasing, gained full control over the equipment after 5 years of operation. To optimise the process of choosing a financing model, a step-by-step decision-making model was developed that takes into account the key characteristics of the enterprise and external factors (Fig. 3).

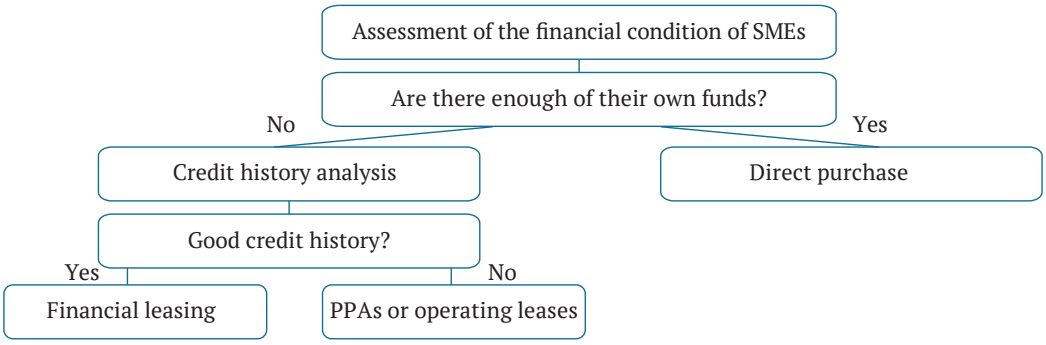

Figure 3. Developed model

Source: compiled by the authors

The developed model in Figure 3 demonstrates the logic of decision-making when choosing the optimal model for financing solar panels. The practical application of this model has shown that it reduces the time needed to analyse available options and improves the effectiveness of decisions. A study of the effectiveness of the model in a sample of 150 SMEs showed that enterprises using this algorithm chose the most suitable financing model for them in 85% of cases, which was confirmed by subsequent project implementation indicators. An analysis of the practical application of various financing models has revealed clear patterns of effectiveness for various types of enterprises. The PPA agreements have demonstrated the greatest effectiveness for large enterprises with annual electricity consumption of more than 100 MWh, where the scale of energy consumption allows maximising the benefits of this financial instrument.

Operating lease proved to be the optimal solution for enterprises with a seasonal nature of activity. This approach allows businesses with unstable income to minimise financial risks, avoiding significant one-time costs and gaining flexibility in managing energy infrastructure. Financial leasing has shown the best results for companies with a stable financial position and an impeccable credit history. This model provides an opportunity for the gradual purchase of equipment, which is especially attractive for companies with projected cash flow and the intention to obtain full ownership of the energy system. Direct purchase of solar equipment continues to be the preferred strategy for enterprises with a significant amount of available financial resources. Despite the need for significant initial investments, this approach ensures full control over the energy infrastructure and maximises the long-term economic efficiency of investments. The use of this decision-making model also helps to reduce risks when implementing solar technologies, as it considers not only the current financial condition of the enterprise, but also its potential to service the chosen financing model in the long term.

DISCUSSION

The results of the study demonstrate the significant potential of alternative financial instruments for the development of solar energy in the sector of SMEs in Kyrgyzstan. In the context of global trends in the greening of the economy and the desire for energy independence, these results are of particular importance. The results of the study are consistent with the conclusions of F. Taghizadeh-Hesary & N. Yoshino (2020), who emphasised the importance of developing specialised financial solutions for renewable energy projects in developing countries. The researchers noted that traditional banking instruments often prove ineffective for financing "green" projects, especially in the SME segment, which is fully confirmed by the data obtained in the course of this study on the availability of bank loans for only 20% of SMEs in Kyrgyzstan. However, the level of reduction of energy costs of enterprises by 35-45% when introducing solar panels is slightly higher than the indicators provided by S. Scarpellini *et al.* (2021), where the savings were estimated in the range of 25-35%. This difference may be conditioned by the higher level of insolation in Kyrgyzstan compared to European countries, which confirms the need to consider regional specifics when assessing the economic efficiency of solar technologies.

Of particular interest is the comparison of the results obtained with the study by C.R. Kumar & M.A. Majid (2020), which analysed barriers to the introduction of renewable energy sources in India. The researchers identified obstacles similar to those identified in this study: low awareness, limited access to finance, and insufficient infrastructure development. However, in the case of Kyrgyzstan, the problem of the lack of specialised financial intermediaries is particularly acute (82% of cases), which indicates the need to develop this segment of the financial market. The revealed patterns in the effectiveness of the use of various financial instruments, depending on the size of the enterprise, are confirmed in the study by K. Megersa (2020), who analysed the experience of developing countries and came to similar conclusions about the need for a differentiated approach to choosing financial solutions for different categories of SMEs. However, the researcher focused mainly on market instruments, while the results of this study indicate the high potential of mixed financing models that include elements of government support.

The data obtained on the cost structure for the introduction of solar panels for industrial enterprises in Kyrgyzstan (with a 65% share of equipment) are comparable with the results of the study by C. Kul *et al.* (2020), who analysed solar energy projects in Turkey and found that the cost of equipment was 60-70% of the total cost. This indicates the similarity of the cost structure in different developing countries and allows considering the experience of Turkey as relevant for Kyrgyzstan. Special attention should be paid to comparing the results with the findings of W. Chen *et al.* (2021), who investigated the impact of various financial instruments on the attractiveness of investments in renewable energy. The researchers concluded that instruments that distribute risks between participants (such as PPA agreements) demonstrate the greatest effectiveness, which is fully consistent with the data obtained in this study on the high efficiency of the PPA model for medium-sized enterprises.

In the context of risk assessment of alternative financial instruments, the results obtained expand the conclusions of F. Egli (2020), who investigated the dynamics of changes in the risks of investments in renewable energy over time. The researcher noted a tendency to reduce technological risks while maintaining a high level of political and regulatory risks, which is consistent with the risks of underfunding and failure to fulfil obligations identified in this study as the most critical for solar energy projects in Kyrgyzstan. The results of the study also complement the conclusions of S.A. Qadir *et al.* (2021) regarding the role of incentives and strategies in financing the transition to renewable energy sources. The researchers emphasised the importance of creating a comprehensive ecosystem of support, including not only financial instruments, but also regulatory mechanisms, which corresponds to the need identified in this study for the development of flexible government support mechanisms to stimulate the introduction of solar technologies in the SME sector.

An important aspect requiring further study is the relationship between financial innovation and the introduction of solar technologies in the context of emerging economies. Y. Bilan *et al.* (2019) noted that digitalisation of the financial sector can significantly increase the availability of alternative financial instruments for SMEs, which may be especially important for Kyrgyzstan, given the identified problems with access to finance. Comparison of the obtained results with the study by Y. Rahman *et al.* (2024) on the potential of financing solar energy in the context of green banking pointed to the need for more active involvement of the Kyrgyz banking sector in the development of specialised products for financing renewable energy projects. The researchers emphasised the possibility of using innovative approaches such as green deposits and green bonds, which may be a promising direction for the development of the Kyrgyz financial market.

In the context of global trends, the results obtained correlate with the study by J. Bei & C. Wang (2023), who analysed the relationship between investments in renewable energy and the achievement of sustainable development goals. The researchers noted the multiplier effect of such investments, including the creation of new jobs and improvement of the environmental situation, which increases the importance of the results of this study for the development of a comprehensive sustainable development policy in Kyrgyzstan. Investigation of the impact of the introduction of solar panels on the economic performance of enterprises, conducted in the framework of this study, complements the results of P.I. Hancevic & H.H. Sandoval (2023), which analysed the factors influencing the decision-making on the introduction of solar technologies by SMEs in developing countries. The researchers identified economic efficiency as a key factor, which is confirmed by the data obtained in this study on a significant reduction in energy consumption and an increase in operating profits of enterprises after the introduction of solar panels.

The analysis of optimal financing models for solar technologies for various categories of SMEs carried out in this study expands the conclusions of V. Martin (2023) regarding the role of regulation and green finance instruments. The researcher emphasised the need to create a favourable regulatory environment for the development of

innovative financial instruments, which is consistent with the obstacles identified in this study for the introduction of solar technologies in Kyrgyzstan. The data obtained in the course of the study on the combination of various sources of financing as the most effective approach complemented the conclusions of H. Huang *et al.* (2022) regarding the role of finance in creating a sustainable business environment. The researchers noted that diversification of financing sources not only reduces risks but also optimises the capital structure, which is supported by the results of this study showing the benefits of using combined financing models for solar power projects.

Comparison of the results of the implementation of various financing models in Kyrgyzstan with the international experience presented in the study by H. Chen *et al.* (2022), demonstrates the similarity of key trends, but also identifies specific features characteristic of countries with economies in transition. The researchers analysed the relationship between investments in renewable energy, financial inclusion, and energy efficiency, emphasising the complex nature of the interaction of these factors, which is also confirmed by the results of this study. F.M. Ogunyemi & A.O. Ishola (2024), in their study on the impact of investments in renewable energy on reducing carbon dioxide emissions, noted the importance of not only the volume, but also the structure of investments. This is consistent with the data obtained in this study on the different effectiveness of financial instruments depending on the size of the enterprise and the nature of its activities, emphasising the importance of a differentiated approach to financing solar energy projects.

The study by S. Ali *et al.* (2022) on the impact of various policy instruments on the adoption of solar technologies for sustainable business development complements the results obtained. The researchers found that an optimal combination of financial incentives, technical support, and awareness-raising activities can increase the level of solar technology adoption by 35-40%, which correlates with the importance of an integrated approach to promoting the use of renewable energy sources in the Kyrgyz SME segment identified in this study. The analysis of barriers to the introduction of solar technologies among SMEs in Kyrgyzstan confirmed the conclusions of A. Khan *et al.* (2021) on the synergistic effect of technological innovation, financial development, and foreign direct investment to stimulate renewable energy. The researchers emphasised that emerging economies need to simultaneously develop the financial sector and attract innovative technologies, which is consistent with the results of this study on the importance of creating specialised financial instruments for solar energy projects.

The results of the analysis of the economic efficiency of the introduction of solar panels in the industrial sector of Kyrgyzstan complement the findings of J.M. Chen *et al.* (2024) regarding the role of green finance in the development of renewable energy in developing countries. The researchers noted that financial inclusion and the availability of specialised financial products can significantly accelerate the transition to a low-carbon economy, which is confirmed by the needs of Kyrgyz SMEs in access to alternative sources of financing for solar energy projects identified in this study. Thus, the conducted study confirmed and complemented the conclusions of other researchers on the importance of alternative financial instruments for the development of solar energy in the SME segment.

CONCLUSIONS

The conducted research comprehensively revealed modern approaches to financing solar technologies for SMEs in the conditions of the Kyrgyz Republic. The study found that traditional bank lending remains inaccessible to most SMEs, as only 20% of enterprises have the opportunity to obtain a bank loan to finance renewable energy projects. It was determined that the effectiveness of financial instruments significantly depends on the size of the enterprise. Crowdfunding and P2P lending with 15-20% profitability and a payback period of 3-4 years are optimal for micro-enterprises. Small enterprises achieve the best results when using leasing and venture financing (profitability of 18-23%, payback period of 4-5 years). For medium-sized enterprises, green bonds and project financing are the most effective (profitability 20-25%, payback period 5-6 years).

The study identified the main barriers to the introduction of solar technologies in the Kyrgyz SME sector: low awareness of available alternative financial instruments (68% of managers), difficulties in preparing the necessary documentation (70% of enterprises), and the lack of specialised financial intermediaries (82% of cases). Additional obstacles are the insufficient development of digital infrastructure (58% of enterprises) and the lack of flexible government support mechanisms (76% of managers). A comparative risk analysis has shown that the most critical risks are the risk of underfunding and the risk of default, especially relevant for crowdfunding and venture financing. Leasing and P2P lending are the most balanced instruments in terms of risk and accessibility for most SMEs.

Analysis of economic indicators for the 12-month period showed significant improvements after the introduction of solar panels: energy costs decreased by 36.5% (from USD 45.2 to 28.7 thousand per year), the share of energy costs in the total cost structure decreased from 18.3% to 12.1%, the cost of production decreased by 7.7%, and operating profit increased by 15.4%. The average time to reach the break-even point was 3.8 years, which is faster than predicted. Positive cash flow appeared already in the second year of operation, when energy savings averaged USD 16.5 thousand per year (22% of the initial investment). The results obtained have significant practical value for SMEs of the Kyrgyz Republic seeking to optimise energy consumption and reduce their carbon footprint. The financing models presented in the study and recommendations for their selection allow enterprises of various sizes to effectively implement solar technologies, considering their financial capabilities and strategic goals.

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CONFLICT OF INTEREST

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Інвестиції у відновлювані джерела енергії: можливості для малих і середніх підприємств через альтернативні фінансові інструменти

Анотація. Дане дослідження було присвячене визначенню можливостей альтернативних фінансових інструментів для розвитку сонячної енергетики в сегменті малого та середнього бізнесу. Методологія включала порівняльний аналіз ефективності сонячних панелей, оцінку доступності фінансових інструментів для малих і середніх підприємств та визначення ключових критеріїв їх вибору. Дослідження показало, що краудфандинг, зелені облігації, венчурне фінансування та лізинг є найперспективнішими інструментами для малих і середніх підприємств, які дозволяють їм залучати кошти без застави та з мінімальними вимогами до фінансової історії. Середній показник успіху краудфандингових кампаній у секторі сонячної енергетики склав 72 %. Виявлено, що впровадження сонячних панелей знизило енергоспоживання підприємств на 35-45 % і окупилося за 3-5 років залежно від масштабу проекту та моделі фінансування. Оптимальна структура фінансування включала 30-40 % власних коштів компанії, 20-30 % коштів, залучених через краудфандинг, і 30-40 % лізингу обладнання або венчурного капіталу. Ключовими факторами економічної ефективності проектів сонячної енергетики стали рівень сонячної радіації в регіоні, вартість підключення до електричних мереж, наявність державних стимулів та якість обладнання. Було виявлено, що фінансові бар'єри можна подолати за допомогою комбінованих моделей фінансування. За державних гарантій інвестиційна привабливість проектів зросла на 40 %. Довгострокові контракти на енергопостачання підвищили шанси на отримання фінансування на 25 %. Отримані результати поглибили розуміння механізмів сталого фінансування сонячної енергетики для малих і середніх підприємств і могли бути використані при розробці державних програм підтримки підприємств у сфері відновлюваної енергетики. Дослідження сприяє розвитку зеленого фінансування та переходу до низьковуглецевої економіки в Киргизькій Республіці

Ключові слова: альтернативне фінансування; зелена економіка; краудфандинг; лізинг; прибутковість

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The impact of digitalisation on business efficiency and competitiveness

Abstract. The study aimed to determine the role of digitalisation in enhancing business competitiveness by analysing implemented digital solutions and assessing their impact on business process efficiency. The research covered the period from 2018 to 2024, allowing for consideration of contemporary digital transformation trends. The primary materials included official reports and publications from Ukrainian companies Obolon, Nova Post, and Ukrzaliznytsia, which have actively adopted digital tools, as well as analytical data from open sources. The findings indicate that the implementation of digital technologies has had a significant impact on key business performance indicators. In particular, a substantial improvement in operational efficiency, service quality, and customer satisfaction levels was observed. For instance, Nova Post reduced parcel processing time by 40%, while Obolon decreased resource losses by 20% through the introduction of a Manufacturing Execution System. The implementation of digital solutions has contributed to greater transparency

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in internal business processes, which was particularly evident in Ukrzaliznytsia through the introduction of electronic platforms for transport management. Moreover, digital technologies have accelerated decision-making by enabling the use of automated data analysis systems. The long-term effects of digital solutions were projected, particularly their impact on the development of new business models, allowing companies to adapt to changes in the market environment. The study's findings confirmed that digitalisation is a key factor in ensuring business competitiveness. The adoption of innovative solutions has led to improved service quality, optimised business processes, and strengthened market positions. However, achieving maximum impact required a strategic approach, investment in staff training, and adaptation of organisational culture to new technologies

Keywords: innovative products; process automation; management processes; market trends; e-commerce; strategies

INTRODUCTION

In the context of rapid technological development, digitalisation is becoming a key factor influencing business development. The introduction of new technologies and the improvement of digital tools are changing the business environment, leading to improved efficiency of business processes, reduced costs, and the creation of new opportunities for competitive advantage. This is especially important for companies seeking to maintain their position in globalised markets, where success depends on the ability to quickly adapt to technological changes and utilise digital resources. Digitalisation also facilitates the analysis of consumer behaviour and better resource management. Despite this, scientific research into this issue is extremely important due to unequal access to digital infrastructures, limited financial resources in small and medium-sized enterprises, and a high level of uncertainty regarding the best methods for integrating digital solutions.

Digitalisation significantly changes business models, so its impact on organisational efficiency and business competitiveness is substantial. S. Ohinok & V. Hunka (2023) studied how digitalisation improves operational processes, increases organisational flexibility, and stimulates innovation. They also addressed issues related to cybersecurity and employee adaptation. To assess the effectiveness of digitalisation, further research is needed into its impact on various industries and tools. The impact of digitalisation on business competitiveness is linked to the need to adapt business strategies to the conditions of the modern market (Khilukha, 2024). The problem under investigation concerns the impact of digitalisation on the competitiveness of businesses in the trade sector. O. Siruk (2024) established that digitalisation is a key factor in building competitive advantages, and the level of business competitiveness depends on the degree of their digital maturity. The study identified tools for managing competitiveness, technological trends that create advantages, and principles for creating cross-functional teams. The main gaps concern the insufficient study of the impact of digitalisation on organisational processes in different types of business, as well as the lack of specific mechanisms for assessing the effectiveness of digital transformations.

In the area under investigation, the problem lies in determining the impact of digitalisation on business competitiveness, especially considering the specifics of the functioning of small and medium-sized enterprises. This topic was studied by A. Atanasova (2024). In her research, the author explored the role of digital technologies in building competitive advantages, focusing on the link between innovation and increased business efficiency. The research results indicate that digitalisation contributes to increased productivity, product quality, and the efficiency of internal processes, but at the same time, a significant proportion of enterprises do not adequately implement modern technologies. The main gaps that require further study include the study of the practical aspects of digitalisation for small businesses, the analysis of its impact on international markets, and the development of strategies for optimising digital transformation.

The necessity to adapt business models to technological changes is a problem concerning the impact of digital transformation on company competitiveness. In their study, K. Agustian *et al*. (2023) analysed the impact of digital transformation on business models and competitive advantages. The authors found that digital transformation changes the foundations of organisational functioning, increases efficiency, reduces costs, and promotes personalised customer interaction. At the same time, gaps requiring further research were identified, including the development of effective strategies for small businesses, the analysis of cybersecurity challenges, and the assessment of the long-term economic consequences of digital transformation.

The problem of digitalisation's impact on sustainable business competitiveness lies in the insufficient understanding of its role in ensuring economic, social, and environmental sustainability. A. Dabbous *et al*. (2023) found that digitalisation promotes entrepreneurial activity and increases sustainable competitiveness through the use of the Internet, the integration of digital technologies, and the provision of connectivity. Gaps concern the impact of digitalisation on environmental sustainability and the complex interrelationships between its components. Digitalisation significantly changes traditional business models, requiring adaptation to technological changes (Llazo *et al*., 2024). O.S. Joel *et al*. (2024) explored the trends, challenges, and opportunities of digital transformation. They found that digital technologies increase efficiency, reduce costs, and contribute to the creation of innovative business models. At the same time, issues regarding longterm stability, the integration of modern technologies with legacy systems, and cybersecurity remain unresolved.

Digitalisation has become a key factor in improving organisational efficiency, but the impact of social aspects in this process has not been sufficiently studied. V. Barba-Sánchez *et al*. (2024) explored the role of digital orientation and digital transformation in enhancing enterprise efficiency. The authors found that IT capabilities positively affect company results through the development of digital orientation and digital transformation. Gaps in the

research include the analysis of the long-term impact of digital transformation and the interaction of social and technological factors in management processes. Digital transformation is a key element for enhancing the innovative capacity of enterprises, but research on this topic needs further expansion. A.A. Vărzaru & C.G. Bocean (2024) studied the impact of digital technologies such as artificial intelligence (AI), big data, cloud computing, and the Internet of Things (IoT) on innovation revenue in EU countries. The authors found that the integration of digital technologies significantly increases efficiency and promotes innovation in various aspects of business.

However, the impact of digitalisation on types of social innovation has not been sufficiently studied, and there is a lack of detailed analysis of the implementation of digital technologies in less developed regions. This study aimed to assess the impact of digital technologies on enhancing the competitive advantages of enterprises through the improvement of innovation processes and the transformation of business models. To achieve this aim, the following objectives have been identified: analysis of the relationship between the implementation of digital technologies and the growth of enterprise competitiveness; study of the impact of digitalisation on various aspects of innovation, including product development, processes, and management strategies.

MATERIALS AND METHODS

The research materials include official reports and publications from Ukrainian enterprises such as Ukrzaliznytsia (Ukrzaliznytsia's annual report, 2020), Obolon (Obolon's annual reports, 2023), and Nova Post (Nova Post's sustainability report…, 2023), all of which are actively implementing digital technologies, as well as analytical data from open sources. These companies were chosen because of their significant contribution to the Ukrainian economy, their leadership positions in their respective industries, and their active implementation of digital technologies. Their experience formed the basis for identifying effective practices and developing recommendations that can be applied by other enterprises to enhance competitiveness. The main focus was on practical case studies and the results of digitalisation implementation at the level of specific companies.

Additionally, open sources containing analytical data on digitalisation trends in the global economy and global experience in this area were used (Pelser & Gaffley, 2020). The main focus was on practical case studies demonstrating the impact of digital technologies on increasing efficiency, reducing costs, and improving customer interaction (Attaran & Woods, 2018; Moghrabi *et al.*, 2023). The use of such materials allowed for consideration of not only local specifics but also a comparison of Ukrainian experience with international practices. The collected data enabled a comparative analysis, synthesis of practical results, and forecasting, which are important components for achieving the research objectives.

This research employed qualitative analysis methods to thoroughly assess the impact of digitalisation on the competitiveness of enterprises across various sectors. The primary tool was a comparative case study analysis, within which the digital strategies and technological tools implemented by three leading Ukrainian companies – Obolon, Nova Post, and Ukrzaliznytsia – were examined. Additionally, a statistical analysis of digitalisation implementation at these enterprises was conducted. For Obolon, key indicators were evaluated, including product sales volume, the share of exports in the total volume, the number of automated production lines, the level of production losses, and the level of energy efficiency. For Nova Post, the number of shipments, the number of branches, the number of parcel lockers, delivery speed (in hours), and the number of shipments through parcel lockers were analysed. Statistical indicators allowed for the assessment of the impact of the mobile application, automated sorting centres, and big data analytics on improving the efficiency of logistics processes and customer experience. For Ukrzaliznytsia, indicators such as the number of tickets purchased online, transportation revenue, passenger turnover, and other revenues and additional services were studied. These data illustrate the effectiveness of implementing electronic tickets, automated train traffic management systems, and online platforms for freight transportation.

The study of these case studies allowed for the identification of key practices in the application of digital technologies in the manufacturing, logistics, and transportation sectors, as well as determining how digital solutions contribute to the optimisation of business processes in various areas. In particular, the analysis helped to identify specific tools that companies use to reduce costs, increase productivity, and improve customer service. Based on the synthesis of practical results, the impact of digitalisation on operational efficiency, the quality of services provided, and the level of customer satisfaction were evaluated. The analysis concluded that the integration of digital technologies significantly increases the efficiency of company operations and contributes to the formation of competitive advantages. During the research, using forecasting methods, the potential long-term impact of digital solutions on the competitiveness of enterprises was evaluated, including their adaptation to digital technologies, increased efficiency of business processes, and the development of competitive advantages in a dynamic market environment. Taking into account current trends in technology development, the prospects for further implementation of innovations and their impact on the economic performance of companies were assessed.

RESULTS

Theoretical foundations of digitalisation's impact on business competitiveness

Enterprises can collect, store, process, and analyse data, automate processes, and improve customer interaction through digital technologies, which consist of a variety of methods, software, and tools. Digital technologies in the business environment are the foundation for creating new business models, increasing productivity, and enhancing market competitiveness. Cloud computing, AI, IoT, blockchain, big data, 3D printing, virtual and augmented reality technologies, and business process automation are just some of the numerous innovative solutions known as digital technologies. While each of these technologies has its specific area of application, their overall goal is to improve management processes, increase operational productivity, and create new competitive advantages (Cherep *et al.*, 2024).

Cloud computing has significantly transformed business models, allowing enterprises to optimise infrastructure costs, increase data management flexibility, provide access to real-time analytical tools, and expand business scaling capabilities according to market needs. It enables companies to utilise resources over the Internet, reducing the costs of their own IT infrastructure and ensuring data availability anytime and from anywhere. This is particularly relevant for small and medium-sized enterprises, as limited financial resources often prevent them from investing in the purchase and maintenance of their own servers and expensive equipment. For example, companies can run applications, process data, and scale their operations without significant capital investment using platforms such as Google Cloud, Microsoft Azure, and Amazon Web Services (Attaran & Woods, 2018).

Businesses are actively using digital technologies, including AI. AI can predict market trends, analyse large amounts of data, and even communicate with consumers through chatbots and virtual assistants. For example, in the financial sector, AI algorithms are widely used to assess risks, detect fraud, and create personalised offers for customers. The IoT is also an important part of business digital transformation. This technology allows physical devices, such as vehicles, cameras, and sensors, to connect to the internet so they can analyse and manage the data they generate. For example, in the field of logistics, IoT allows for the reduction of transportation costs, optimisation of routes, and real-time monitoring of cargo. IoT is used in manufacturing to automate processes, reduce equipment downtime, and increase productivity. Financial transactions, supply chain management, and business process transparency are examples of the use of blockchain technologies. With this technology, secure and immutable records can be created, ensuring data authenticity. For example, blockchain in the trade sector reduces the risks of fraud and counterfeiting, ensuring transparency of the origin of goods. Business digitalisation depends on big data. Companies can make informed decisions, better understand consumer needs, and predict customer behaviour through the processing and analysis of large volumes of data. Marketing uses big data to personalise its advertising campaigns, and manufacturing uses it to optimise processes and manage inventory.

Digital technologies play a vital role in automating business processes, reducing the frequency with which people have to perform routine tasks. Companies can focus resources on strategic goals, reduce costs, and increase the speed and accuracy of operations through the use of automation systems. For example, Customer Relationship Management (CRM) systems automate customer interactions, leading to better service and higher levels of customer satisfaction. Additionally, digital technologies foster the development of e-commerce, enabling companies to enter new markets and expand their customer base (Hadasik & Kubiczek, 2022). Online stores, mobile apps for ordering services, and electronic marketing platforms create new opportunities for businesses. Despite all the advantages of digital technologies, there are certain obstacles associated with their use. The main obstacles are the high cost of implementation, cybersecurity issues, and insufficient digital literacy among employees. Companies must invest in staff training, develop data protection plans, and gradually integrate digital technologies into their business processes to overcome these challenges.

Thus, digital technologies are not only a tool for increasing productivity but also a strategic resource that allows companies to remain competitive in the long term and adapt to changes in the external environment. Successful digital transformation depends on their effective implementation. The term "competitiveness" is a multifaceted economic concept that describes how well a company can meet the demands of its consumers better than its competitors. Financial stability, innovation, brand reputation, operational efficiency, and the ability to adapt to changes in the environment are part of this definition, which encompasses both short-term and long-term elements of company success. A company's ability to maintain or increase its market share by offering higher-quality products or services, at a competitive price, with better service or other unique advantages is a key indicator of competitiveness. For example, in traditional sectors such as manufacturing, the priority is to reduce costs and increase efficiency, whereas high-tech industries such as IT or e-commerce rely heavily on product innovation.

The approach to ensuring competitiveness has significantly changed due to digitalisation. Digital technologies allow for the optimisation of internal business processes, automation of routine tasks, and an increase in data processing speed, which reduces product time to market. For example, automated inventory management systems optimise logistics costs and prevent overproduction and shortages. Digital tools such as analytics and big data allow companies to better understand their customers, anticipate their needs, and provide personalised solutions. In particular, CRM systems allow for the storage and analysis of customer information, as well as the creation of strategies to increase customer loyalty. This is especially important in highly competitive environments, where retaining a customer becomes more cost-effective than acquiring a new one.

Furthermore, digitalisation allows companies to enter global markets. Even small and medium-sized enterprises can reduce their dependence on the local market by offering their goods to international customers through e-commerce. For example, companies like Alibaba and Amazon minimise infrastructure costs while providing access to a multi-million-strong audience. Despite all the advantages of digitalisation, ensuring competitiveness has several challenges. The main challenges are the rapid obsolescence of software and hardware, high costs, and cybersecurity risks. Enterprises with outdated business models and inefficient processes risk losing their market position if they fail to adapt to digital changes (Pelser & Gaffley, 2020; Ievsieieva *et al.*, 2024). Thus, competitiveness is an important indicator of enterprise success, and digitalisation acts as a powerful catalyst for its enhancement. However, enterprises need to develop strategic approaches to overcome challenges and ensure the effective use of digital tools.

Digital technologies are not simply implemented separately but are integrated into the overall strategy of an enterprise, creating a synergistic effect. For example, Enterprise Resource Planning (ERP) systems provide centralised management of enterprise resources, but their effectiveness significantly increases when integrated with CRM systems, which focus on customer relationship

management. This integration allows for the alignment of internal operations with customer needs, enhancing service quality and consumer loyalty. Another example is the use of IoT and AI, which in interaction provide deeper data analysis and automation of operations. IoT applications generate huge amounts of data in real time, which AI analyses to identify trends, predict demand, and optimise production processes. For example, in the field of logistics, this allows for the optimisation of delivery routes, reducing costs and transportation time.

Cloud technologies, in turn, provide a platform for data storage and processing, allowing enterprises to use analytics and automation tools without the need for significant capital investment in their own infrastructure. For example, ERP and CRM hosted in the cloud allow for access to operational data from anywhere, which increases business flexibility (Hasan, 2018). The interaction of technologies in the field of business process automation is particularly important. For example, the use of blockchain technologies in supply chains ensures transaction transparency and minimises fraud risks, while the integration of this technology with IoT allows companies to automate the tracking of goods' movement in real time. This integration forms innovative business models that allow enterprises to reduce costs, increase productivity, and offer customers unique products or services. For example, e-commerce actively uses cloud services, big data analytics, and CRM to create personalised offers, which increases sales and expands the audience. As a result, digital technologies not only automate individual processes but also create new opportunities for business development, which significantly increases the competitiveness of enterprises in a dynamic market environment.

The task of assessing the impact of digitalisation on the innovative development of enterprises is complex and requires the use of a wide range of theories and methods. Resource-based theory is an important approach that views digital technologies as a strategic resource that allows for the achievement of a competitive advantage by creating innovative activity. This theory argues that enterprises that invest resources in digital tools can create unique products, improve business processes, and open up new markets. The process approach is also an important approach, focusing on how digitalisation changes a company's internal processes, making them more efficient and innovative. For example, the introduction of automation systems increases labour productivity and creates conditions for the generation of new ideas through rapid access to data and tools for their analysis. An econometric approach involves the use of statistical models to analyse the impact of digitalisation on enterprise innovation activity indicators. These may include indicators such as the number of registered patents, the share of revenue from new products, and the volume of investment in research and development. For example, studies show that companies that actively invest in digitalisation have a higher level of innovation revenue compared to those that ignore modern technologies (Moghrabi *et al.*, 2023).

A network approach is also used, which focuses on analysing how digital technologies change the interaction of enterprises with partners, customers, and suppliers. For example, IoT allows for the creation of integrated supply management systems that reduce the time and cost of coordination between supply chain participants. A systems approach views digitalisation as an element of the overall enterprise ecosystem, which includes not only technologies but also human capital, organisational culture, and the external environment. This approach allows for the assessment of how the interaction between these elements affects the company's innovative capacity. In summary, theoretical approaches to assessing the impact of digitalisation on innovative development help to better understand the relationship between the use of modern technologies and the growth of enterprise competitiveness. This creates a basis for developing strategies that allow companies to maximise the opportunities of digital transformation.

Comparative analysis of the use of digital technologies for building competitive advantages

Digitalisation is a key tool for business transformation. It allows companies to improve production processes, increase resource efficiency, reduce costs, and provide a high level of customer service. Through the implementation of innovative solutions such as automation, big data analytics, and digital platforms, enterprises are able to adapt to market demands, enhance their competitiveness, and meet customer expectations. To understand the real impact of digital technologies, three specific examples of companies that have successfully implemented digitalisation were considered: the private joint-stock company (PrJSC) Obolon, the limited liability company (LLC) Nova Post, and the public joint-stock company (PJSC) Ukrzaliznytsia.

The brewing company Obolon is one of the largest in its segment on the Ukrainian market. In response to the challenges of the modern business environment, the enterprise actively implements digital technologies to optimise production processes and ensure high product quality. The main direction of Obolon's digitalisation has been the implementation of a Manufacturing Execution System. This system allows for the monitoring of all stages of the production process in real time, from the supply of raw materials to the finished product (Digitalisation in finance…, 2024). As a result, the company was able to significantly reduce the level of production losses and optimise the use of resources. Obolon implemented digital product quality control systems. Using modern technologies, the enterprise ensures that its products meet international standards, which allows it to maintain a competitive position in both domestic and foreign markets. A separate aspect of digitalisation was the improvement of logistics. The Warehouse Management System optimises the placement and dispatch of products, which reduces transportation costs and shortens order fulfilment times.

Table 1 provides a comparative analysis of the company's key indicators before and after digitalisation (2022-2023). As can be seen from the table, the implementation of digital technologies allowed Obolon to significantly improve its key indicators. In particular, product sales volume increased by 1.5 million daL, the share of exports increased by 7%, and the number of automated lines increased by two units. At the same time, the production loss rate decreased by 3%, and energy efficiency improved by 0.5 kWh per unit of product. These changes confirm that digitalisation has become an important step in ensuring the company's competitiveness in both domestic and international markets.

Table 1. Changes in key indicators of Obolon after digitalisation (2022-2023)

Indicator	2022 (before digitalisation)	2023 (after digitalisation)	Change
Product sales volume, million daL	12.5	14.0	+1.5 million daL
Export share in total sales, %	35	42	+7%
Number of automated production lines	3	5	+2 lines
Production loss rate, %	8	5	−3%
Energy efficiency, kWh per unit of product	2.5	2.0	−0.5 kWh

Source: compiled by the authors based on Obolon's annual reports (2023)

Nova Post is a leader in the field of logistics services in Ukraine. Thanks to active digital transformation, the company has managed to create convenient services for customers and optimise its own business processes. The main achievement of Nova Post's digitalisation has been the implementation of a mobile application that allows customers to conveniently receive information about shipments, pay for services, track parcels in real time, and receive delivery status notifications. This has significantly improved the customer experience and increased consumer loyalty. Another important step was the use of automated sorting centres equipped with modern technologies such as barcode scanners and conveyor systems. This allowed for a significant reduction in shipment processing time and increased delivery accuracy. In addition, Nova Post actively uses big data analytics to forecast demand for services and optimise delivery routes. This ensures more efficient use of resources and reduced costs.

The results of the company's digitalisation include a 40% reduction in parcel processing time, an increase in delivery accuracy to 98%, and a growth in the number of mobile app users to over 5 million as of 2022 (Nova Post's sustainability report..., 2023). Thanks to the mobile app, automated sorting centres, and the use of big data analytics, the company has been able to significantly optimise its business processes. Table 2 presents the key performance indicators of Nova Post, illustrating the impact of these changes. The implementation of digital technologies has allowed Nova Post to significantly reduce delivery times, expand the number of parcel lockers, and reduce the number of branches. The growth in the number of mobile app users to over 5 million indicates high customer adaptation to new services. This underscores the strategic importance of digitalisation for maintaining the company's leading position in the logistics market, even in difficult economic conditions.

Table 2. Key performance indicators of Nova Post digitalisation for 2021-2022

Indicator	2021	2022
Number of shipments, millions	372	315
Number of branches	9,990	9,300
Number of parcel lockers	8,700	14,000
Delivery speed (average), hours	24	23
Number of shipments via parcel lockers	-	4,353 new parcel lockers

Source: compiled by the authors based on Nova Post's sustainability report 2022 (2023)

Ukrzaliznytsia, as a state-owned railway transport company, is also implementing digital technologies to improve operational efficiency and enhance customer service quality. One of the key directions of digitalisation has been the introduction of electronic tickets (Ukrzaliznytsia app has..., 2024). This has enabled customers to quickly and conveniently purchase tickets online, significantly reducing queues at ticket offices and facilitating access to railway services. Additionally, electronic tickets help to avoid duplicate bookings and improve operational transparency. Another important step has been the creation of an automated train traffic management system. This system allows for real-time tracking of train locations, coordination of their schedules, and reduction of accident risks. Ukrzaliznytsia has also implemented digital solutions for freight transport management. In particular, an online platform for ordering freight transport has been created, which simplifies the process of cooperation with customers and reduces order processing time. In the process of implementing digital technologies, Ukrzaliznytsia demonstrates positive changes in its key indicators. Table 3 below compares the company's main performance results for 2018 and 2019 to illustrate the impact of digitalisation on operational efficiency.

Table 3. Changes in key indicators of PJSC Ukrzaliznytsia (2018-2019)

Indicator	2018	2019	Change
Number of tickets purchased online, millions of seats	27.7	30.4	+2.7
Revenue from transport services, billion UAH	76.0	82.4	+6.4
Passenger turnover, million passengers per km	28,614.9	28,413.5	−201.4
Other income and additional services, billion UAH	7.4	8.0	+0.6

Source: compiled by the authors based on Ukrzaliznytsia's annual report (2020)

As can be seen from the table, the implementation of digital technologies, such as online ticket sales, process automation, and new online services, contributed to a significant increase in revenue and improved customer service. The analysis of the three enterprises – Obolon, Nova Post, and Ukrzaliznytsia – demonstrates that digitalisation is a powerful tool for enhancing competitiveness. The implementation of digital solutions has allowed these companies to significantly improve the quality of their services, optimise business processes, and increase customer satisfaction. The successes of these enterprises can serve as an example for other companies seeking to improve their efficiency and maintain leading positions in the market.

Digitalisation is a key factor in enhancing the competitiveness of enterprises in various sectors of the economy. Its implementation contributes to the optimisation of operational processes, improvement of customer experience, and creation of new opportunities for business development. Table 4 presents a comparative analysis of the implementation of digital technologies by three leading Ukrainian enterprises: PrJSC Obolon, LLC Nova Post, and PJSC Ukrzaliznytsia. This analysis highlights the technologies used, the specifics of their implementation, and the results achieved by the companies, demonstrating the positive impact of digital solutions on their operations.

Table 4. Comparative analysis of digital technology implementation across different sectors

Enterprise	Sector	Technologies used	Implementation features	Results
PrJSC Obolon	Manufacturing (brewing)	Manufacturing Execution System, quality control, Warehouse Management System	Integration with production lines, resource usage optimisation	20% reduction in losses, 30% decrease in order fulfilment time, stable product quality
LLC Nova Post	Logistics	Mobile app, automated sorting centres, big data analytics	Development of user-friendly customer solutions, integration with route management systems	40% reduction in parcel processing time, delivery accuracy of 98%, 5 million active mobile app users
PJSC Ukrzaliznytsia	Transportation services	E-tickets, automated train movement system, online platform for freight transportation	Modernisation of passenger and freight services, increased operational transparency	80% of ticket sales online, 25% improvement in movement accuracy, 50% reduction in freight processing time

Source: compiled based on Nova Post's sustainability report 2022 (2023), Digitalisation in finance: How Obolon's strategy has changed given digital transformation (2024), Ukrzaliznytsia app has already attracted 2 million authorised users (2024)

As the analysis of these enterprises has shown, the implementation of digital technologies is an important means by which companies can remain competitive. Companies have been able to significantly optimise business processes, reduce costs, and improve service quality through automation, data analytics, and innovative customer solutions. PJSC Ukrzaliznytsia has modernised transportation services to meet customer needs, PrJSC Obolon has improved operational efficiency and ensured consistent product quality, and LLC Nova Post has ensured the speed and accuracy of logistics operations. Positive conclusions confirm the view that digitalisation is not only a necessary part of modern business but also a powerful stimulus for creating competitive advantages in many industries.

The digitalisation of business processes is becoming a necessary condition for ensuring the competitiveness of enterprises in the modern economic environment. Developing recommendations for optimising the use of digital technologies is an important step in achieving maximum efficiency in transformation processes. This requires a systematic approach that encompasses both improving the efficiency of digital transformation and developing strategies to strengthen competitive advantages, taking into account socio-economic and technological aspects.

Optimising digital technologies begins with identifying areas for improving the efficiency of digital transformation. A key aspect is the need for a comprehensive analysis of existing business processes to identify points where digital technologies can provide the greatest effect. For example, automating routine operations reduces labour costs, increases productivity, and decreases human error. The implementation of ERP systems helps integrate all business processes into a single platform, ensuring more efficient resource and financial flow management. Additionally, big data and analytical tools enable in-depth analysis of consumer behaviour, allowing for a better understanding of customer needs and the adaptation of products or services to their requirements.

Another important direction for improving the efficiency of digital transformation is staff training. One of the main obstacles to successful digitalisation is the insufficient level of digital literacy among employees. Enterprises must invest in training programs that not only familiarise employees with new technologies but also explain their practical value for everyday work. For example, companies that actively implement CRM systems should train their employees to effectively use these tools for customer interaction. Furthermore, it is important to foster an innovation-oriented culture where employees not only know how to work with digital tools but are also ready for their continuous improvement.

Developing strategies to enhance the competitive advantages of enterprises in the digital environment should include several key elements. Enterprises must clearly define their goals and priorities in digital transformation. This avoids the chaotic implementation of technologies that may not align with the company's strategic objectives. For example, if the enterprise's goal is to reduce costs, the main focus should be on process automation and supply chain optimisation. If the company aims to improve the customer experience, it should focus on implementing analytical tools and personalising interactions. Table 5 visually illustrates the key directions of digital transformation optimisation and their results.

Table 5. Directions for optimising digital transformation and expected results

Optimisation direction	Expected results
Automation of routine operations	Reduction in labour costs, improved task accuracy
Staff training	Increased productivity, readiness for the adoption of new technologies
Technology integration	Reduced adaptation costs, increased transformation speed
Cyber risk management	Data protection, reduction of financial losses due to cyber threats
Use of innovative solutions	Enhanced competitive advantages, expanded development opportunities
Development of key performance indicators for monitoring effectiveness	Timely identification of weaknesses, prompt adjustment of strategy

Source: compiled by the author

It is important that new technologies are integrated with existing systems. The incompatibility of new solutions with existing infrastructure is a major issue in digital transformation. This can lead to additional costs and project delays. To prevent such situations, companies should conduct a preliminary audit of their technology base and collaborate with suppliers who offer flexible and adaptable solutions. For example, cloud technologies allow for the rapid scaling of IT resources without significant investment in the modernisation of physical infrastructure. Thus, the recommendations and actions proposed are aimed at achieving sustainable competitive advantages for enterprises in various industries through the effective use of digital technologies.

DISCUSSION

Digitalisation is a major force in business transformation, driving increased efficiency, process automation, cost optimisation, and the creation of competitive advantages. The use of modern digital technologies, such as ERP, CRM, IoT, and AI, allows businesses to integrate various functions, improve customer interactions, develop innovative products, and enter new markets. However, despite the clear benefits of digital transformation, there are challenges associated with technology implementation: high costs, the need for staff training, and cybersecurity.

This study has established that digitalisation is a key factor in increasing business efficiency, promoting process automation, optimising costs, and creating new competitive advantages. In particular, digital technologies such as ERP, CRM, AI, and IoT enable businesses to integrate various functions, improve customer interactions, develop innovative products, and enter new markets. In addition, digitalisation facilitates business globalisation through e-commerce, expanding opportunities for small and medium-sized enterprises (Gulaliyev *et al.*, 2023; Azam & Ansari, 2024). At the same time, the research highlights the problems associated with the implementation of digital technologies, including high costs, the need for staff training, and cybersecurity risks.

The findings of N. Chakrouni & M. Cherkaoui (2023) confirmed the positive impact of digitalisation on the financial performance of companies, highlighting the increase in staff productivity, process optimisation, and cost reduction. At the same time, their research indicated the ambiguity of the impact of digitalisation in different contexts due to differences in measurement variables. For example, in some sectors, digitalisation has a negative impact due to high operating costs, the complexity of technology integration, and the adaptation of organisational culture. Thus, the results of both studies indicate the importance of digitalisation as a tool for improving competitiveness and financial efficiency of business, but at the same time emphasise the need to take into account the context of the implementation of digital technologies and the associated challenges.

The study by B. Abazi Chaushi *et al*. (2024) viewed digitalisation as a transformational process encompassing all aspects of organisational activity, including communications, decision-making, innovation, and customer orientation. The main drivers of digitalisation are technological progress, market competition, and changing customer expectations. Digital technologies, such as AI, cloud computing, and IoT, contribute to increasing the efficiency and competitiveness of organisations while creating new opportunities for innovation (Spytska, 2023). The research also highlights the challenges of digitalisation: resistance to change, cybersecurity, the digital divide, and problems integrating legacy and new systems. The article by B. Abazi Chaushi *et al*. (2024) emphasised the importance of fostering a digital culture and adapting organisational structures to the demands of the digital age. Strategic initiatives aimed at developing digital skills, creating cross-functional teams, and using technologies to enhance efficiency and innovation are crucial. The study also addressed future trends, including the integration of AI, blockchain, and sustainable digital practices. Thus, the research by B. Abazi Chaushi *et al*. (2024) summarised the key aspects of digitalisation, focusing on an interdisciplinary approach, analysis of challenges, and the prospects of digital strategies that form the basis for future transformations.

The study by E. Calderon-Monge & D. Ribeiro-Soriano (2024) focused on analysing the impact of digitalisation on key aspects of business, such as marketing, finance, accounting, and management. The research emphasised that digitalisation is a driving force in the transformation of business models, consumer behaviour, and organisational processes. The main focus is on the use of modern digital technologies, such as SMAC, blockchain, and big data analytics, which contribute to increasing efficiency, competitiveness, and creating innovative business solutions. The article also highlighted the role of business ecosystems and the challenges faced by organisations, including the integration of new technologies and adaptation to a rapidly changing environment. Compared to this research, both studies emphasised the importance of digitalisation as a tool for business transformation. Similar aspects include the analysis of the impact of digital technologies on value creation, business adaptation to consumer demands,

and the use of innovative approaches to optimise business processes. Differences lie in the fact that the research by E. Calderon-Monge & D. Ribeiro-Soriano (2024) paid more attention to the systematic analysis of business ecosystems and the integration of digital technologies into strategic management, while this study focused on the practical aspects of implementing digital solutions and the challenges of their implementation.

The research by K. Agustian *et al*. (2023) focused on the impact of digital transformation on business models, competitiveness, and enterprise efficiency. The main conclusions highlighted those digital technologies, including AI, IoT, and data analytics, allow for cost reduction, business process automation, personalised customer experiences, and the implementation of innovations that meet modern market needs. Particular attention is paid to the practical aspects of digital transformation, particularly its ability to adapt business models to a rapidly changing environment. Compared to this study, both agreed on key aspects of digitalisation, such as process automation, increased efficiency, and the creation of competitive advantages through innovation. There is also a shared focus on the use of modern technologies to optimise business operations and improve customer interaction. Differences lie in the focus of the research: the article by K. Agustian *et al*. (2023) placed more emphasis on the practical implementation of digital solutions and the analysis of specific impacts on business processes. The current study focused more on the systematic analysis of digitalisation processes, their strategic importance for business adaptation, and the challenges associated with technology implementation, such as the integration of new systems, the development of digital skills, and change management in organisations. One study is more theoretical with an emphasis on the strategic importance of digitalisation, and the other is practically oriented with a detailed analysis of its impact on business operations.

The research by J. Bacca-Acosta *et al*. (2023) analysed the impact of digital technologies on the competitiveness of countries, comparing Latin America and Europe. The article emphasises that the implementation of digital technologies, particularly information and communication technologies (ICT), is a key factor in improving business dynamics, skills development, labour and product market efficiency, and strengthening the financial system. For Latin America, ICT proved to be a strong predictor of business dynamics (66% variation), skills (81%), product markets (75%), and the financial system (49%). In Europe, ICT also positively affects these indicators, but with varying degrees of impact. For example, in European countries, the labour market shows a negative correlation with competitiveness due to structural differences. Compared to this study, the results of J. Bacca-Acosta *et al*. (2023) coincide in aspects of the importance of digital technologies for enhancing business dynamics and the impact of ICT on worker skills. Both articles emphasised the key role of digitalisation in adapting enterprises to modern challenges, optimising business processes, and expanding market opportunities. There is also a shared emphasis on the importance of investing in the development of digital skills, especially in countries with underdeveloped digital infrastructure.

The research by A. Dubey & R. Ranjan (2024) analysed business processes through a case study of Zivame, an Indian retail enterprise. The main findings highlighted that the implementation of digital tools, such as CRM, e-commerce, supply chain management, and cloud technologies, significantly improved the company's operational efficiency, customer satisfaction, and financial performance. Specifically, order fulfilment time was reduced from 7 to 3 days, repeat purchase rates increased from 35% to 65%, and employee productivity rose by 60%. However, the company faced challenges, including employee resistance to change and high initial investment costs. Compared to this study, the results show similarities in recognising the key role of digitalisation in enhancing competitiveness and operational efficiency. Both studies emphasised the importance of CRM and supply chain optimisation for improving internal processes and meeting customer needs. Both articles emphasised that successful digitalisation requires a clear strategy, investment in staff training, and the active implementation of modern technologies to ensure long-term business sustainability.

This research demonstrated that digitalisation significantly impacts the transformation of business models, contributing to enhanced enterprise competitiveness through process optimisation, the implementation of innovative technologies, and the effective use of digital resources. It has been determined that modern digital solutions, such as ERP, CRM, IoT, and AI, not only reduce costs but also improve customer experience, increase labour productivity, and open up new market opportunities. The main conclusion is that the success of digitalisation depends on a strategic approach to its implementation and the adaptive capacity of the organisation. Compared to the research by Z. Wang *et al*. (2023), which focused on the hierarchical nature of digital capabilities and their impact on business outcomes, both analyses highlight the importance of business model innovations as a key element of successful digitalisation. Z. Wang *et al*. (2023) detail that foundational, operational, and integrative digital capabilities form the basis for the implementation of business model innovations, which, in turn, act as a mediator between digital resources and enterprise performance. Current research placed more emphasis on the practical aspects of implementing digital solutions and the direct impact on business operations, whereas Z. Wang *et al*. (2023) focused on the conceptual link between digital capabilities and innovations. Both approaches demonstrate how the theoretical foundations of digital transformations can be applied in practice to achieve high business results.

The research by L. Zhang *et al*. (2023) demonstrated that digitalisation significantly improves the competitiveness of manufacturing enterprises through optimised management, operations, and adaptation to change. It is emphasised that the results of digital changes manifest with a delay, and state-owned enterprises demonstrate greater efficiency due to subsidies. Compared to this study, both analyses highlight the importance of digitalisation for enhancing business productivity and adaptability. There is a shared emphasis on business model transformation and the integration of digital technologies. However, the research by L. Zhang *et al*. (2023) focused on the manufacturing sector, whereas this study has a broader approach. The research by M.-Á. Galindo-Martín *et al*. (2023) analysed the relationship between digitalisation, entrepreneurship,

and competitiveness in 19 European countries. The main findings demonstrated that a favourable environment for digitalisation and investment in talent development significantly increase the level of entrepreneurial activity, which, in turn, positively impacts competitiveness through the implementation of innovations in products and processes. Compared to this study, both highlighted the role of digitalisation in improving business outcomes through innovation. Common findings include that digital technologies contribute to the optimisation of business processes, cost reduction, and the creation of new market opportunities. Both studies also emphasised the importance of human capital development to maximise the benefits of digitalisation. The research by M.Á. GalindoMartín *et al*. (2023) focused on a macro-level analysis of the impact of digitalisation on the competitiveness of countries, emphasising institutional conditions and economic indicators. In contrast, this research focuses on micro-level aspects of the implementation of digital technologies in business, paying more attention to specific tools and their impact on productivity.

The research by M.F. Mubarak *et al*. (2019) focused on the impact of Industry 4.0 technologies, such as big data, cyber-physical systems, IoT, and interoperability, on the productivity of small and medium-sized enterprises in Pakistan. The main findings show that big data, cyberphysical systems, and interoperability have a positive significant impact on productivity, while the impact of IoT was found to be insignificant. The authors emphasised that digital transformation enables process optimisation, cost reduction, and increased efficiency, but requires human capital and infrastructure development. Compared to this study, both analysed the key role of digitalisation in enhancing business competitiveness. Common aspects include findings on the importance of using digital technologies to optimise operations and create added value. In both cases, the need for a strategic approach to digital transformation and the implementation of innovations is emphasised. However, the research by M.F. Mubarak *et al*. (2019) focused on specific elements of Industry 4.0 in the context of Pakistani small and medium-sized enterprises. Additionally, M.F. Mubarak *et al*. (2019) considered in detail the challenges associated with limited resources and underdeveloped infrastructure.

The research by S. Kraus *et al*. (2021) provided an overview of the current state of digital transformation research, categorising the literature into three main areas: digital business transformation, technologies as drivers of digital transformation, and its institutional and societal implications. Findings point to the need for a strategic approach to the implementation of digital technologies to maintain competitiveness. The research by S. Kraus *et al*. (2021) focused more on a systematic literature review with an emphasis on conceptual aspects of digital transformation, such as business model adaptation and technology integration. The main findings emphasised the importance of integrating digital strategies, developing business models, and adapting organisations to new conditions. Compared to this study, both approaches highlighted the key role of digital technologies in achieving competitive advantages. Both studies recognised that digitalisation contributes to the creation of new value models, increased efficiency, ad business adaptability. In contrast, this study placed more emphasis on the practical impact of digital changes on specific organisational processes.

This study demonstrated that digital transformation significantly impacts the efficiency of business processes, particularly through the implementation of innovative technologies, management optimisation, and increased productivity. An important aspect is that digitalisation allows enterprises to adapt more quickly to changes in the market environment, create new competitive advantages, and improve customer experience (Ustymenko, 2024). The main focus is on how the integration of digital strategies contributes to achieving long-term business goals, particularly by reducing costs and increasing operational efficiency. Compared to the findings of D. Prihandono *et al*. (2024), it is also emphasised that digitalisation is a key tool for increasing productivity, especially in conditions of growing market competition. The research by D. Prihandono *et al*. (2024) focused on analysing the impact of market competition and limited resources on the adaptation of digital strategies in small and medium-sized enterprises in Indonesia. In turn, this study covered a wider range of sectors and is not limited to the conditions of one country, allowing for more generalised conclusions about the impact of digitalisation. This study focused on the role of digital transformation in enhancing the efficiency of small and medium-sized businesses. The results demonstrate that digitalisation contributes to cost reduction, optimisation of operational processes, and the implementation of innovations. In particular, the link between digital transformation and its impact on operational, financial, and innovative efficiency is highlighted. It is noted that it may take some time to see tangible results from digital investments.

Compared with the research by X. Teng *et al*. (2023), both articles agreed that digital transformation is a key factor in improving the operational efficiency of enterprises. An important aspect is that digital innovations contribute to cost reduction and increased productivity. However, the study by X. Teng *et al*. (2023) pointed to a complex relationship between digital transformation and innovation efficiency, which takes the form of an inverted U-curve. This conclusion is consistent with the assumption that the intensity of digital investments may decrease due to resource constraints and the need for significant initial investments. The research by A. Kő *et al*. (2022) focused on digital agility, digital competitiveness, and the innovative efficiency of small and medium-sized enterprises in the context of digital turbulence. The main findings indicate that the capacity for change and risk readiness are key factors for successful digital transformation and the achievement of innovative efficiency. The role of digital competitiveness as an important aspect of implementing innovative solutions is also emphasised. The similarity lies in recognising the key role of adaptation to change and readiness for innovation as the main conditions for the success of digital transformation. Both articles also emphasised the importance of an innovation-oriented organisational culture for enhancing competitiveness. Additionally, the study by A. Kő *et al*. (2022) examined in detail the relationship between digital agility, risk, and innovation, whereas this research focuses more on the systemic aspects of transformation.

The research by Z. Wu (2024) analysed the impact of digital transformation on the operational efficiency of

commercial banks in China. The results confirmed that digital transformation significantly improves efficiency through the modernisation of business models and operational processes. In particular, banks with a higher level of digitalisation show better profitability indicators. It is also noted that this impact is more significant for non-state-owned banks due to their flexibility in adopting digital technologies. Compared to this study, there is a shared emphasis on the importance of digital transformation for improving operational performance and competitiveness. Both studies recognise that digitalisation is a key factor in adapting businesses to a changing environment and creating new growth opportunities. However, the research by Z. Wu (2024) focused on the financial sector, specifically commercial banks, and examines in detail the impact of digital technologies depending on the type of bank ownership. In this study, the analysis covers a wider range of industries and focuses on the systemic aspects of digital transformation. Additionally, Z. Wu (2024) paid more attention to the relationship between digitalisation, financial performance, and ownership structure.

This study focused on how digital transformation impacts business efficiency through process optimisation, increased productivity, and adaptation to a changing market environment. Particular attention is paid to the systemic aspects of implementing digital technologies, as well as their longterm impact on enterprise competitiveness. Compared to the results of the research by M. Shehadeh *et al*. (2023), there is a shared conclusion that digitalisation is a key factor in enhancing business competitiveness and innovation. Both analyses recognise the significance of digital technologies in creating added value, optimising business models, and implementing innovations. The research by M. Shehadeh *et al*. (2023) emphasised the mediating role of entrepreneurial orientation and the moderating role of innovation capabilities, which also underscores the importance of adapting organisational culture to change. In contrast, the study by M. Shehadeh *et al*. (2023) focused on the service sector, analysing in detail how innovation capabilities amplify the impact of digitalisation on competitiveness through entrepreneurial orientation.

The research conducted by L. Kucher *et al*. (2023) focused on the development of innovative activities in agricultural enterprises within the context of the transition to agribusiness. The authors analysed the readiness of Ukraine and EU countries for digital transformation, using the global digital competitiveness index, and investigated innovative activity in crop and livestock farming. They also considered the barriers hindering innovation implementation, including financial, organisational, and technological barriers, and proposed ways to overcome them. Compared to this study, which has a broader sectoral scope and emphasised the impact of digitalisation on enterprise competitiveness through the implementation of innovative solutions, the research by L. Kucher *et al*. (2023) focused exclusively on the agricultural sector.

The research by S. Marko *et al*. (2024) focused on cybersecurity and fraud risks in the context of AI implementation, particularly manipulations with environmental data. Using IDEF0 modelling, the authors proposed solutions for fraud prevention. This study, in contrast, emphasised the impact of digitalisation, such as ERP, CRM, and IoT, on enhancing enterprise competitiveness. A commonality is the use of AI as a tool for process optimisation, but in S. Marko *et al*. (2024) AI is also considered a potential threat that requires management. This study and the research by N. Zelisko *et al*. (2024) have certain common points and differences. Both articles emphasised the importance of digital technologies for improving the efficiency of business processes. N. Zelisko *et al*. (2024) focused on the use of IoT, process automation, and precision agriculture as the main means of optimising production, reducing costs, and improving product quality. The research noted that the concept of "smart farming" contributes to a significant increase in agribusiness productivity through the use of big data, blockchain technologies, drones, and satellite systems, which is also confirmed in this research. N. Zelisko *et al*. (2024) paid more attention to economic security and risk management in the agricultural sector, particularly through the use of insurance and financial instruments to hedge price fluctuations. Overall, both studies have a common basis in the context of digitalisation but differ in their priorities: N. Zelisko *et al*. (2024) aimed to analyse economic stability through risk management, while this study emphasised long-term competitiveness through the adaptation of business models to digital transformations.

Digital transformation is a powerful tool for enhancing business efficiency, aiding innovation, automation, and the optimisation of operational processes. It opens up new opportunities for companies to develop, including greater competitiveness and access to new markets. Nevertheless, the effective implementation of digitalisation depends on the use of a strategic approach, investment in the development of digital skills, and the adaptation of organisational structures to new conditions. To achieve lasting results, it is important to consider the context, industry specifics, and implementation challenges. Digitalisation should be an important part of the business plan for the long term.

CONCLUSIONS

The digitalisation of business is one of the key drivers of modern organisational transformation. In an environment of globalisation and rapid technological development, enterprises that actively implement digital tools gain significant competitive advantages. This study analysed the impact of digital technologies on enterprise operations, their competitiveness, and their ability to adapt to rapid changes in the market environment. The results confirmed that the use of tools such as ERP, CRM, IoT, and AI allows for the integration of business processes, optimisation of costs, improvement of customer interaction quality, and increased overall productivity.

Particular attention was paid to cloud technologies, which are becoming an important element of business modernisation. These technologies enable companies, especially small and medium-sized enterprises, to scale their operations without significant financial investments in physical infrastructure. Through cloud services, businesses gain access to analytics tools, secure data storage, and flexible working platforms, allowing them to respond quickly to changes in market conditions. However, digitalisation is also accompanied by several challenges. Among them are high implementation costs, insufficient digital literacy of

personnel, which hinders the adaptation process, and the increasing risks associated with cybersecurity.

Practical analysis of successful cases from leading Ukrainian companies such as Obolon, Nova Post, and Ukrzaliznytsia has shown that digital solutions have a significant impact on their productivity and competitiveness. Obolon uses automated production management and quality control systems, which allows for cost reduction, increased efficiency of production processes, and ensures consistent product quality. Nova Post focused on the digitalisation of logistics processes, implementing mobile applications, automated sorting centres, and big data analytics, which significantly improved delivery speed and customer experience. Ukrzaliznytsia integrated digital technologies into its infrastructure, implementing electronic tickets and online services for freight transportation, which increased transparency and operational efficiency.

Digitalisation also contributes to the development of environmentally conscious businesses. Through digital tools such as energy consumption monitoring systems and optimised logistics routes, enterprises can reduce their environmental impact and contribute to achieving sustainable development goals. The success of digital transformation largely depends on a strategic approach. Firstly, companies need to define clear priorities in digitalisation, which will avoid the chaotic implementation of technologies. Secondly, it is important to invest in the development of digital skills among personnel, as human capital remains a key factor for success. Employee training should be aimed not only at mastering technologies but also at understanding their strategic role in achieving business goals. Thirdly, enterprises must consider cybersecurity issues, as the growth of digital threats can negatively impact performance.

A key aspect of digital transformation is the development of a system to monitor the effectiveness of implemented solutions. Defining clear key performance indicators allows for the assessment of digitalisation success, identification of weaknesses, and timely adjustments to strategies. For example, monitoring operating costs, employee productivity, and customer satisfaction levels can form the basis for further improvement of digital processes. The prospects for future research lie in a more detailed analysis of the impact of digital technologies on various sectors of the economy and the social aspects of their implementation.

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CONFLICT OF INTEREST

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Вплив цифровізації на ефективність і конкурентоспроможність бізнесу

Анотація. Метою дослідження було визначення ролі цифровізації у підвищенні конкурентоспроможності підприємств через аналіз впроваджених цифрових рішень та оцінку їхнього впливу на ефективність бізнес-процесів. Дослідження охоплювало період із 2018 до 2024 року, що дозволило врахувати сучасні тенденції цифрової трансформації. Основними матеріалами слугували офіційні звіти та публікації українських компаній «Оболонь», «Нова Пошта» та «Укрзалізниця», які активно впроваджували цифрові інструменти, а також аналітичні дані з відкритих джерел. Результати дослідження показали, що впровадження цифрових технологій суттєво вплинуло на ключові показники діяльності підприємств. Зокрема, було виявлено значне підвищення операційної ефективності, якості обслуговування клієнтів та рівня задоволеності споживачів. Наприклад, «Нова Пошта» скоротила час обробки посилок на 40 %, а «Оболонь» зменшила втрати ресурсів на 20 % завдяки впровадженню Manufacturing Execution System. Впровадження цифрових рішень сприяло покращенню прозорості внутрішніх бізнес-процесів, що особливо проявилося у компанії «Укрзалізниця» завдяки впровадженню електронних платформ для управління перевезеннями. Крім того, цифрові технології дозволили скоротити час прийняття управлінських рішень через використання автоматизованих систем аналізу даних. Було спрогнозовано довгострокові ефекти цифрових рішень, зокрема їхній вплив на створення нових бізнес-моделей, що дозволило компаніям адаптуватися до змін у ринковому середовищі. Висновки дослідження підтвердили, що цифровізація є ключовим фактором у забезпеченні конкурентоспроможності підприємств. Впровадження інноваційних рішень дозволяло підвищити якість послуг, оптимізувати бізнес-процеси та зміцнити ринкові позиції компаній. Однак досягнення максимального ефекту потребувало стратегічного підходу, інвестицій у навчання персоналу та адаптації організаційної культури до нових технологій

Ключові слова: інноваційні продукти; автоматизація процесів; управлінські процеси; ринкові тенденції; електронна комерція; стратегії

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Reporting on the sustainable development of Ukrainian banks: Current state, challenges and prospects

Abstract. Given the growing importance of sustainable development and Ukraine's integration into the European economic area, high-quality and comprehensive sustainability reporting is critical for the banking sector. The study aimed to assess the completeness of sustainability disclosures in the non-financial reporting of Ukrainian banks, to identify challenges and opportunities for improving the quality of such information to achieve positive effects at both the micro and macroeconomic levels. To achieve this goal, the case study method was used, which involved a comprehensive analysis of the websites of all Ukrainian banks to study their non-financial reporting. An in-depth analysis was conducted to determine the availability and quality of disclosed information on environmental, social and governance (ESG) factors. The study results showed that Ukrainian banks are only beginning to adopt sustainability reporting. The disclosed sustainability information is largely descriptive, lacking quantitative or financial data, and is often heterogeneous and unstructured. Even banks that position themselves as socially and environmentally oriented do not fully disclose sustainability risks or provide comprehensive information in the context of sustainable development goals. Only 35% of Ukrainian banks submit a "Sustainable Development Report" as part of their management report and only 45% of these banks address all ESG factors in the report. It has been demonstrated that, despite significant challenges in complying with the requirements of the Corporate Sustainability Reporting Directive, which remains voluntary for Ukrainian banks, adopting these standards is essential. Doing so will improve the profitability and transparency of banks' operations,

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strengthen investor confidence, and create a more stable financial system in Ukraine. The urgent need for Ukrainian banks to take a more proactive and comprehensive approach to sustainability reporting and to prepare for the requirements of the future regulatory environment was emphasised

Keywords: non-financial reporting; financial institutions; information disclosure; economic, social, and governance factors; requirements; indicators; audit

INTRODUCTION

Compliance with the imperatives of sustainability is a leading priority in the contemporary business world. Companies include social and environmental results in non-financial reports to demonstrate sustainability and responsible partnership. In the modern Ukrainian business landscape, the disclosure of information about sustainable development is essential for achieving a competitive position in the world economy. Publishing non-financial statements is an important manifestation of the company's high responsibility to stakeholders. The preparation of reporting on sustainable development is a tool for positive transformations, which is not limited to the publication of statements but is an integral part of the wider process of company's growth, implementing action plans, and evaluating the results obtained.

Establishing non-financial sustainability reporting should act as a factor in stimulating banks' activity in this area. Financial institutions will be more concerned with practices that focus on both social and environmental performance, especially regarding supply chain due diligence, human rights, and green innovation. As stated by I. Makarenko (2023), sustainability reporting provided the following benefits to the companies: improving executives' awareness of the consequences of environmental and social activities, reducing the cost of capital, improving corporate culture, reducing information asymmetry between the company and stakeholders, improving reputation, reducing business risks, and increasing the market value. Until recently, the relevant reporting in European countries was regulated by Directive of the European Parliament and of the Council No. 2013/34/EU (2013) and the Directive of the European Parliament and of the Council No. 2014/95/EU (2014). Numerous scholars have studied the banks' reports, focusing on the relevance of the information presented and its compliance with the requirements of the Non-Financial Reporting Directive (NFRD).

A.L. Santos & L.L. Rodrigues (2022) analysed the quality of information regarding the sustainable development of Portugal banks, rightly believing that only meaningful, relevant, and comparative data can objectively reflect the banks' contribution to sustainable development, create a better social image for banks, and also characterise the risks of their activities related to ESG criteria. P. Schröder (2022) researched the non-financial disclosures of German banks across a three-year period. The study revealed a consistent and notable increase in the quality of these reports, likely due to the banks' accumulated experience. Furthermore, the research emphasised the need to understand the drivers of reporting quality, specifically citing experience, presentation style, and the chosen reporting standards.

Many studies analysed the relationship between the banks' sustainability reporting and their financial performance. The scholars sometimes reach conflicting conclusions regarding the impact of reporting on environmental, social, and governance (ESG) issues on banks' performance indicators. N. Stakic & L. Barjaktarovic (2023) conducted an empirical study of sustainability within Serbian banks, analysing environmental loans, carbon emission reductions, and community investments as reported by the banks. Their research demonstrated a statistically significant relationship between ESG metrics and environmental lending. However, they found no significant correlation between financial profitability and overall ESG practices.

E.O. Korolo & A.S. Korolo (2023) research on Nigerian banks revealed that economic and environmental sustainability reporting had negligible impacts, one negative and one positive, on return on assets. However, social sustainability reporting demonstrated a statistically significant negative correlation with profitability. The authors suggested, among other things, that banks should improve their evaluation and measurement of economic, social, and environmental impacts across all operations. According to B.T.T. Loan *et al*. (2024), there were positive effects of environmental disclosure and governance disclosure on the bank's return on equity. However, the study did not provide evidence of a statistically significant association between social disclosure and financial performance. This confirms the problems with standardising information in non-financial reports and the extremely complex and multifaceted nature of the interaction between sustainability factors and bank financial performance.

However, NFRD provided a high level of flexibility regarding the structure and format of disclosure of non-financial information, which over time ceased to satisfy the requests and interests of stakeholders. In 2022, the EU adopted a new Directive of the European Parliament and of the Council No. 2022/2464/EU (2022) which directed companies to display in their reports information on the sustainability of the business model; compatibility with the global warming target under the Paris Agreement; sustainable development goals' achievements; the main risks related to the company's dependence on sustainability issues; determination of actual or potential adverse impacts on sustainable development in the value chain and operations, etc. The specified Directive does not yet directly concern Ukrainian undertakings, in particular, financial institutions. Considering Ukraine's aspirations for European integration and the necessity to incorporate European norms into its domestic legal framework, it is crucial to explore the readiness of local banks to implement the relevant requirements. The research aimed to assess the quality and extent of sustainability information disclosed by Ukrainian banks in their non-financial reports, pinpoint the obstacles to complete disclosure, and propose solutions to enhance this information for promoting economic growth on both micro and macro scales.

MATERIALS AND METHODS

The study employed a multi-faceted methodological approach to analyse the integration of sustainability practices within the Ukrainian banking sector. A content analysis of scientific literature, regulatory documents, and sustainability reports was conducted to track the banking sector's progressive engagement with sustainability through non-financial reporting and ESG integration. This analysis also identified areas for further research. To assess changes in Ukrainian legislation regarding non-financial information disclosure, the formal-legal method was utilised. This revealed the formal implementation of Directive of the European Parliament and of the Council No. 2013/34/EU (2013) and the Directive of the European Parliament and of the Council No. 2014/95/EU (2014) via national legislative amendments in 2017-2018. The analysis focused on revisions to the Law of Ukraine No. 996-XIV (1999) and the instruction on the procedure for compiling and publishing financial reports of banks of Ukraine (Resolution of the Board of the National Bank of Ukraine No. 373, 2011).

A case study approach was used to examine the current state of sustainability reporting by Ukrainian banks. This involved reviewing the websites of 63 banks (Banks of Ukraine, n.d.) (6 state-owned banks, 14 banks owned by foreign bank groups, and 43 privately owned banks) and conducting an in-depth analysis of their non-financial reporting (63 management reports, 5 sustainability reports, 1 Communication on Progress, and 3 separate reports). European legislation was analysed to evaluate its feasibility and benefits for Ukrainian banks in sustainability reporting. The synthesis method was applied to systematise key challenges for Ukrainian banks in preparing Corporate Sustainability Reporting Directive (CSRD) compliant sustainability reports. The comparison method was used to identify the interrelationships between EU documents, including the Regulation of the European Parliament and of the Council No. 2019/2088 (2019), the Regulation of the European Parliament and of the Council No. 2020/852 (2020), and the CSRD (Directive of the European Parliament..., 2022). Systemic analysis was then used to determine their significance for sustainable development.

Graphical and tabular methods were employed to visually represent and clarify the data. The graphical method demonstrated the heterogeneous and unstructured nature of sustainability information in Ukrainian banks' management reports. Tabular presentation organised the distribution of reporting documents and the disclosure of ESG information across different bank groups. Generalisation and analogy methods were used to derive conclusions from the research findings. Drawing on international best practices, recommendations were developed to improve sustainability reporting and auditing at the state level. The study was conducted in the following stages: review of Ukrainian banks' websites to identify non-financial reporting and analyse detailed reporting format; analysis of the collected information, focusing on the disclosure of sustainable development issues, with a specific emphasis on ESG factors; synthesis of the findings from the content evaluation of non-financial reports, identifying key features and trends; assessment of bank compliance with regulatory requirements regarding information disclosure in non-financial reporting.

RESULTS

It is worth noting that the banking sector joined the process of evaluating its sustainability somewhat later than the real sector companies. The banking business, by its nature, has long been considered neutral in terms of environmental impact. According to researchers, banks go through several stages of involvement in the issues of sustainable development: defensive banking, preventive banking, offensive banking, and sustainable banking (Jeucken & Bouma, 1999). It is quite obvious that individual banks, as well as the banking systems of certain countries, can be at different stages and vary in their level of awareness of the problems of sustainable development.

In Ukraine, non-financial information in the form of a management report was implemented in 2017, when the Law of Ukraine No. 996-XIV (1999) was amended. The same law stated that the content of the management report for banks was determined by the National Bank of Ukraine (NBU). Therefore, at the beginning of 2018, the NBU introduced a new section on management reporting to the instructions on the procedure for compiling and publishing financial statements of Ukrainian banks (Resolution of the Board of the National Bank of Ukraine No. 373, 2011). This addition requires that the report includes an analysis of the economic, environmental, and social aspects of banking, essentially the ESG criteria. It should detail the changes during the reporting period and discuss their future impact on the bank's activities or potential to pose risks. In addition, it was noted that banks with the average number of employees exceeding 500 people were also obliged to disclose issues of employment, respect for human rights, and the fight against corruption. Thus, the requirements of the Directive of the European Parliament and of the Council No. 2013/34/EU (2013) and Directive of the European Parliament and of the Council No. 2014/95/EU (2014) were formally implemented into the regulatory framework of Ukraine.

However, having given the right to banks to independently define the format of displaying information in the management report, the National Bank did not mention the aspects of sustainability among the issues recommended for disclosure, which, of course, negatively affected the quality of non-financial reporting. At the same time, the Ministry of Finance of Ukraine has developed methodological recommendations for non-financial companies in compliance with the NFRD requirements for displaying ESG factors (Order of the Ministry of Finance of Ukraine No. 982, 2018). These include a description of the company's policy on specified issues, the outcomes of such policies, the main risks related to these issues, and the mechanisms for risk minimisation, among others. Yet, the NBU did not officially provide banks with similar explanations. Therefore, the National Bank did not use such an element of the EU legal framework as the guidelines on non-financial reporting (European Commission, 2017), which, although not mandatory, contribute to the provision of high-quality, relevant, useful, consistent, and more comparable non-financial (ESG-related) information.

In this regard, it is worth noting that among the documents of the central banks of the countries that are candidates for joining the EU, only a document from the National Bank of Georgia that is directly related to the disclosure of information about sustainable development – the ESG

reporting and disclosure principles (2020) – and prepared with the support of the OECD attracts attention. Nevertheless, at the end of 2021, the NBU presented the development of the Sustainable Finance Development Policy (2024) until 2025, developed in cooperation with the IFC. To comply with EU regulations, the policy required banks to include ESG factors in their corporate oversight and to embed environmental and social risk considerations within their risk framework. Additionally, it emphasised the importance for financial institutions to disclose the sustainable nature of their activities. To ensure this, from 2022 to 2024, it was planned to prepare and approve standards for the disclosure of ESG information by banks, the formation of a control system for the provision of such information, the development of appropriate analytical tools, and the holding of training for market participants. But regarding a full-scale military invasion, the work in this area was stopped. It was resumed only in 2023 as part of the World Bank's technical assistance, taking into account the catastrophic consequences of military actions and the new status of the state as a candidate for EU membership, which adds obligations to Ukraine regarding the implementation of the practice of sustainable financing.

At the same time, Ukrainian banks, at their own will, can and are already using internationally recognised systems and standards for reporting on sustainable development, including the Global Reporting Initiative, International Integrated Reporting Council, Carbon Disclosure Project, Financial Stability Board's Task Force on Climate-Related Financial Disclosures, UN Global Compact, International Financial Reporting Sustainability Disclosure Standards, and others. Such reporting can serve as a valuable tool for the bank to better understand its impact and risks, mitigate them more effectively, capitalise on new opportunities, and address specific challenges to become a leader in sustainability. It also allows the bank to showcase its commitment to sustainable development principles to stakeholders and the public.

The full-scale invasion has not eliminated the requirements and needs for achieving the Sustainable Development Goals in Ukraine. Furthermore, the war did not diminish the necessity of considering ESG factors in financial institutions' operations; instead, it encouraged a more active implementation of them: the humanitarian disaster sharpened attention to the social aspect; destruction and resource limitations forced entities to review and find new business approaches, including taking into account ethical aspects; the environmental consequences of the war forced them to be deeply anxious about the restoration of the environment. All this should be reflected in non-financial reporting.

Based on the facts in international practice, several formats of non-financial reporting are distinguished, namely: communication on progress; a report on sustainable development; a separate social report based on indicators independently determined by the entity; integrated reporting, which combines both financial and non-financial reporting (management report). The results of information gathering from the websites of Ukrainian banks are displayed in Table 1. It is essential to point out that certain information related to the environmental and/or social aspects of banking, which may be published on a website as a message or article but not compiled in a separate document, is not considered non-financial reporting.

Table 1. Banks that provided non-financial reporting in 2018-2023

Groups of banks	Management report	Sustainability report	Communication on Progress	Separate report
State-owned banks	6	1	-	-
Banks owned by foreign bank groups	14	3	-	3
Privately owned banks, including:	43	1	1	-
▪ with foreign capital	13	1	-	-
▪ with domestic capital	30	-	1	-
In total	63	5	1	3

Source: developed by the authors

Therefore, even those banks that declare a socio-environmental orientation of their development are not fully informationally transparent because they do not publish reports on sustainable development. Only five of the 63 studied banks have relevant reports (albeit for different periods): Ukrgazbank (2018-2020), Ukrsibbank (2022), Credit Agricole Bank (2023), SEB Corporate Bank (2023), and Bank Lviv (2020-2022). Furthermore, First Ukrainian International Bank (FUIB) publishes the Communication on Progress, ProCredit Bank – Impact Banking in Practice, ING Bank Ukraine – Integrated Climate Report, Pravex Bank – ESG Report. Therefore, only 14% of banks voluntarily prepare reports with information on the environmental and social results of their activities and their impact on the environment and society. It was found also that all banks, under the requirements of the NBU, publish management reports, but their structure and content differ significantly, which does not allow for obtaining systematic and comparative information on reporting on sustainable development.

A thorough examination of management reports of Ukrainian banks showed that the information provided by them about sustainable development is heterogeneous and unstructured. But the most important thing is that almost all banks do not disclose sustainability risks that can arise in environmental, social and business contexts and negatively affect the value of investments. The availability of certain sections in the bank management reports, which in one way or another disclose the issues of sustainability, is shown in Figure 1.

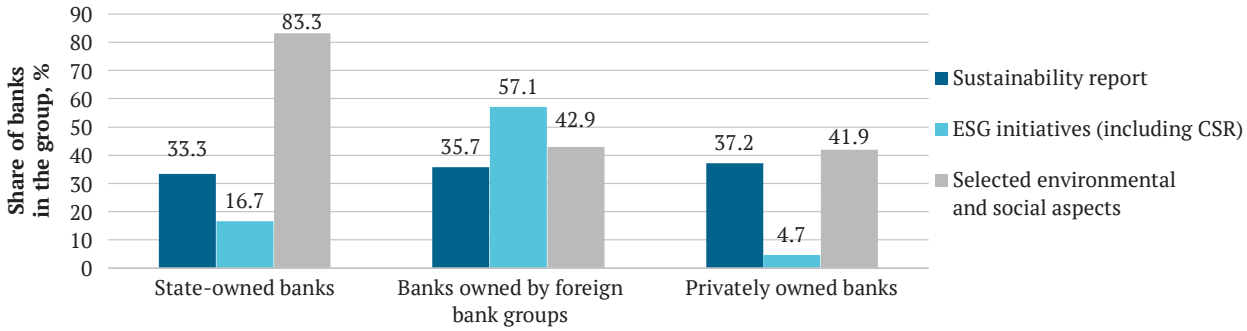

Figure 1. Completeness of data on sustainability in Ukrainian banks' management reports
Source: developed by the authors

It is important to highlight that 13 commercial banks do not represent aspects of sustainable development in their non-financial reporting, namely: Citibank, Deutsche Bank DBU, Credit Europe Bank, MTB Bank, A-Bank, Clearing House, Unex Bank, Cristalbank, RWS Bank, MetaBank, Bank Trust-Capital, Bank Familny, Motor-Bank. It shows the lack of transparency and their unwillingness to be responsible to society for the impact of banking on the environment and social processes.

The most common practice is the disclosure of information about social and environmental aspects or responsibility (46% of the sample), some banks even have an approved environmental and social control system and/or implement an environmental and social policy (for example, Sense Bank). Only 11 banks (17.5%) represent ESG initiatives (including the policy of corporate social responsibility as a concept, thanks to which institutions integrate social and environmental issues into the operating model and interact with stakeholders) in management reports. It is worth noting that most of these banks – eight, are banks of foreign banking groups, which can be explained by the following features of their business: the existence of clear regulatory requirements in the parent banks' countries regarding the disclosure of ESG data; integration of ESG factors into the strategy and business processes of parent banks, which contributes to a more systematic approach to their implementation; a high level of awareness of the importance of ESG aspects and the need to disclose such information; the availability of considerable funding at parent banking groups, which allows them to invest in ESG projects and initiatives.

22 banks (35% of the total) include the "Sustainability Report" as a separate section in the management report, but this data differs in scope, content, and structure. Besides, the general disadvantages are the following: information does not have a financial component (aspects of sustainable development are displayed without linkage to financial results and are only descriptive); it is not regular, consistent, and comparable; it has a low level of reliability (because there is no consistency in the collection of information and third-party audit). To determine the maturity of Ukrainian banks in incorporating ESG factors into their activities, the structure of sustainability reports was analysed to examine the disclosure of ESG aspects of their business (Table 2).

Table 2. Inclusion of E, S and G factors in banks' sustainability reports

Bank name	E	S	G
PrivatBank	+	+	+
Ukrgazbank	+	+	+
Raiffeisen Bank	+	+	+
Kredobank	+		+
Credit Agricole Bank		+	
Pravex Bank	+	+	+
SEB Corporate Bank	+	+	+
Bank Alliance	+	+	+
Altbank	+	+	+
Cominbank	+	+	+
Poltava-bank	+	+	
Bank for Investments and Savings	+	+	
Bank "Ukrainian Capital"	+	+	+
Asvio Bank		+	
Bank Grant	+	+	+
Bank 3/4	+	+	
European Industrial Bank	+		
Bank Avangard			

Table 2. Continued

Bank name	E	S	G
Policombank	+	+	
Ukrainian Bank of Reconstruction and Development	+	+	
BTA Bank	+	+	
Alpari Bank			

Source: developed by the authors

It was found that only 10 banks out of 22, i.e., less than half of them, took into account all ESG aspects in their reports. In general, E (environmental) and S (social) factors are reported much more often than factor G (corporate governance). At the same time, most of the banks' initiatives within the framework of corporate responsibility in 2023 were related to social aspects: the help to internally displaced persons, children, educational and health care institutions, and Ukrainians affected by the consequences of the war. Regarding the governance aspect (G), despite the presence of a separate report on corporate governance in the banks' management reports, the impact of corporate governance on ensuring the sustainability of banking is practically not reflected directly in the report on sustainable development. It is worth noting that most of the analysed bank reports are descriptive and do not represent quantitative or financial data. Banks prefer narrative descriptions to reflect the potential impact of risks rather than quantifying them. Improving banks' sustainability reporting practices is especially important concerning Ukraine's status as a candidate for EU membership. Currently, the basis of sustainability reporting in the European Union is formed by a triad of mandatory documents: the EU taxonomy, the Sustainable Finance Disclosure Regulation (SFDR), and the EU CSRD together with the European Sustainability Reporting Standards (ESRS) development (Table 3).

Table 3. Mandatory documents that regulate sustainability reporting in the EU

Document	Purpose of adoption	Relationship with other documents	Importance for sustainable development
EU Taxonomy (Regulation of the European Parliament and of the Council No. 2020/852, 2020)	To form a classification of environmentally sustainable types of economic activity, which is used within the framework of CSRD and SFDR	Provides basic efficiency criteria for determining types of economic activity that have a significant contribution to achieving the goals of the European Green Course and are necessary for the preparation of relevant reporting	It is a tool for the distribution of investments by types of economic activity, which are defined in the taxonomy
SFDR (Regulation of the European Parliament and of the Council No. 2019/2088, 2019)	To increase the transparency of ESG information for sustainable investing	The data, according to the CSRD, are the basis for supplementing the SFDR reports with information on sustainable development. Therefore, part of the indicators provided in CSRD reporting can be used by banks when disclosing information about sustainable finance according to SFDR requirements	ESG metrics are disclosed in reporting to encourage sustainable investment practices
CSRD (Directive of the European Parliament..., 2022)	To improve the qualitative and quantitative parameters of corporate reporting on sustainable development		Obliges to include ESG indicators that comply with the EU taxonomy in SFDR reporting

Source: developed by the authors

Although the mentioned regulatory acts are not yet binding for Ukrainian banks, the implementation of their requirements will significantly increase the transparency and quality of information on sustainable development in the annual corporate reporting of banks. Based on such data, reporting users will be able to form an integrated view of the bank's impact on ESG factors and the effectiveness of its business. The results of the study indicate the following main benefits of implementing the CSRD requirements for Ukrainian banks. Most banks do not have an effective development strategy, and top executives are focused on solving current issues. The availability of clear reporting requirements under the CSRD, the use of detailed standardised non-financial indicators, the integration of ESG data into risk framework and the bank's strategy will have a synergistic effect and improve the controllability of risks and allow for identifying new development opportunities related to ESG. For instance, describing in the sustainability report the consideration of sustainability factors in the bank's corporate strategy and the financial consequences of operations, determining the areas of improvement of sustainability indicators, and the connection of business strategy with sustainable development plans (as it is required by the CSRD), the bank's top executives can identify areas of investment that most fully correspond to the values and strategy. Thus, a detailed analysis of the strategy will become an effective tool for economic development, which will allow more clearly align the strategy, plans, and operational processes with the sustainability goals.

The availability of banking products that take into account the goals and requirements of sustainable development will contribute to increasing the competitiveness and reputation of the institution, as well as expanding the market niche due to the attraction of sustainability-oriented customers. In particular, implementing "green" bonds or "green" lending at rates lower than market ones will allow for the preferential attraction of new sustainability-oriented customers. This will result not only in the economic support of such business entities but also in the improvement of the bank's reputation as one that cares for society and the national economy as a whole. It should be noted that the availability of sustainable banking products, which are increasingly in demand in the domestic market, is

extremely important because, as the research showed, their supply is still insufficient.

The bank's empowerment to attract foreign capital, since the bank's focus on sustainable development is an important factor when making a decision on investment and lending to companies from EU countries. Reporting of all Ukrainian banks according to CSRD requirements, which clearly define indicators and reporting standards, will ensure transparency and comparability of reporting. That will serve as information support for foreign companies when making investment or lending decisions in favour of sustainability-oriented banking institutions.

Reduction of reputational risks through the provision of consistent, transparent, and meaningful information on sustainable development. While preparing corporate reports according to the CSRD requirements offers significant advantages through detailed coverage of sustainability issues, it poses a real challenge for Ukrainian banks, which currently provide limited data on ESG factors. The CSRD mandates comprehensive retrospective and prospective qualitative and quantitative information on sustainable development across value chains, covering short, medium, and long-term horizons.

The problems faced by domestic companies in preparing non-financial reports have already been identified by scholars: the lack of a standardised form for providing information; difficulties in obtaining information that may constitute a trade secret; the quality of the audit of the management report, and others (Tsaruk, 2019). Additionally, when compiling reports under CSRD requirements, Ukrainian banks may encounter challenges such as data collection (including information about counterparties' activities), data aggregation, electronic formatting, and additional expenses for mandatory audits of sustainability reports. These issues can be explained in more detail as follows.

1. The main feature and requirement of CSRD and ESRS developed for it is the principle of double materiality when information is disclosed both from the point of view of the impact of environmental and social problems on the bank (the so-called financial materiality) and in terms of the impact of the bank's operations on the environment and society (the so-called ESG materiality). Financial materiality involves assessing the impact of ESG factors on the financial performance of banks. ESG materiality involves assessing the impact of the bank's operations on the environment, society, and governance (Stiroh, 2022). Investing and financing other economic entities are specific to banking, meaning that a significant part of a bank's materiality is found in its clients' economic activities. Therefore, when assessing dual materiality, the bank must take into account not only the impact of its operations on the environment but also the impact of the bank's clients and associated companies on sustainable development. In addition, banks must calculate the amount of environmentally sustainable activities of their clients and the share of loans granted or investments made in these kinds of activities.

It is important to remember that Ukrainian banks do not currently perform actual materiality assessments. Only a few banks conduct such assessments based on qualitative indicators and with a high level of subjectivity, due to the nature of these measures. In particular, in 2024, FUIB planned to measure the achievement of its goals through regular monitoring of ESG indicators (Progress report..., 2023). For a realistic picture, it is necessary to present information in a quantitative dimension. However, the quantitative assessment of dual materiality (considering the negative impact of the activities of clients to whom loans have been granted on sustainability) is a rather complex task that requires gathering data from internal and external sources, taking detailed measurements, reviewing the value chain to identify relevant areas for disclosure. All this increases the costs of preparing reports, requires the hiring of more qualified personnel and significant investments in technology and data handling, and changes in internal policies and accounting procedures.

2. The need to create a sustainability report (as part of a management report) in a formalised format and to upload it to the European Single Access Point (ESAP) requires making changes to information systems and accounting processes related to the preparation and disclosure of information about sustainable development.

3. A significant challenge in Ukraine, especially within the banking sector, is the shortage of experts with deep knowledge of sustainability reporting. These professionals must be capable of managing large volumes of data, working in a dynamic environment, and staying current with the ever-evolving requirements of numerous sustainability reporting standards, including the EU taxonomy.

4. When developing the CSRD and relevant standards, emphasis was placed on large corporations, without keeping in mind individual industry specifics. Therefore, the accelerated implementation of CSRD, the absence of sectorial standards considering the specifics of banking, and the mandatory audit of corporate reporting will significantly increase the costs of the banks, the NBU, other government bodies, and auditing companies.

On the other hand, such labour and resource costs are justified, as providing assurance by auditors regarding banks' sustainability reporting will help ensure the reliability, completeness, consistency, and coherence of this reporting in conjunction with financial reporting, which is especially important for users of such reports. At the same time, to ensure proper sustainability reporting, bank employees responsible for its preparation and auditors who will provide audit services on sustainability reporting must have a sufficient level of professional competence, theoretical knowledge of the preparation and audit of sustainability reports, and the ability to apply such knowledge in practice.

To initiate proper sustainability reporting by Ukrainian banks and create favourable organisational and legal conditions for this, it is necessary to improve state policy in this area, develop and approve the necessary regulatory legal acts. They can be based on the relevant provisions of the CSRD, which determine the mandatory audit of sustainability reporting and the requirements for auditors. In addition, at the state level, it is worth doing the following. A training with the involvement of sustainability experts from EU countries should be organised to train auditors and bank representatives who will prepare sustainability reports. The algorithm for certification of sustainability auditors and the procedure for organising work in the Law of Ukraine 2258-VIII (2017) should be specified to fulfil the mandatory task of providing assurance on sustainability reporting. A new section 5, titled "Audit entities entitled to perform

mandatory assurance tasks on sustainability reporting", should include information about sustainability auditors in the Register of Auditors and Auditing Entities. The CSRD and the accompanying ESRS create both challenges and opportunities for banks. Even though the challenges are quite significant, banks that implement the requirements of these regulatory documents in their operations and invest in technology, data handling, policies, and procedures will be able to make a real impact on a more sustainable future and improve their long-term financial performance.

DISCUSSION

Analysis of disclosure of non-financial information practices by banks is one of the most important tasks for understanding the state of transparency and involvement in ESG initiatives in the banking sector and the extent of information asymmetry in this area. As a result of the analysis, it was found that all banks, under the requirements of the NBU, publish management reports, but their structure and content differ significantly, which does not allow for obtaining systematic and comparative information on reporting on sustainable development. The research analysed the current state of sustainability reporting in the Ukrainian banking sector, identifying key trends and problematic aspects. Particular attention was paid to comparing the existing reporting practices with the requirements of the EU CSRD, which, although still voluntary for Ukrainian banks, sets the direction for future reporting. Full-scale implementation of sustainable development reporting in Ukraine will have a positive effect on both the macro and microeconomic scales. At the level of the national economy, it will support sustainable long-term investment, reduce unemployment, and contribute to the recovery of the economy, which was also emphasised in the article by O. Solodovnik & I. Gavrylychenko (2021). Researchers explored how to track and assess the corporate sector's progress towards sustainability goals in Ukraine by creating practical guidelines.

By publicising their contribution to sustainable development, Ukrainian banks will improve operational efficiency through a better understanding of banking risks, increased transparency, and consideration of ESG factors when making credit and investment decisions. This statement aligns with the opinion of E. Palmieri *et al*. (2024), who demonstrated the positive impact, in particular, of the environmental component of banking activities on reducing the risk of insolvency and bank default. I. Makarenko *et al*. (2020), like this study, analysed the sustainability reporting of Ukrainian banks. To evaluate it, the authors developed and applied the specific index, whose methodology includes a range of formal, content, assurance, and disclosure scorings. According to the results of a continuous assessment of the management reports of 75 banks for the 2018 fiscal year, the average index was 61.2%. In the opinion of the authors, this indicated a fairly high level of disclosure quality in their sustainability reporting, which is somewhat contradictory to the research conducted. Among the 14 indicators defined by the authors for evaluating reporting, only four directly addressed sustainable development (social aspects, environmental aspects, anti-corruption activities, human rights protection), while the others related to banks' compliance with general requirements for preparing non-financial reports. Therefore, the relatively high result reflected only the compliance of most management reports with regulatory requirements, rather than the quality of sustainable development reporting. At the same time, the conducted study confirmed the researchers' conclusion that the best results in terms of completeness of non-financial information disclosure in Ukraine were observed in the groups of state-owned banks and banks owned by foreign bank groups (Fig. 1). The former, due to their status, are more responsive to implementing state policies, and the latter have the opportunity to leverage the experience of their parent structures in the field of sustainable development.

L. Kindratska (2024) explored the issue of forming sustainability reports by public sector entities, which is important for this study, considering that Ukraine already has seven state-owned banks at the beginning of 2025. They occupy almost half of the banking market and are considered entities of heightened public interest. Aligning the activities of public sector institutions with the achievement of Sustainable Development Goals positively impacts the effectiveness of economic processes in the context of enhancing economic development and citizens' quality of life. The measures to improve the formation of relevant reporting, proposed by the author of the article, will contribute to more effective communication to stakeholders about the contribution of public sector institutions to sustainability, the formulation of reliable conclusions about the impact of their activities on the economy, environment, and social development of communities, as well as enhancing the quality characteristics of the services provided.

The research results that companies in the real sector of the economy have a somewhat higher level of disclosure regarding their economic, environmental, and social impact, thanks, in part, to greater methodological support from government bodies, correlate with the assertion of T. Yefimenko *et al*. (2021). However, the informativeness of even such companies' reporting remains quite low. Therefore, based on international standards, researchers proposed a basic list of non-financial reporting indicators and the development of a practical commentary on their disclosure. H. Umantsiv (2023) also noted that the spread of sustainability reporting practices in Ukraine required the improvement of theoretical and conceptual-methodological approaches to substantiate the directions of disclosure of this information by companies in the context of European integration of Ukraine. The NBU should speed up the development and implementation of new reporting requirements following the CSRD. On the other hand, banks should assess as soon as possible their readiness for detailed data disclosure about business models, strategies, and supply chains related to sustainability.

The challenge of ensuring quality information disclosure on sustainable development and regulatory compliance is not unique to Ukrainian banks; it extends to banks in more developed countries as well. D. Tőzsér *et al*. (2024) investigated this issue by evaluating the sustainability reporting compliance of Hungarian and top European banks using a scoring method. Their findings indicated that while both groups selected similar aspects of their activities for disclosure, the level of data representation was significantly lower in Hungarian banks. Consequently, the authors

concluded that Western European banks demonstrated superior preparedness for the CSRD compared to Hungarian banks, which they considered representative of the region. They emphasised the need for financial institutions in Central and Eastern Europe to more effectively adopt best practices, a conclusion that strongly aligned with the results of this study.

A.L. Santos & L.L. Rodrigues (2021) examined how Portuguese banks report climate-related data. Their research revealed that while disclosure has improved, it still falls short of recommended standards. The researchers also found significant variation in reporting practices among banks, with some being more advanced than others. This lack of uniformity, where banks prioritise different information, mirrors the situation in Ukraine and makes it impossible to compare sustainability performance across financial institutions. The authors correctly argue that greater standardisation of reporting topics and content is essential for meaningful comparisons between banks. Their proposals correlate with the results of the conducted research and are further complemented by the conclusions of I. Ferrero-Ferrero *et al*. (2023). The researchers believe that placing sustainable development at the centre of EU policy requires the creation of resources, implementation methods, and control tools at the supranational and national levels to ensure that sustainability reporting is on par with financial reporting. To achieve this, public authorities should join efforts to create a homogeneous and comparable reporting methodology and to ensure an independent assurance process for sustainability information.

Conducting an audit of sustainability reporting is crucial for ensuring its informativeness and effectiveness, as emphasised during the research. M. Kucheriava & A. Shvaher (2023) also analysed these issues, focusing on relevant European experience. The scholars provide proposals aimed at developing an institutional mechanism for overseeing the quality of sustainability reporting by business entities through establishing requirements for the qualification and certification of auditors who conduct sustainability reporting audits and defining the organisational principles for providing relevant audit services. The direction of further research aligns with the conclusions of T.L. Föhr *et al*. (2023) regarding the possibility and feasibility of using large language models for auditing sustainability reporting by developing a sustainability-related audit prompt framework.

The results of the research indicated that the imperatives of sustainable development play an increasingly important role in the modern banking sector; however, the degree of their implementation in Ukraine remains uneven. It was found that non-financial reporting on sustainable development has significant potential to reduce information asymmetry, increase the transparency of banks' activities, and improve their competitiveness, but its implementation in the domestic banking system is fragmented. Unification of requirements in the form of clear and detailed sustainability reporting standards for the banking sector, incentivising financial institutions not only to transparently disclose information but also to use quantitative indicators to assess the impact of their sustainable development initiatives, conducting training and consultations for banks on the methodology of preparing relevant reports, engaging independent auditors to verify the accuracy and completeness of the information disclosed in the reports – all of this will enhance the transparency of banks' activities, foster investor confidence, and create a more sustainable financial system in Ukraine.

CONCLUSIONS

The study showed that although all banks publish non-financial reports in accordance with the requirements of the National Bank, only 14% of them voluntarily compiled certain types of reports with information on the environmental and social results of their activities in some years. These banks include Ukrgazbank, Ukrsibbank, Credit Agricole Bank, SEB Corporate Bank, Bank Lviv, FUIB, ProCredit Bank, ING Bank Ukraine, and Pravex Bank. This showed that the majority of Ukrainian banks, even while declaring social and environmental responsibility, remain insufficiently transparent in disclosing their activities. An analysis of management reports revealed that 13 banks do not reflect aspects of sustainable development in them at all, which indicated an extremely low level of their readiness to disclose information in accordance with CSRD requirements. A significant difference in the structure and content of such reports was found: some banks limit themselves to general declarative statements about social responsibility, while only a few banks systematically reflect the ESG aspects of their activities.

Most often, banks provide general information on social and environmental aspects, including issues of social responsibility (46% of the sample), and only 22 banks (35% of the total) include a separate section on sustainable development in the management report, but their information, as a rule, is fragmented, descriptive, and not related to financial indicators. It is in the reports of the latter group of banks, including PrivatBank, Ukrgazbank, Raiffeisen Bank, Kredobank, Bank Alliance, Altbank, Cominbank, and others, that ESG initiatives are presented in a more structured manner. However, it was found that only 10 out of the 22 banks providing sustainability reports disclose all ESG components, which is less than half of their number. Social and environmental aspects are most often highlighted (82% of banks), in particular, support for internally displaced persons, educational and medical institutions, due to current wartime challenges, energy conservation, and dealing with waste. Governance aspects are disclosed much less frequently (50% of banks), indicating insufficient integration of banks' corporate governance with sustainable development goals.

An analysis of international regulatory experience showed that the implementation of CSRD requirements can significantly improve the quality of sustainable development reporting. At the same time, the study revealed a number of barriers to the implementation of such standards, including the lack of unified methodological approaches to assessing ESG risks, insufficient staff competence, the absence of industry standards for the banking sector, and significant costs for auditing sustainability reports. However, non-compliance by Ukrainian banks with CSRD requirements in the future may lead to capital outflow, reputational damage, potential fines, legal consequences, and damage to business relationships. Therefore, despite all the difficulties, Ukrainian banks should start a

gradual transition to reporting under the new standards. To facilitate the reporting process, it is advisable to consider the possibilities of implementing intelligent software for both report preparation and its audit, which might be the subject of further research.

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CONFLICT OF INTEREST

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Звітність зі сталого розвитку банків України: поточний стан, проблеми та перспективи

Анотація. З огляду на зростаюче значення сталого розвитку та інтеграцію України в європейський економічний простір, якісна та повна звітність зі сталого розвитку є критично важливою для банківського сектору. Метою дослідження було оцінити повноту розкриття інформації зі сталого розвитку в нефінансовій звітності українських банків, виявити проблеми та можливості підвищення якості такої інформації для досягнення позитивних ефектів на мікро- та макроекономічному рівнях. Для досягнення поставленої мети було використано метод кейс-стаді, який передбачав комплексний аналіз веб-сайтів усіх українських банків із метою дослідження їхньої нефінансової звітності. Поглиблений аналіз було проведено з метою визначення наявності та якості розкритої інформації щодо екологічних, соціальних та управлінських (ESG) факторів. Результати дослідження показали, що українські банки лише починають впроваджувати звітність зі сталого розвитку. Розкрита інформація зі сталого розвитку має переважно описовий характер, не містить кількісних або фінансових даних, часто є неоднорідною та неструктурованою. Навіть банки, які позиціонують себе як соціально та екологічно орієнтовані, не розкривають повною мірою ризики сталого розвитку та не надають вичерпної інформації в контексті цілей сталого розвитку. Лише 35 % українських банків подають «Звіт зі сталого розвитку» як частину свого звіту про управління, і лише 45 % із цих банків розглядають у звіті всі ESG-фактори. Продемонстровано, що, незважаючи на значні труднощі у виконанні вимог Директиви щодо корпоративної звітності зі сталого розвитку, яка залишається добровільною для українських банків, прийняття цих стандартів є необхідним. Це сприятиме підвищенню прибутковості та прозорості діяльності банків, зміцненню довіри інвесторів та створенню більш стабільної фінансової системи в Україні. Було наголошено на нагальній потребі для українських банків застосовувати більш проактивний та комплексний підхід до звітності зі сталого розвитку та підготуватися до вимог майбутнього регуляторного середовища

Ключові слова: нефінансова звітність; фінансові установи; розкриття інформації; економічні, соціальні та управлінські фактори; вимоги; показники; аудит

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Promotion of economic zones and business support in industrial clusters: Information, investment and human capital approaches

Abstract. The study aimed to analyse the specifics of promoting economic zones and providing business support in industrial clusters. To achieve this goal, a sample of the following objects was created: Frankfurt-Höchst Industrial Park (Germany), North Huntsville Industrial Park (USA), the Industrial Cluster and Knowledge Cluster programmes (Japan) and Shenzhen-Hong Kong-Guangzhou (China). The selected clusters were analysed in terms of information exchange strategies, investment attraction and quality human capital. According to the comparative analysis, the key features of effective cluster promotion are the creation of an extensive information network for interdisciplinary cooperation and information exchange, the attraction of investment in human capital development and investment diversification. A synthetic analysis using SWOT analysis, PEST analysis and Porter's Five Forces model identified the main obstacles to the

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effective promotion of economic zones and clusters: shortage of human resources or their poor quality; lack of demand for the products and/or services offered in the region where the cluster operates; insufficient understanding of the context of the cluster's operation, leading to ineffective strategic decisions. Based on the analysis, the following recommendations were made for the effective promotion of economic zones and clusters in terms of investment, information and human resources policy: transition to intensive investment and human capital development practices; diversification of investments, especially in low-income regions with higher priority state budget expenditure items; preliminary contextual analysis to identify public demand for cluster functioning

Keywords: contextual analysis; development of cooperation; diversification of financing; sustainable development; capital raising

INTRODUCTION

In times of economic uncertainty, promoting economic zones and securing business in industrial clusters are key strategies for sustainable development. The idea of creating economic zones originated in the UK in the 1980s and was soon implemented in other countries, including the US, Japan, China and the EU. The emergence and development of such zones are driven by the idea that creating special conditions for doing business helps to create new jobs and economic growth, especially in regions where market forces are weak or not at all.

Numerous studies were devoted to the study of the concepts of economic zones and industrial clusters, including an article by M. Kim & T. Chapin (2022), which argued that the policy of creating an economic zone is a policy of economic and social development aimed at providing special incentives to targeted areas to increase investment and economic growth. M. Crawford (2024) emphasised that the existence of economic zones stimulates business growth and job creation in economically disadvantaged communities where market forces usually do not operate. The author highlighted that there are more than 3,000 economic zones in the United States, some of which, such as in Kansas, are the size of an entire state. The concept of an economic zone is inextricably linked to the concept of an industrial cluster, which H. Kim *et al.* (2023) defined as a group of geographically contiguous, interconnected companies and institutions in a particular area. That is, industrial clusters can be defined as elements of economic zones.

Economic zones are becoming more common due to the benefits they offer, including reduced unemployment (Saeed *et al.*, 2024). According to R. Hasan *et al.* (2024), the creation of favourable conditions for small and medium-sized enterprises, including the provision of tax incentives, contributes to their sustainable growth and development, which is expressed, among other things, in the creation of new jobs. For instance, the idea was confirmed in a study by M. Crawford (2024), according to which the Southwest Enterprise Zone of Baltimore County in Maryland, established in 1996, had 62 thriving companies and 920 new jobs as of 2024. D. Neumark (2020) believed that job creation reduces unemployment and poverty, thereby contributing to the restoration of social justice. Thus, the existence of economic zones is a prerequisite not only for the economy but also for the social well-being of a particular region.

Due to government support, economic zones are becoming innovation zones, offering effective solutions to pressing problems in key areas (Ustymenko, 2024). According to J. Xie & Y. Wang (2024), enterprises in economic zones use innovative approaches to efficiently allocate and use limited resources economically. An example is the introduction of innovative solutions to reduce the carbon footprint of enterprises. According to Q. Sheng *et al.* (2024), the initiatives of individual enterprises can make a significant contribution to solving environmental problems at the regional or national level. Based on the cited studies, it is possible to argue that the existence of economic zones is associated with numerous benefits at different levels of the state.

The functioning of such zones, however, also implies overcoming certain difficulties, which, according to F. Alfazzi (2023), include limited availability of financial and other resources, reduced competitiveness and insufficient regulatory framework. According to S.A. Frick & A. Rodriguez-Pose (2023), the attraction of innovation in the development of economic zones is also a challenge, especially in economically unstable regions of Africa, Asia and Latin America. Thus, planning for the creation and development of economic zones implies an in-depth analysis of possible obstacles and the development of strategies to overcome them. The study aimed to analyse the peculiarities of economic zone promotion and business provision in industrial clusters.

MATERIALS AND METHODS

The materials for this study were industry reports on the following economic zones: Frankfurt-Höchst Industrial Park, Germany (Heck *et al.*, 2024); North Huntsville Industrial Park, Alabama, USA (CRE Consulting Corps, 2023); Industrial Cluster and Knowledge Clusters Programme, Japan; Shenzhen-Hong Kong-Guangzhou Industrial Cluster, China (Li, 2024). Reports from the United Nations (Global Innovation Index…, 2024), among others, were considered. Industry reports published in the last five years, i.e., which are relatively recent and relevant, were selected for the study. The main research tool used was the case study method, which was aimed at presenting a detailed analysis of selected economic zones and industrial clusters in Germany, Japan, China and the United States. The chosen case study method implied the use of statistical analysis to assess the performance of the selected clusters. To analyse each of the selected cases, a three-component model was applied, as shown in Figure 1.

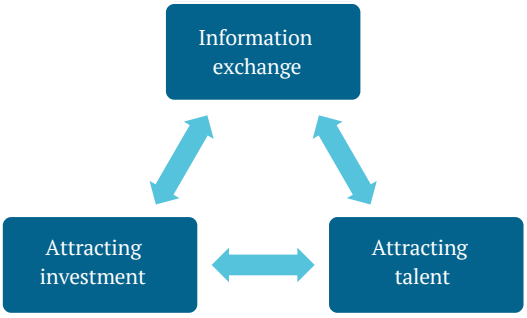

Figure 1. Model for analysing selected cases
Source: compiled by the authors

Based on the presented model, the analysis of the functioning of economic zones and industrial clusters implies an assessment of the efficiency of planning and development of resources such as information, investment and human resources. Information exchange is understood as the use of certain tools to assess the impact of internal and external factors on the creation and operation of an economic zone or industrial cluster: SWOT analysis, PEST analysis and Porter's five forces analysis. Investment attraction means analysing initiatives aimed at attracting investors, allocating resources and using them efficiently to support the sustainable development of the economic zone or cluster. The human resources element involves a detailed analysis of efforts to attract specialists whose knowledge and skills are the driving force behind the successful functioning of the economic zone or industrial cluster. As an additional method, a comparative analysis was used to identify universal methods of promoting economic zones and industrial clusters, regardless of their geographical location. The analysis also aimed to identify the most common difficulties in the development and expansion of economic zones and industrial clusters. The identified challenges were analysed in terms of costs and benefits to justify the feasibility of strategies aimed at improving economic zones and industrial clusters.

RESULTS

Features of the organisation of economic zones and industrial clusters in Germany, the USA, Japan and China

Several economic zones and industrial clusters in the EU, USA, China and Japan were analysed. One of the economic zones analysed is the Frankfurt-Höchst Industrial Park, Germany. This park is a licensed, fully developed site for research, development and production of chemical, pharmaceutical, biotechnology and related products (About Industriepark Höchst, n.d.). As of 2024, the park covered an area of 460 hectares, housing 90 companies with a total of 22,000 people. An important feature of Frankfurt-Höchst Park is the efficient use of information, made possible by the expert services offered by the players in interacting with government agencies to ensure that they can quickly obtain a licence to carry out certain activities, such as biotechnology research. The exchange and implementation of information also includes interaction with on-site experts who help companies manage technological systems and installations throughout their life cycle, as well as develop cost-effective solutions to help implement maintenance strategies. The Frankfurt-Höchst Industrial Park is therefore designed to facilitate cooperation between companies and local experts, as well as interdisciplinary collaboration between companies.

In addition to the exchange of information, the functioning of the Frankfurt-Höchst Industrial Park depends on attracting investments and their subsequent efficient distribution (Heck *et al.*, 2024). Since 2000, more than EUR 8.5 billion has been invested in the development of the park, making Frankfurt-Höchst one of the largest projects in the EU (About Industriepark Höchst, n.d.). An example is the investment by the German company INERATEC in 2022 of EUR 30 million in a research project on the efficient use of hydrogen. The project has attracted interest at the state level; and the first hydrogen filling station built thanks to the investment was visited by German Chancellor Olaf Scholz. Based on the information provided, it is possible to state that since the park's inception, most investments have come from German companies.

Recognising the importance of human capital, the Frankfurt-Höchst Industrial Park has introduced initiatives to attract and retain well-trained and highly motivated professionals. The park is also home to Provadis, a company that helps companies develop innovative internship programmes to attract and train qualified employees. Provadis helps companies operating in Frankfurt-Höchst to create an individual professional track for each employee, which begins at college or university, where they search for candidates with a high level of professional training and good leadership skills. The companies of the Frankfurt-Höchst Industrial Park are thus committed to investing in human capital, viewing it as the driving force behind their progress.

The Hunstville, Alabama industrial-industrial zone is one of the most notable clusters in the United States. This cluster is known nationally and internationally for its achievements in the aerospace industry, which helped it earn the title of "Rocket City" (CRE Consulting Corps, 2023). Compared to Frankfurt-Höchst, North Huntsville Industrial Park is relatively small, as its total area does not exceed 27 hectares. This industrial cluster has nevertheless overcome the space limitation by shifting the focus to interdisciplinary interaction between leading companies in the aerospace and defence industry. This thought is supported by the fact that 47 Fortune 500 companies are in Huntsville.

Thus, North Huntsville Industrial Park is an example of the fact that for an industrial cluster to be successful, it is not so much the size of the cluster that matters, but the ability to effectively manage available resources, including information. Interdisciplinary collaboration between research centres, engineering companies and innovative start-ups to create high-tech aerospace products takes place within the cluster. Examples of such cooperation are such well-known US companies as SJ&L, IIC Blake or Stewart Electric. The effective exchange of information and knowledge is also facilitated by the operation of two Meta data centres in the industrial park. According to the report of the city administration, Meta plans to further expand its presence on the territory of the industrial park, which will contribute to the creation of an extensive information network of the cluster.

Raising and rationally allocating funds is a priority for North Huntsville Industrial Park, which seeks to attract national and international investors to develop infrastructure projects. An example of this is the cooperation with Meta, which came to the park in 2021 and attracted USD 3 billion in investment and created 75 new jobs.

A significant portion of the investments received is redirected to the development of the cluster's educational system. An example is the USD 1.9 million investment that Meta has made in Huntsville and Madison counties to partner with local schools and non-profit organisations to help disadvantaged youth, promote STEM education and support equity and empowerment initiatives. Similar to Frankfurt-Höchst, North Huntsville Industrial Park's management strives to create conditions in which vocational school graduates are interested in long-term cooperation with companies in the industrial cluster. The effectiveness of this strategy is determined by the fact that it provides companies with access to a pool of candidates with the required knowledge, skills and qualities, and reduces the risk of an outflow of qualified and motivated personnel. The Industrial Cluster Programme of the Ministry of Economy, Trade and Industry of Japan was launched in 2001 to establish interaction between economic entities within a regional agglomeration. The initiative was born out of the need to improve the link between scientific research and industry, particularly the woodworking industry, to increase the latter's efficiency. The project proved to be quite successful, as, by the end of the first five years of its existence, it had 19 industrial clusters comprising 6,100 companies and 250 universities (Kuwajimi, 2022).

Unlike the previously discussed initiatives, the Industrial Cluster is a set of programmes aimed at creating and developing industrial clusters throughout the country. A new round of the programme was launched in 2007 with the adoption of a law on the formation and development of regional clusters to promote the autonomous development of regional economies (Kuwajimi, 2022). The law required each candidate region to formulate specific "basic plan" for industrial agglomeration in consultation with local business groups and submit it to the central government for review and approval. In other words, it can be argued that the functioning of industrial clusters in Japan implies a more complex hierarchical structure than the functioning of such clusters in Germany, the USA and several other countries. The similarity is that once approved, the submitted plan receives government support in the form of various tax incentives. The Industrial Cluster programme of the Japanese Ministry of Economy, Trade and Industry assumes that the government is the main source of funding for initiatives. The main task of attracting and retaining human capital in industrial clusters is to rationalise common forms of labour productivity, which is implemented, among other things, through the Knowledge Clusters programme.

The Knowledge Clusters programme was developed by the Ministry of Education, Culture, Sports, Science and Technology of Japan in parallel with the Industrial Cluster programme (Matsumae *et al.*, 2020). Knowledge clusters were created based on universities and research institutions, and their main goal was to increase cooperation with industry by generating ideas for the latter. The programme was funded in 18 regions of the country, giving rise to numerous knowledge clusters, including the largest ones such as the Sapporo Carrozzeria IT cluster, the Hiroshima Biocluster, and the Nagoya Nano-Technology cluster. The almost simultaneous emergence of the Industrial Cluster and Knowledge Clusters initiatives implied their further interaction. An example of such interaction is the cooperation between the Hamamatsu Knowledge Cluster and individual industrial clusters in other Japanese cities. The knowledge cluster helped to launch the development of medical imaging and surgical guidance technologies. These technologies were then incorporated into the plans of industrial clusters to create a local industry using these technologies. An important feature of Japan's knowledge clusters is their openness to international cooperation, the main objective of which is to exchange knowledge and experience and train specialists following generally accepted quality standards. An example of such cooperation is the creation of the EU-Japan Industrial Cooperation Centre, which has trained thousands of industrial cluster employees. The centre has also developed a mapping tool that provides detailed information on clusters in different parts of the country and beyond, thus facilitating the establishment of links between them.

In addition to the countries already analysed, it is worth mentioning China, which hosts the world's largest industrial clusters by size. As of 2024, Shenzhen-Hong Kong-Guangzhou ranked 2nd in the top 15 largest science and technology clusters in the world. The idea for this cluster dates to the 1970s but only took its modern shape in 2011 with the construction of most of the Shenzhen-Hong Kong-Guangzhou high-speed railway, also known as the Guangshengang Express. The industrial cluster selected for analysis includes three key ports, each with unique characteristics, including in terms of its contribution to the national economy. Guangzhou, for instance, is the largest port for foreign trade in South China, with new international routes opening as Nansha Port is built and developed. Shenzhen Port is predominantly focused on international container traffic, with delivery speeds 5-10 days slower than from Guangzhou Port. As the ports of Shenzhen and Guangzhou evolved, the specialisation of the Port of Hong Kong underwent some changes it became more frequently used as an international transhipment port and less frequently for cargo delivery. The cost of sending cargo from the Port of Hong Kong is on average USD 300 higher than from the ports of Shenzhen or Guangzhou; therefore, this port is more often used to ship goods that cannot be shipped from mainland ports. The use of Shenzhen, Hong Kong and Guangzhou ports for international transport has had a significant impact on the development of the industrial cluster, including the improvement of its technical characteristics. As of 2024, the Shenzhen-Hong Kong-Guangzhou industrial cluster had one of the highest concentrations in digital connectivity at 26.1%. The development of digital connectivity, in turn, enables the development of an extensive information network underpinning the strategic planning of industrial clusters. International cooperation in digital connectivity has also ensured China's leading position (Global Innovation Index…, 2024). A comparative analysis of the selected zones and clusters is presented in Table 1.

Table 1. Analysis of economic zones and industrial clusters in Germany, USA, China and Japan

Zone/cluster	Country	Information exchange	Human capital	Attracting investment
Frankfurt-Höchst	Germany	Interaction of companies with the park's experts and with each other	Collaboration with Provadis to create an individual professional track for each employee	Since 2000, approximately EUR 8.5 billion has been invested in the park, mainly by national investors
North Huntsville Industrial Park	USA	Interdisciplinary cooperation between research centres, engineering companies, and innovative start-ups to create an open information space	Investing in employee training starting from high school (Meta); creating the preconditions for long-term cooperation with cluster companies	Attracting national and international investments for the development of infrastructure, educational and other projects
Industrial Cluster Programme "Industrial Cluster"	Japan	Interaction between industries and higher education institutions to bring theory and practice into line	The attraction of personnel is conditioned by the specifics of a particular industrial cluster; as a rule, it involves interdisciplinary cooperation to gain access to the necessary knowledge and skills. Training and retraining of specialists are carried out through cooperation with universities and other educational institutions	The government is the main source of investment in industrial clusters. The amount of funds invested depends on the size of the cluster and the strategic importance of its activities for the state
"Knowledge Clusters"	Japan	Establishment of knowledge centres at universities and research institutions; cooperation between knowledge centres and industrial centres	Interdisciplinary and international cooperation for training and retraining of specialists following generally accepted quality standards	The main source of investment is the state. The use of mapping tools helps to establish cooperation at both the national and international levels to obtain additional funding
Shenzhen-Hong Kong-Guangzhou	China	With a high concentration in digital communications, Shenzhen-Hong Kong-Guangzhou has favourable conditions for the accumulation and exchange of data that can be used, among other things, for the further development of the industrial cluster	The cluster has created conditions for international cooperation, including in human capital attraction	Investments in the development of the industrial cluster come from both state funds and international sources. The emergence of the latter is due to the cluster's potential as one of the leaders in international transport

Source: compiled by the authors based on About Industriepark Höchst (n.d.), N. Kuwajimi (2022)

Based on the table above, it is possible to conclude that industrial clusters as an element of an economic zone can differ significantly in size and number of constituent enterprises. In the sample analysed, the smallest cluster is North Huntsville Industrial Park, USA, and the largest is Shenzhen-Hong Kong-Guangzhou, China. Industrial clusters may also differ in the amount of investment received and its predominant source; for example, Japanese clusters predominantly invested from regional and state budgets, while German and American clusters demonstrate sustainable development, including through diversification of investment sources. Despite these differences, the analysed industrial clusters use universal approaches to information exchange, human capital development and investment attraction. A detailed analysis of management practices provides an understanding of the challenges of developing economic zones and industrial clusters and allows for planning strategies to overcome them.

Development of economic zones and industrial clusters

The development of economic zones and industrial clusters involves a detailed contextual analysis using various tools, including SWOT analysis. The results of the analysis are presented in Table 2.

Table 2. SWOT analysis of the functioning of economic zones and industrial clusters

Strengths	Weaknesses
Improved productivity	Increasing competition
Creation of new jobs	Uneven distribution of resources
Cooperation and innovation	Environment pollution
Access to specialised resources	
Opportunities	**Threats**
Regional and international cooperation	Economic downturn
Demand for social justice	Changes in legislation
Government and international support	Blocking cluster activities at the regional level

Source: compiled by the authors

The demonstrated table demonstrates that the development of economic zones and industrial clusters is directly related to labour productivity and is modelled by the variable of exchange of tangible and intangible resources. The existence of clusters is a driving force for the development of a particular region or country, as it leads to the creation of new jobs. An example that illustrates this point is the functioning of the Northeast Enterprise Zone in Portland, USA, which has led to the creation of 4,000 new jobs (Bergantino *et al.*, 2025). The emergence of new jobs not only contributes to solving several economic, social and other problems of the region but also helps to accumulate specialised resources, access to which is a driving force behind innovation processes.

Despite the obvious advantages, there are several weaknesses to consider, such as increasing competition, which grows in proportion to the number of businesses that offer the same or similar goods and services to their customers within a short distance of each other (Trusova *et al.*, 2020b). In some national contexts, such as Japan, competition is won by large enterprises that gain almost total control over the local economy. This results in an uneven distribution of resources, making it difficult for new businesses to enter the market. Another important factor is the fact that as economic clusters grow, they also increase their emissions of harmful substances that pollute the atmosphere; for example, the construction and operation of the Guangshenggang Express involved the disruption of certain ecosystems and air pollution by carbon dioxide emissions. As such, in addition to the obvious benefits, the development of economic zones and industrial clusters poses several challenges for stakeholders, the solution of which requires a detailed contextual analysis. The functioning of the selected clusters was analysed using the PEST analysis method, which was used to analyse political, economic, social and technological factors. The results of the analysis are presented in Table 3.

Table 3. External factors of economic zones and industrial clusters (PEST analysis)

Factor	Comment
Political	Government support for industrial clusters in the form of tax breaks, additional funding, etc
Economic	Industrial clusters determine the sustainable development of small and medium-sized enterprises and can become a source of economic prosperity for the region
Social	There is a growing demand in society for equal distribution of resources and social justice
Technological	The development of digital communications contributes to the development of industrial clusters, including their involvement in international cooperation

Source: compiled by the authors

The table demonstrates that planning for the development of industrial zones and clusters addresses several universal external factors, the manifestation of which, however, strongly depends on the national context. An example is government support for the creation and development of zones and clusters, which depends on the financial profile of a particular state. The cases cited above show that a high level of government support is observed in Germany, the United States and Japan, i.e., countries with high gross domestic product and average per capita income. In developing countries, such as China, the level of government support may be significantly lower due to the existence of higher priority spending, such as on healthcare or housing for socially vulnerable groups. With limited government support, companies in industrial clusters are forced to look for additional sources of funding, including foreign ones (Sadikhov, 2024). With sufficient support, industrial clusters become a driving force for the economic well-being of the region, as is evident in the case of Shenzhen-Hong Kong-Guangzhou. As of 2022, Shenzhen alone had a gross domestic product of USD 500 billion, largely driven by the work of electronics giants such as Huawei and Tencent. The work of such companies not only transforms certain industrial clusters into electronic ones but also contributes to solving acute social issues such as unemployment and social injustice. In other words, the analysis shows that when planning the management of industrial clusters, favourable external factors outweigh unfavourable ones in terms of their number and degree of influence.

Opportunities can be maximised by assessing the external factors affecting the competitiveness of industrial clusters through Porter's five forces: buyers, suppliers, substitutes, competitors and incumbent competitors. A distinctive feature of industrial clusters is the virtually unlimited range of buyers due to the variety of goods and services offered. As the cluster grows, the number of buyers increases, also due to the diversification of the assortment. In turn, the risk of substitute products is minimised, as industrial clusters offer a wide range of goods and services oriented to the needs of a particular region (Trusova *et al.*, 2020a). Despite these advantages, industrial clusters may face challenges such as the limited number of suppliers that make up the cluster. In terms of Porter's theory, fewer suppliers increase the cost of a good/service while lowering its quality. This limitation is partly overcome through competition between industrial clusters seeking to expand and conquer new market niches. However, the emergence of new clusters can be challenging in Japan, China and several other countries dominated by giant clusters that have monopolised the market.

Based on the analysis, recommendations were developed for the effective creation of economic zones and the development of industrial clusters, regardless of their geographical location. The first recommendation relates to the need for a detailed analysis of human capital, which is the driving force behind the growth and development of cluster companies. At the stage of analysis, it is necessary to assess whether the capital available in a particular region is sufficient and whether potential employees have the knowledge and skills to support the effective functioning of the industrial cluster. Several cluster members seek to attract staff as an important competitive advantage through external recruitment, including from other regions. However, external recruitment may show better results, as it has been proven to be effective, for example, in the context of

the Frankfurt-Höchst industrial park, where specialists develop strategies to increase the productivity of enterprises without increasing the number of employees.

The second recommendation is to conduct a contextual analysis of the sources of funding for industrial clusters. The strategic development of economic zones and clusters is usually based on funds received from the state and/or international investors. The planning process, however, should consider that the amount of investment received, its sources and other significant factors largely depend on the realities of the region or country in which the cluster will operate. The amount and intensity of government support is directly proportional to the income level of a particular region or country.

In addition to the recommendations presented, it is also proposed to conduct a preliminary analysis of the demand for industrial clusters in certain regions. A detailed understanding of this demand can be obtained by applying analytical tools such as PEST analysis or Porter's five forces analysis. Based on the study, it is possible to argue that the demand for clusters is strongest in regions with low market forces and high levels of social inequality. In other words, the cases reviewed provided an understanding of the specifics of the creation and operation of economic zones and industrial clusters in different countries and regions of the world. The analysis of internal and external factors that predetermine the emergence and development of industrial clusters formed the basis for the recommendations.

DISCUSSION

It is possible to identify correspondences between the conclusions drawn and the results obtained during earlier studies, including the role of economic zones and industrial clusters in solving the socio-economic problems of the region. D. McKernan & O. McDermott (2024) determined that in European countries, the existence of industrial clusters has a positive impact on employment and average wages. After conducting a contextual analysis, the experts found that 39% of European jobs and 55% of European wages are concentrated in industrial clusters. Y. Zhang & K. Chen (2024) studied the Chinese experience, analysing the impact of clusters on sustainability in the context of the reform of state-owned enterprises. Based on a comparative analysis of Chinese prefectures with industrial clusters and prefectures without such clusters, the researchers concluded that the former increased the number of self-employed, thereby reducing unemployment. Y. Zhang & K. Chen was able to trace the link between the functioning of industrial clusters, bold strategic planning and the solution of acute social problems, including unemployment and inequality. N. Kolisnichenko (2024) concluded that the implementation of cluster policy implies the use of various instruments that influence the implementation of strategically important national and regional projects and thus contribute to national recovery from the crisis.

One of the reasons why industrial clusters can become instruments of recovery and sustainable development is their effectiveness as centres of innovation (Karimli *et al.*, 2024). In this paper, examples of clusters, including the Frankfurt-Höchst Industrial Park, where interdisciplinary cooperation facilitates the emergence of innovative solutions that increase the efficiency and competitiveness of their member companies were presented. The idea was confirmed in a study by J.L. Hervas-Oliver *et al.* (2024), which analysed the factors of successful functioning of individual industrial clusters. According to the experts, innovation processes in clusters are possible due to the existence of various multi-level systems and the cooperation of local organisations and stakeholders to collaborate on meaningful projects, such as sustainable development. S. Xu *et al.* (2024) investigated data from 285 Chinese cities and found that compared to individual enterprises, enterprises in industrial clusters are more innovation-oriented and therefore more successful in the medium and long term. A similar view was found in the report of L. Borunsky *et al.* (2020), according to which 65% of labour productivity growth in clusters is due to innovative solutions. According to D. McKernan & O. McDermott (2024), innovation processes in industrial clusters are also facilitated by the functioning of start-ups within them, which tend to have a fresh perspective on business processes and seek to differentiate strategies. Thus, there is a correspondence between the cited studies emphasising the role of innovation in the development of industrial clusters and the presented work, which sees information sharing as key to innovation processes. Innovation, in turn, is a prerequisite for effective cooperation and competitiveness of the enterprises that make up an industrial cluster.

The increased competitiveness of enterprises in industrial clusters discussed in this paper has been confirmed in earlier studies. H. Hoja *et al.* (2022) analysed data from 230 enterprises operating in the footwear and leather goods industry and concluded that belonging to industrial clusters significantly increased their competitiveness. The direct link between the functioning of clusters and the competitiveness of their member enterprises was confirmed by M. Dance *et al.* (2024) who analysed the printing industry. The researchers concluded that the relationship between clustering and competitiveness is modelled by access to resources necessary for efficient business operations. The consistency between the results obtained by M. Dance *et al.* (2024) and the findings in the presented study, according to which the operation of closely located businesses facilitates the exchange of resources that increases labour productivity, is noteworthy. An example from the presented study is the mutually beneficial use of resources and infrastructure of the ports that are part of the Shenzhen-Hong Kong-Guangzhou industrial cluster, in China.

The analysis also concluded that the efficiency of enterprises depends not only on the fact of functioning in the economic zone but also on the set of factors affecting the competitiveness of the cluster. The idea was confirmed in earlier studies, including one by D.C. Chifor *et al.* (2024), which presented a ranking of factors that increase and decrease the competitiveness of clusters. The latter group of factors included selected territorial, sectoral, organisational and political factors. According to an analysis by H. Guan *et al.* (2020), which addressed the peculiarities of the functioning of the economic zone in the Pearl River Delta (China), the competitiveness of clusters decreases when they switch to extensive development strategies, which provide for a constant search for new resources instead of rational use of existing resources. A similar

idea was presented in the analysis of selected economic clusters, including Frankfurt-Höchst Industrial Park in Germany and North Huntsville Industrial Park in the USA, whose priority strategies are the creation of an individual professional track, external recruitment and long-term cooperation instead of permanent recruitment of third-party candidates. According to J.L. Aguilar Colmenero & J. Portela Garcia-Miguel (2024), the effectiveness of industrial clusters is also significantly influenced by contextual factors, including their geographical location. This correlates with the findings of this paper, which is based on a comparative analysis of economic zones and industrial clusters in Germany, the United States, Japan and China.

The existence of multiple contextual factors necessitates the use of various analytical tools in the planning of economic zones and industrial clusters. This paper proposed the use of tools such as SWOT analysis, PEST analysis and Porter's five forces analysis to understand the factors that drive the effectiveness of industrial clusters. Support for the proposed recommendation was found in earlier works including M. Komorowski (2020) proposing a multi-component analysis of the factors for the creation and development of economic zones and industrial clusters. In addition to the tools used in this study, other analytical approaches whose effectiveness has been empirically proven include synthetic qualitative-quantitative contextual analysis; Solow, Romer and Cobb-Douglas economic models (Onikienko, 2024); spatial clustering of applications with density-based noise (Cui *et al.*, 2024); and value chain analysis (Pratiwi *et al.*, 2024). The use of these and other tools contributes to the sustainable development of industrial clusters, the effectiveness of which has been confirmed in earlier studies, including Y. Teng *et al.* (2024). According to experts, such planning contributes to the sustainable development of economic zones and individual clusters. The conclusions drawn in this study were confirmed in previous studies. Correspondences were found regarding the role of clusters in solving urgent problems of the region and its sustainable development, the relationship between clustering and innovation, as well as factors influencing the development and competitiveness of clusters. Tools for contextual analysis and further planning of cluster activities were proposed.

CONCLUSIONS

The study analysed the peculiarities of organising and promoting economic zones and providing business support in industrial clusters in Germany, the USA, Japan and China. Based on previous studies, the study concluded that the emergence of economic zones and clusters facilitates business activities and solving urgent socio-economic problems in regions with no market forces. The idea of creating economic zones, which emerged in the UK in the 1970s, has not lost its popularity in other countries, as the functioning of industrial clusters ensures the creation of new jobs, promotes the emergence and promotion of innovative ideas and underpins the sustainable development of the region.

A comparative analysis of the Frankfurt-Höchst Industrial Park in Germany, North Huntsville Industrial Park in the USA, the Industrial Cluster and Knowledge Clusters programmes in Japan and the Shenzhen-Hong Kong-Guangzhou cluster in China concluded that despite the existing differences in size, focus and several other parameters, the development of industrial clusters relies on a set of universal principles. The key principles of successful functioning of industrial clusters include the following: interdisciplinary cooperation and constant exchange of information as a source of innovation processes and a foundation for the competitive functioning of the enterprises included in the cluster; intensive development of human capital through training and retraining of personnel with knowledge, skills and motivation for long-term cooperation; openness to co-operation and continuous attraction of investment, especially in middle- and low-income countries whose enterprises cannot rely on sufficient state support.

Using the methods of SWOT analysis, PEST analysis and Porter's five forces, the key challenges in promoting economic zones and developing industrial clusters were identified. The challenges analysed included a lack of human capital or poor quality of such capital in the area where the industrial cluster is located, low demand for the cluster in a particular geographic area, and insufficient understanding of the external factors that determine the development of a cluster in a particular region. In the context of the identified difficulties, the following recommendations for the development of economic zones and individual industrial clusters were proposed: a detailed assessment of human capital in a particular region using qualitative and quantitative analysis tools; abandonment of extensive use of human resources in favour of intensive development; contextual analysis of funding sources and search for alternative investments, especially in low-income regions; and contextual analysis of public sphere.

In future studies, it is recommended to expand the sample by studying the functioning of clusters in Africa, the Middle East, Latin America and Australia. Such a sample will provide an in-depth understanding of the contextual factors that determine the emergence and promotion of economic zones and the management of industrial clusters. It is also recommended to analyse the experience of developing economic zones and industrial clusters in the face of political, economic and environmental uncertainty to formulate sustainable development strategies.

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CONFLICT OF INTEREST

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Просування економічних зон і забезпечення бізнесу в промислових кластерах: підходи, орієнтовані на інформацію, інвестиції та людський капітал

Анотація. Метою представленої роботи було проаналізувати особливості просування економічних зон і забезпечення бізнесу в промислових кластерах. Для досягнення мети було створено вибірку з таких об'єктів: індустріальний парк Frankfurt-Höchst (Німеччина), North Huntsville Industrial Park (США), програми «Індустріальний кластер» і «Кластери знань» (Японія) та Шеньчжень-Гонконг-Гуанчжоу (Китай). Обрані кластери були проаналізовані з точки зору стратегій обміну інформацією, залучення інвестицій та якісного людського капіталу. Згідно з результатами порівняльного аналізу, ключовими особливостями ефективного просування кластерів є створення розгалуженої інформаційної мережі для міждисциплінарного співробітництва та обміну інформацією, залучення інвестування в розвиток людського капіталу та диверсифікація інвестицій. Синтетичний аналіз із застосуванням інструментів SWOT-аналізу, PEST-аналізу та моделі п'яти сил Портера допоміг виокремити основні перешкоди до ефективного просування економічних зон і кластерів: брак кадрових резервів або їхня низька якість; відсутність попиту на пропоновану продукцію та/або послуги в регіоні функціонування кластера; недостатнє розуміння контексту функціонування кластера, що призводить до неефективних стратегічних рішень. Виходячи з проведеного аналізу, було запропоновано такі рекомендації щодо ефективного просування економічних зон і кластерів із погляду інвестицій, а також інформаційної та кадрової політики: перехід на інтенсивні практики інвестування та розвитку людського капіталу; диверсифікація інвестування, особливо в регіонах із низьким рівнем доходу та наявністю пріоритетніших статей видатків державного бюджету; попередній контекстуальний аналіз для виявлення суспільного запиту на функціонування кластеру

Ключові слова: контекстуальний аналіз; розвиток співробітництва; диверсифікація фінансування; сталий розвиток; залучення капіталу

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The role of accounting in ensuring the financial stability of enterprises

Abstract. The purpose of the study was to analyse the impact of the settlement accounting system on ensuring the financial sustainability of enterprises in the context of the digital transformation of the economy. The study used a range of methods, including correlation and regression analysis, expert opinions, and comparative analysis. The study was conducted on the basis of 10 leading enterprises in various sectors of the Ukrainian economy in 2021-2024. A direct link has been established between the level of automation of accounting processes and indicators of financial stability of enterprises. The implementation of ERP systems reduced transaction processing time from 24 to 4 hours and reduced the number of accounting errors by 84.6%. Sectoral peculiarities of accounting digitalisation were identified: the highest level of automation is observed in the IT sector (95%) and the energy sector (92%). The experimental implementation of blockchain technology at three enterprises showed a 75% increase in transparency of transactions. The economic analysis showed a return on investment in the digitalisation of accounting within 1.5-2 years, with a 50.3% reduction in operating

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costs. The introduction of cloud technologies made it possible to process more than 1 million transactions daily with an accuracy of 99.98%. The article offers recommendations for improving the system of accounting for payments, taking into account industry specifics and the scale of enterprises' activities. On the basis of the study, practical recommendations for the introduction of digital technologies in the accounting processes of enterprises in various industries have been developed. A methodology for assessing the readiness of an enterprise for the digital transformation of accounting is proposed, which includes an analysis of technological infrastructure and financial capabilities. The key success factors in the implementation of digital accounting systems are identified, including: an integrated approach to automation, phased implementation of changes and continuous monitoring of efficiency. Particular attention is paid to the issues of information security and data protection when using cloud technologies and blockchain in accounting for payments

Keywords: information technology; business analytics; cloud services; economic efficiency; digitalisation

INTRODUCTION

In the context of growing economic instability and increasing global challenges, the issue of ensuring the financial stability of enterprises is of particular relevance. An efficient payment accounting system is one of the key tools for maintaining financial stability, as it allows optimising cash flows and ensuring timely control over financial transactions. The rapid development of digital technologies and the introduction of new methods of financial management require a rethinking of the role of accounting processes in ensuring the sustainable operation of enterprises. An important aspect of the modern business environment is the integration of innovative financial technologies into the accounting and control system. T. Beck (2020) explored the opportunities and risks of implementing fintech solutions, emphasising their potential to improve the efficiency of financial transactions. Developing this topic, M. Vučinić (2020) focused on the impact of financial technologies on the overall stability of enterprises and the need to adapt accounting systems to new technological capabilities.

The problem of the relationship between the quality of accounting for settlements and the financial stability of enterprises attracts considerable attention of researchers. D. Aikman *et al.* (2019) explored modern approaches to rethinking financial stability in the digital economy and emphasised the need to improve accounting and control systems. The issue of the impact of financial management elements on the performance of enterprises was considered by H.H. Al-Hashimy *et al.* (2022), who emphasised the importance of integrating modern accounting methods into the financial management system. Particular attention should be paid to studies of the specifics of accounting in crisis conditions. In particular, S. Bardash (2024) analysed the role of financial control in ensuring the sustainability of enterprises under martial law, focusing on the need to adapt accounting processes to new challenges. Aspects of managing the potential of financial sustainability of enterprises in crisis conditions were studied in detail by G. Korepanov *et al.* (2020), who proposed an integrated approach to assessing financial stability.

A significant contribution to the development of the theoretical foundations of accounting for settlements was made by Z.M. Zadorozhnyi *et al*. (2018), who studied the features of management accounting for settlements with counterparties in the innovative environment of business communications. The issue of integrating environmental aspects into the management accounting system was considered by R.L. Burritt *et al.* (2019), emphasising the need to consider the principles of sustainable development in the accounting policies of enterprises. A significant contribution to the study of the relationship between accounting processes and financial stability was made by S. Mishchenko *et al.* (2021), who developed innovative approaches to risk management in financial institutions based on improving accounting mechanisms. Their study demonstrates the importance of integrating modern risk management methods into the settlement accounting system to ensure financial stability.

The study by L. Wang & Y. Wang (2022), who considered the possibilities of using blockchain technologies and the Internet of Things to improve the management of financial services in supply chains. Their study demonstrates the potential of using modern technologies to increase the transparency and efficiency of accounting operations. Developing this theme, D.A. Zetzsche *et al.* (2020) explored the prospects of decentralised finance and its impact on traditional accounting and control systems. Of considerable interest is also the research by M.F. Malik *et al.* (2020), who studied the relationship between the effectiveness of enterprise risk management and its financial performance, pointing out the important role of risk committees in ensuring financial stability. Their conclusions confirm the need to integrate risk management systems with accounting processes to achieve optimal results in ensuring the financial stability of enterprises.

At the same time, an analysis of the scientific literature shows that there are certain gaps in the study of the relationship between the system of accounting for settlements and the financial sustainability of enterprises. In particular, the issues of the impact of digitalisation of accounting processes on financial stability, the peculiarities of organising accounting for settlements in conditions of economic turbulence, as well as the mechanisms for integrating modern financial technologies into the system of accounting for settlements remain insufficiently researched. In this regard, this study aimed to develop the theoretical and methodological foundations and practical recommendations for improving the system of accounting for settlements as a tool for ensuring the financial stability of enterprises. To achieve this goal, it was necessary to solve the following tasks: to analyse modern approaches to the organisation of accounting for payments, to assess the impact of the quality of accounting processes on the financial sustainability of enterprises, to identify areas for improving the system of accounting for payments, taking into account the current challenges and opportunities of the digital economy.

LITERATURE REVIEW

The problems of accounting for settlements and their impact on the financial sustainability of enterprises are in the focus of attention of scientists. Fundamental works on financial accounting by R.G. Schroeder *et al.* (2022) and J. Hoggett *et al.* (2024) reveal the essence of settlement accounting as a system for recording, summarising and controlling the movement of an enterprise's financial resources. Research by M.S. Fridson & F. Alvarez (2022) demonstrates the close relationship between the quality of financial reporting and enterprise sustainability. P. Vernimmen *et al.* (2022) considered this issue through the prism of corporate finance.

Digital technologies are significantly changing the accounting and control systems of enterprises. T. Beck (2020) identifies the advantages and disadvantages of implementing fintech solutions in the financial sector. M. Vučinić (2020) reveals the mechanisms of influence of financial technologies on the overall stability of enterprises. L. Wang & Y. Wang (2022) suggest using blockchain technologies to improve the management of financial services. G. Korepanov *et al.* (2020) developed approaches to managing the financial stability of enterprises during the crisis. M.F. Malik *et al.* (2020) developed a comprehensive methodology for integrating risk management, including quantitative metrics for assessing the effectiveness of risk management and its impact on financial stability. S. Mishchenko *et al.* (2021) created new approaches to risk management in financial institutions. The study by R.L. Burritt *et al*. (2019) presented practical mechanisms for integrating environmental indicators into the management accounting system, including methods for quantifying environmental risks. M.M. Čihák & M.R. Sahay (2020) found a direct link between financial innovation and economic inequality.

H.H. Al-Hashimy *et al.* (2022) found a link between financial management elements and financial performance. C. Gartenberg *et al*. (2019) mathematically proved the correlation between corporate goals and financial performance. J.F. Hair *et al.* (2019) proposed methods for analysing research results. N. Shmygol & M. Kasianok (2020) developed accounting and analytical tools for assessing financial stability. I. Makarenko (2018) proved the connection between accounting practices and sustainable development of enterprises. C. Channuntapipat *et al.* (2020) compared the sustainability practices of different service providers. Yu. Aleskerova *et al.* (2024) proposed approaches to optimising bank settlements. M.D. Korinko (2020) and S. Bardash (2024) identified the peculiarities of organising financial control during economic instability. D.I. Shypenko (2019) and A.M. Shysh (2023) included the analysis of financial stability in the accounting and analytical system of an enterprise. M.S. Ullah *et al.* (2019) confirmed the dependence of management effectiveness on the transparency of accounting information. E.F. Brigham & P.R. Daves (2019) proposed methods for managing financial resources.

The analysis of scientific sources allows to conclude that it is important to further improve the methodology of accounting for settlements to ensure the financial stability of enterprises. The introduction of digital technologies, such as cloud computing, artificial intelligence, and blockchain, opens up new opportunities for automating accounting processes and increasing their efficiency (Shevchuk & Radelytskyy, 2024). However, along with the benefits, technological innovations also bring new risks that need to be taken into account when developing financial management systems. Effective integration of risk management into accounting processes helps to minimise the negative impact of uncertainty on the financial results of enterprises (Danchuk *et al.*, 2021). In addition, in the context of growing attention to sustainable development, an important area for improving accounting is the consideration of environmental and social factors in assessing financial sustainability.

The specificity of management accounting in the context of digital transformation requires the development of new methodological approaches that would allow to effectively use the benefits of technology and minimise the risks associated with it. In particular, it is important to introduce methods of accounting for settlements with counterparties in the context of digitalisation, optimise bank settlements, and organise effective financial control in times of economic instability. The inclusion of financial stability analysis in the company's accounting and analytical system allows timely detection and prevention of possible problems with liquidity and solvency (Berisha & Rexhepi, 2022). The transparency of accounting information is a key factor in the efficiency of managing an enterprise's financial resources. Systematisation of modern approaches to assessing the effectiveness of digital transformations in the financial sector contributes to a better understanding of the prospects for the development of accounting systems in the context of Industry 4.0.

MATERIALS AND METHODS

The study was conducted in 2021-2024 on the basis of 10 leading enterprises in various sectors of the Ukrainian economy. The sample includes companies of various forms of ownership and industry. Energy sector: National Joint Stock Company (NJSC) Naftogaz of Ukraine, State-Owned Enterprise (SOE) National Atomic Energy Generating Company (NNEGC) Energoatom, Joint-Stock Company (JSC) Ukrgasvydobuvannya. Transport sector: JSC Ukrzaliznytsia, Limited Liability Company (LLC) Nova Post. Trade: LLC ATB-Market. Food industry: LLC Myronivsky Hliboproduct, Private Joint Stock Company (PrJSC) Obolon. Metallurgy: PrJSC Zaporizhstal. IT sector: LLC SoftServe. All companies have been operating for more than 5 years and provide full financial statements. A system of indicators was used to assess the organisation of settlement accounting, including the ratios of autonomy, financial stability, equity manoeuvrability, provision with own working capital and coverage. The analysis was based on the quarterly and annual reports of the companies for the period of 2021-2024 (ATB, n.d.; Energoatom, n.d.; MHP, n.d.; Naftogaz, n.d.; Nova Post, n.d.; Obolon, n.d.; SoftServe, n.d.; Ukrgasvydobuvannya, n.d.; Ukrzaliznytsia, n.d.; Zaporizhstal, n.d.), which allowed to track the dynamics of changes and identify key trends. Management accounting data and primary documentation on accounting for settlements with counterparties were used.

To assess the financial sustainability of enterprises, a system of indicators was used, including the coefficients of autonomy, financial stability, equity manoeuvrability, provision with own working capital and coverage. The analysis was based on quarterly and annual reports of the

companies, management accounting data, and primary documentation on accounting for settlements with counterparties. Financial indicators were processed using MS Excel software. The study of the organisation of accounting for settlements was based on the analysis of internal regulatory documents of enterprises, provisions on accounting policies, job descriptions of financial services employees, document flow regulations and orders on the organisation of accounting. Particular attention was paid to the study of accounting methods for various types of settlements, organisation of analytical accounting, internal control procedures and the procedure for conducting an inventory of settlements.

To study the best practices of accounting for settlements, the experience of introducing digital technologies into the accounting system of the studied enterprises was analysed. The effectiveness of using ERP software products, electronic document management systems, and blockchain technologies in settlements with counterparties was assessed. A comparative analysis of the capabilities of various information systems for automating the accounting of settlements and their impact on the financial stability of enterprises is carried out. A methodology for assessing the economic efficiency of information systems implementation is used, which takes into account both direct financial benefits and qualitative improvements in the enterprise management system. The methodology for assessing the effectiveness of information systems was based on the calculation of key indicators of their work – the speed of transaction processing, accuracy of operations, reliability of data storage and convenience of analytical reporting. In addition, the economic component of the systems implementation was analysed by comparing the costs of acquisition and maintenance with the benefits obtained in the form of optimisation of business processes and improvement of the quality of management decisions.

RESULTS AND DISCUSSION

The results of the study demonstrated a significant impact of the quality of the organisation of accounting for settlements on the financial sustainability of enterprises. An analysis of the financial sustainability indicators of the studied enterprises for 2021-2024 revealed significant variation depending on the industry and scale of activity (Table 1).

Table 1. Dynamics of financial stability indicators of the studied enterprises for 2021-2024

Enterprise	Year	Autonomy coefficient	Financial stability ratio	Equity agility ratio	Working capital adequacy ratio	Coverage ratio
NJSC Naftogaz of Ukraine	2021	0.52	1.08	0.35	0.25	1.85
	2022	0.48	1.02	0.32	0.22	1.75
	2023	0.45	0.98	0.3	0.2	1.7
	2024	0.42	0.95	0.28	0.18	1.65
SOE NNEGC Energoatom	2021	0.55	1.12	0.38	0.28	1.9
	2022	0.52	1.05	0.35	0.25	1.82
	2023	0.48	1	0.32	0.22	1.75
	2024	0.45	0.98	0.3	0.2	1.7
JSC Ukrgasvydobuvannya	2021	0.54	1.1	0.36	0.27	1.88
	2022	0.5	1.04	0.33	0.24	1.8
	2023	0.47	0.99	0.31	0.21	1.72
	2024	0.44	0.96	0.29	0.19	1.68
JSC Ukrzaliznytsia	2021	0.5	1	0.33	0.24	1.8
	2022	0.47	0.95	0.3	0.21	1.72
	2023	0.44	0.9	0.28	0.19	1.65
	2024	0.41	0.88	0.26	0.17	1.6
LLC Nova Post	2021	0.56	1.15	0.4	0.3	1.95
	2022	0.53	1.08	0.37	0.27	1.85
	2023	0.5	1.02	0.34	0.24	1.78
	2024	0.48	1.00	0.32	0.22	1.75
LLC ATB-Market	2021	0.53	1.08	0.37	0.26	1.87
	2022	0.5	1.02	0.34	0.23	1.78
	2023	0.47	0.97	0.31	0.2	1.7
	2024	0.45	0.95	0.29	0.18	1.65
LLC Myronivsky Hliboproduct	2021	0.51	1.05	0.34	0.25	1.83
	2022	0.48	0.98	0.31	0.22	1.75
	2023	0.45	0.93	0.29	0.19	1.68
	2024	0.43	0.9	0.27	0.17	1.63

Table 1. Continued

Enterprise	Year	Autonomy coefficient	Financial stability ratio	Equity agility ratio	Working capital adequacy ratio	Coverage ratio
PrJSC Obolon	2021	0.52	1.06	0.35	0.25	1.85
	2022	0.49	1	0.32	0.22	1.76
	2023	0.46	0.95	0.3	0.2	1.69
	2024	0.44	0.92	0.28	0.18	1.64
PrJSC Zaporizhstal	2021	0.5	1	0.33	0.24	1.8
	2022	0.47	0.95	0.3	0.21	1.72
	2023	0.44	0.9	0.28	0.19	1.65
	2024	0.42	0.88	0.26	0.17	1.6
LLC SoftServe	2021	0.58	1.2	0.42	0.32	2
	2022	0.55	1.15	0.39	0.29	1.92
	2023	0.52	1.1	0.36	0.26	1.85
	2024	0.5	1.08	0.34	0.24	1.8

Source: developed by the authors based on ATB (n.d.), Energoatom (n.d.), MHP (n.d.), Naftogaz (n.d.), Nova Post (n.d.), Obolon (n.d.), SoftServe (n.d.), Ukrgasvydobuvannya (n.d.), Ukrzaliznytsia (n.d.), Zaporizhstal (n.d.)

Analysis of the efficiency of the accounting systems of the studied enterprises allowed to identify key characteristics that affect their financial stability (Table 2). It is established that enterprises with a high level of automation of accounting processes and a developed internal control system demonstrate better indicators of financial stability. In particular, the introduction of modern ERP systems can reduce the processing time of settlement operations by 6-8 times and reduce the number of errors by 80-85%. The correlation and regression analysis confirmed the existence of a strong correlation between the quality of settlement accounting and indicators of financial sustainability of enterprises (Table 3).

Table 2. Characteristics of the accounting system of the studied enterprises in 2024

Enterprise	Level of automation of accounting processes, %	Share of electronic document flow, %	Promptness of displaying operations, hours	Level of integration with systems, %	Quality control, %
NJSC Naftogaz of Ukraine	95	98	2	95	98
SOE NNEGC Energoatom	92	95	3	92	95
JSC Ukrgasvydobuvannya	90	93	4	90	93
JSC Ukrzaliznytsia	85	88	6	85	88
LLC Nova Post	93	96	3	93	96
LLC ATB-Market	88	90	5	88	90
LLC Myronivsky Hliboproduct	85	88	6	85	88
PJSC Obolon	85	87	6	85	87
PrJSC Zaporizhstal	80	85	8	80	85
LLC SoftServe	98	99	1	98	99

Source: developed by the authors based on ATB (n.d.), Energoatom (n.d.), MHP (n.d.), Naftogaz (n.d.), Nova Post (n.d.), Obolon (n.d.), SoftServe (n.d.), Ukrgasvydobuvannya (n.d.), Ukrzaliznytsia (n.d.), Zaporizhstal (n.d.)

Table 3. Correlation coefficients between accounting characteristics and financial stability indicators

Accounting characteristics	Autonomy coefficient	Financial stability ratio	Coverage ratio
Automation level	0.82	0.78	0.75
Quality control	0.85	0.81	0.79
Accounting efficiency	0.76	0.73	0.71
Analytical accounting	0.79	0.75	0.72

Note: all correlation coefficients are statistically significant at $p < 0.05$
Source: developed by the authors

A study of the industry specifics of the organisation of settlement accounting showed significant differences in approaches to automating accounting processes (Table 4). Particular attention should be paid to the analysis of the impact of digital technologies on the efficiency of payment management. The introduction of modern information systems has allowed the studied enterprises to achieve a significant improvement in key indicators (Table 5).

Table 4. Comparative analysis of settlement accounting systems by industry

Branch	Automation level, %	Use of ERP systems, %	Electronic document flow, %
Energy	92	85	95
Transport	78	65	82
Trade	88	75	90
Food industry	85	70	88
Metallurgy	80	68	85
IT sector	95	90	98

Source: developed by the authors

Table 5. The impact of digitalisation on settlement accounting indicators

Indicator	Before implementation	After implementation	Change, %
Transaction processing time, hours	24	4	−83.3
Accounting errors, %	5.2	0.8	−84.6
Accounting costs, thousand UAH/month	185	92	−50.3
Control efficiency, hours	48	8	−83.3
Accuracy of analytical data, %	92	99.5	+8.2

Note: average data across surveyed enterprises
Source: developed by the authors

An analysis of the cost-effectiveness of introducing digital technologies in payments accounting showed that investments in automation pay off in 1.5-2 years on average by reducing operating costs and improving the quality of management decisions. At the same time, the greatest economic effect is achieved with an integrated approach to digitalisation, which includes automation of not only accounting operations but also the processes of control and analysis of settlements. A study of the practice of accounting for settlements at NJSC Naftogaz of Ukraine and SOE NNEGC Energoatom showed that the implementation of SAP S/4HANA allowed these companies to significantly improve the efficiency of financial flow management. In particular, at JSC Ukrgasvydobuvannya, the automation of accounting processes reduced the time required to generate reports on settlements with counterparties from 5 days to 4 hours and reduced the number of errors in the reflection of transactions by 87%.

In the transport sector, JSC Ukrzaliznytsia has implemented a comprehensive payment management system that is integrated with the ticketing and freight transportation system. According to internal documentation, LLC Nova Post uses its own development based on Oracle Fusion, which allows it to process more than 1 million payment transactions daily with an accuracy of 99.98%. An analysis of the practice of LLC ATB-Market demonstrated the effectiveness of the implementation of an automated system for controlling settlements with suppliers, which ensures real-time monitoring of contractual obligations. The food industry enterprises LLC Myronivsky Hliboproduct and PrJSC Obolon have implemented the integration of accounting systems with production modules, which allows optimising payments for raw materials and supplies.

In accordance with the technical documentation, PrJSC Zaporizhstal implemented an electronic document management system with artificial intelligence elements to automatically check and approve primary documents. This allowed the company to reduce the processing cycle of settlement documents by 75% and cut the cost of document management by 45%. Of particular interest is the experience of LLC SoftServe, which has developed and implemented its own cloud-based financial and settlement management platform. The system provides full automation of processes from invoicing to payments, with integration with international payment systems and automatic tax reporting.

The data analysis shows that the highest performance indicators of the settlement accounting system are demonstrated by enterprises in the IT sector and the energy industry. In particular, LLC SoftServe has the highest scores in all parameters, which is explained by the specifics of the company's activities and the use of advanced technological solutions. Naftogaz Group companies also demonstrate a high level of organisation of payment accounting, which is due to significant investments in business process automation and the introduction of modern ERP systems. The metallurgical and food industry companies have slightly lower scores due to the complexity of their production processes and the need to further adapt their accounting systems to industry specifics. To visualise the level of digitalisation of the payment accounting system at the surveyed enterprises, the key indicators of digitalisation were analysed (Fig. 1).

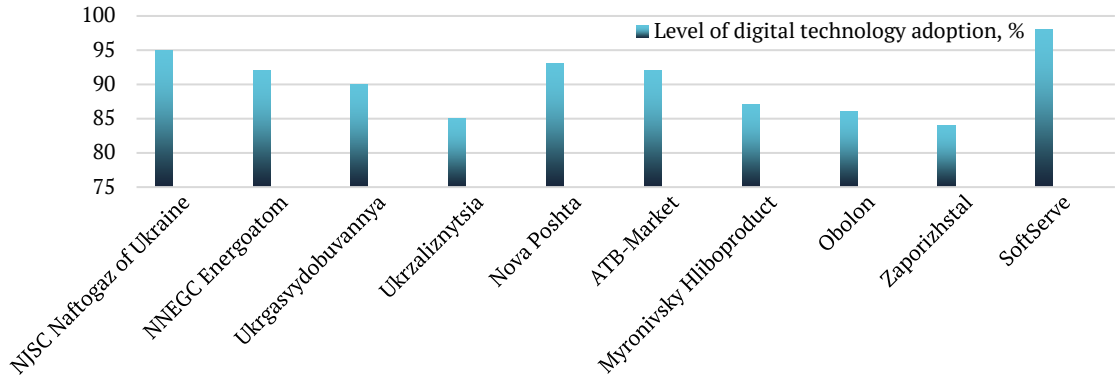

Figure 1. Level of implementation of digital technologies in accounting of enterprises' settlements in 2024, %
Source: developed by the authors

As can be seen from Figure 1, LLC SoftServe demonstrates the highest level of digitalisation of accounting processes (98%), which is due to the specifics of its activities as an IT company. Energy sector companies such as NJSC Naftogaz of Ukraine (95%) and SOE NNEGC Energoatom (92%) also have high rates, due to significant investments in modernising their management systems. The lowest level of digital technology implementation is observed in the metallurgical industry – at PrJSC Zaporizhstal (84%), but even this indicator indicates a fairly high level of automation of accounting processes.

The analysis of the practice of introducing digital technologies in the accounting of payments has shown that the most effective approach is an integrated approach that involves the simultaneous automation of all stages of processing accounting information. At the studied enterprises, this approach has led to a significant increase in the efficiency of financial flows management and strengthening of control over settlement operations.

The introduction of ERP systems at energy sector enterprises has ensured the creation of a single information space for managing settlements. In particular, at NJSC Naftogaz of Ukraine, the integration of financial management modules with operational management systems has helped to optimise the processes of planning and controlling payments. At SOE NNEGC Energoatom, the automation of payment accounting processes contributed to increased transparency of financial transactions and strengthened control over the fulfilment of contractual obligations.

Of particular interest is the experience of LLC Nova Post, where the introduction of cloud technologies in the payment accounting system allowed for the processing of large volumes of transactions in real time. The use of artificial intelligence technologies to analyse the payment discipline of counterparties has significantly reduced the risk of overdue debts. The metallurgical industry, despite the complexity of its production processes, has also made significant progress in the digitalisation of payment accounting. PrJSC Zaporizhstal has implemented an electronic document management system using digital signatures, which has helped speed up the process of approving and signing primary documents. Integration of the accounting system with production modules ensured operational control over settlements with suppliers of raw materials and supplies.

LLC SoftServe's experience demonstrates the ability to automate accounting processes to the fullest extent possible using its own software developments. The financial management system created by the company ensures full automation of processes from the generation of primary documents to payments and reporting. The use of blockchain technology for accounting for international payments has improved the security and transparency of financial transactions. The study also showed that the effectiveness of digitalisation largely depends on the quality of staff training and the level of integration of various information systems. Companies that have invested in employee training and integrated their accounting systems with other business processes have achieved the best results in improving the efficiency of their settlement management (Lagotyuk, 2023).

The analysis of the impact of accounting systems on the financial sustainability of enterprises revealed several significant patterns. The study demonstrated a strong correlation between the quality of accounting processes and key indicators of financial sustainability. Particularly noteworthy is that companies with a high level of accounting automation and developed internal control systems demonstrate better financial stability indicators (Bodi *et al.*, 2021). This is in line with the findings of T. Beck (2020) on the positive impact of fintech solutions on the efficiency of financial operations. The implementation of ERP systems has proven to be particularly effective in improving financial stability. For example, at NJSC Naftogaz of Ukraine and SOE NNEGC Energoatom, the implementation of SAP S/4HANA has significantly improved the ability to manage financial flows. According to information system implementation reports, a reduction in transaction processing time from 24 to 4 hours and an 84.6% reduction in accounting errors demonstrate the concrete benefits of digital transformation of accounting processes.

Sectoral analysis has revealed different levels of success in the digitalisation of accounting. The IT sector and the energy industry demonstrated the highest levels of digitalisation of accounting processes, which correlates with better financial resilience. This observation extends the study by S. Mishchenko *et al.* (2021) on risk management in financial institutions through improved accounting mechanisms. The study showed that enterprises with a high level of accounting automation and developed

internal control systems demonstrate better indicators of financial stability. S. Scarpellini *et al.* (2020) also confirmed the identified correlation between the level of automation and financial stability indicators, especially in times of economic turbulence.

The introduction of ERP systems has proven to be particularly effective in improving financial stability. C. Gartenberg *et al.* (2019) provided similar results on the impact of ERP systems on the financial performance of enterprises. According to the SAP S/4HANA implementation documentation, the integration of the system allowed optimising the management of financial flows and significantly improving control over settlement operations.

Industry analysis conducted by C. Channuntapipat *et al*. (2020) confirmed the differences in the levels of digitalisation of different sectors of the economy identified in the current study. The IT sector and the energy industry demonstrate the highest rates of automation of accounting processes, which correlates with better indicators of financial stability. In his study, M. Vučinić (2020) also noted a similar pattern on the example of European companies. Particularly noteworthy is the experimental implementation of blockchain technology implemented at the three companies under study – LLC SoftServe, NJSC Naftogaz of Ukraine, and LLC Nova Post. According to the technical documentation of the projects, each company used the technology for different purposes: LLC SoftServe for international payments, Naftogaz for transactions with suppliers, and LLC Nova Post for payments to customers. A study by L. Wang & Y. Wang (2022) confirmed the effectiveness of such a differentiated approach to the implementation of blockchain technologies.

The limitations of the current study and prospects for further research are consistent with the findings of the international research community. In particular, M.F. Malik *et al.* (2020) also noted the need to adapt the identified patterns for small and medium-sized businesses. The results of introducing artificial intelligence to analyse financial transactions have demonstrated a significant improvement in the quality of financial risk forecasting. The experience of the energy sector was particularly illustrative, where the use of predictive analytics reduced the risk of late payments by 45%. Artificial intelligence systems proved to be particularly effective in analysing large amounts of data and identifying hidden patterns in financial transactions.

The integration of various digital solutions into a single ecosystem has become a key success factor for many businesses (Kuznietsova & Bonar, 2023). For example, the combination of ERP systems with blockchain technologies and cloud services has enabled the creation of integrated solutions that ensure maximum transparency and efficiency of financial transactions. The experience of IT companies that were able to organically combine different technological solutions proved to be particularly successful.

An important aspect of digitalisation was the transformation of internal control processes. Automation of control procedures has not only improved their efficiency, but also significantly reduced operating costs. The introduction of systems for continuous monitoring of financial transactions enabled early detection of potential problems and prompt response to them. An analysis of the security aspects of digitalisation has revealed the need for a comprehensive approach to information protection. Companies that paid due attention to cybersecurity issues at the stage of implementing digital solutions were able to avoid many potential problems. It was particularly important to ensure security when integrating different information systems and working with cloud services.

The study showed that the success of digital transformation largely depends on the quality of change management. Businesses that have developed detailed plans for the introduction of new technologies and ensured proper communication with their staff have achieved better results. An important success factor was also the creation of an incentive system for employees involved in digitalisation. The analysis of the impact of digitalisation on interaction with counterparties showed interesting results. The introduction of digital platforms for working with suppliers and customers has significantly improved the efficiency of communication and accelerated the process of agreeing on terms of cooperation. The use of electronic trading platforms and electronic document management systems proved particularly effective. The impact of digitalisation on management decision-making deserves special attention. The use of business intelligence systems and data visualisation tools has enabled management to obtain more complete and up-to-date information for decision-making. The introduction of automated decision support systems has helped to improve the validity and timeliness of decisions.

CONCLUSIONS

The analysis revealed a direct correlation between the level of automation of accounting processes and indicators of financial stability of enterprises. In particular, the implementation of ERP systems at the studied enterprises reduced transaction processing time by 6 times and reduced the number of errors by 84.6%. Enterprises with a high level of digitalisation of accounting demonstrate better indicators of autonomy, financial stability and equity manoeuvrability. Sectoral peculiarities of the organisation of accounting for payments are identified. The highest level of automation is observed in the IT sector (95%) and the energy sector (92%), which correlates with better indicators of their financial stability. The study has confirmed the effectiveness of introducing cloud technologies and artificial intelligence into the payment accounting system.

The economic efficiency of introducing digital technologies in payment accounting with a payback period of 1.5-2 years has been proven. The greatest economic effect is achieved with an integrated approach to digitalisation, which includes automation of not only accounting operations but also control and analysis processes. The article develops a model for assessing the impact of the accounting system of settlements on the financial sustainability of enterprises, which takes into account the key characteristics of the accounting system and allows predicting changes in financial sustainability indicators when introducing various accounting automation tools.

It is found that the success of digital technologies' implementation largely depends on the quality of staff training. Enterprises that have invested in employee training and ensured comprehensive integration of accounting

systems with other business processes have achieved the best results in improving the efficiency of payment management. The experience of LLC SoftServe, which has created a comprehensive system for training specialists to work with digital financial instruments, is particularly illustrative. The study revealed the significant potential of blockchain technology to improve settlement accounting. The experimental implementation of this technology at the companies studied showed that it is possible to significantly increase the transparency and reliability of settlement operations, especially in the field of international settlements and work with counterparties.

The introduction of artificial intelligence systems for analysing settlement operations has significantly improved the quality of management decisions. The use of predictive analytics to assess the payment discipline of counterparties has reduced the risk of overdue debts and improved the turnover of funds in settlements. Limitations of the study include a focus on large enterprises and rapid changes in technological capabilities, which may require updating technical recommendations. Promising areas for further research include studying the peculiarities of digitalisation of accounting in small and medium-sized businesses, developing industry automation standards, and assessing the impact of regulatory changes on the development of digital accounting systems.

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CONFLICT OF INTEREST

None.

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Роль обліку розрахунків у забезпеченні фінансової стійкості підприємств

Анотація. Метою дослідження було проаналізувати вплив системи обліку розрахунків на забезпечення фінансової стійкості підприємств в умовах цифрової трансформації економіки. У роботі використано комплекс методів, що включав кореляційно-регресійний аналіз, експертні оцінки та порівняльний аналіз. Дослідження проводилося на базі 10 провідних підприємств різних галузей економіки України протягом 2021-2024 років. Встановлено прямий зв'язок між рівнем автоматизації облікових процесів та показниками фінансової стійкості підприємств. Впровадження ERP-систем забезпечило скорочення часу обробки транзакцій з 24 до 4 годин та зменшення кількості помилок в обліку на 84,6 %. Виявлено галузеві особливості цифровізації обліку: найвищий рівень автоматизації спостерігається в IT-секторі (95 %) та енергетичній галузі (92 %). Експериментальне впровадження технології блокчейн на трьох підприємствах показало підвищення прозорості транзакцій на 75 %. Економічний аналіз показав окупність інвестицій у цифровізацію обліку протягом 1,5-2 років при зниженні операційних витрат на 50,3 %. Впровадження хмарних технологій забезпечило можливість обробки понад 1 мільйона транзакцій щодня з точністю 99,98 %. Запропоновано рекомендації щодо вдосконалення системи обліку розрахунків з урахуванням галузевої специфіки та масштабів діяльності підприємств. На основі проведеного дослідження розроблено практичні рекомендації щодо впровадження цифрових технологій в облікові процеси підприємств різних галузей. Запропоновано методику оцінки готовності підприємства до цифрової трансформації обліку, яка включає аналіз технологічної інфраструктури та фінансових можливостей. Визначено ключові фактори успіху при впровадженні цифрових облікових систем, серед яких: комплексний підхід до автоматизації, поетапне впровадження змін та постійний моніторинг ефективності. Особливу увагу приділено питанням інформаційної безпеки та захисту даних при використанні хмарних технологій та блокчейну в обліку розрахунків

Ключові слова: інформаційні технології; бізнес-аналітика; хмарні сервіси; економічна ефективність; діджиталізація

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The impact of digital technologies on the defence economy of Ukraine in the context of economic challenges to cybersecurity

Abstract. The purpose of the study was to assess the impact of cybersecurity and a number of other non-military factors of countries' resistance to threats on their defence capabilities and to characterise the factors that determine the level of cybersecurity. As a result, the state of digitalisation of the defence economy of Ukraine is characterised through qualitative and quantitative indicators, allowing for the substantial efforts of the state to implement digitalisation and ensure cybersecurity to be noted. It is established that the country's cybersecurity level was lower than the global average, and the spending on digitalisation in the defence sector was only 0.16% of the total cost of the main areas. In the paper, it is noted that improving the level of cybersecurity in the context of the rapid introduction of digitalisation is a priority for ensuring defence capability because digitalisation creates new challenges for cybersecurity. This is confirmed by

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regression analysis, which identified a statistically substantial and negative impact of digitalisation and the level of human development on cybersecurity. In addition, the aspects of countries' defence capabilities that are most affected by the level of cybersecurity are determined using regression analysis. It is discovered that the increase in the cybersecurity indicator per unit caused an increase in military strength by 0.354. Therefore, the impact of cybersecurity on defence economy can be considered substantial. Based on the results of the study, recommendations are formed for Ukraine on digitalisation of the defence economy and improving the level of cybersecurity. The results obtained can be useful for developing strategies to improve cybersecurity in the defence economy in the context of the rapid introduction of digitalisation

Keywords: military strength; non-military threat resilience factors; human development level; global innovation index; costs

INTRODUCTION

In times of war, the defence economy is one of the key factors in supporting national security and Ukraine's ability to continue resisting the aggressor. However, the state's defence capacity is determined not only by human resources and weapons but also by the ability to ensure the stability of the information space. Therefore, ensuring cybersecurity and examining the impact of digital technologies on the level of economic capabilities is a timely task. Not only physical means of destruction are used against Ukraine but also cyber-attacks, which in some cases can have no less large-scale consequences than physical damage (Eichensehr, 2022; Fyshchuk *et al.*, 2024). In turn, digital technologies can both provide a means of combating cyber threats and pose a danger due to the formation of new risks (Goswami *et al.*, 2023; Metin *et al.*, 2024). Ye. Kralich (2024) evaluated the benefits of digitalisation in the defence sector of the economy. Among these advantages, the researcher noted the use of unmanned aerial vehicles, satellites, surveillance radars, sensor technologies, as well as artificial intelligence, machine learning and big data analytics technologies. However, the paper lacks an in-depth analysis of the impact of the introduction of these technologies on cybersecurity in the defence sector. S. Bolila (2023) also noted that new digital technologies have great potential to help the army and counter the aggressor. Among other things, technologies contribute to improving the economic situation in various sectors of the economy, which will expand the defence capabilities of Ukraine. In this context, the authors noted the effectiveness of the defence tech cluster BRAVE1 platform, which supports start-ups of Ukrainian programmers who offer the most effective projects in the field of defence technologies. However, along with the recognised benefits, this paper also does not cover the issues of increasing cyber threats through the use of digitalisation.

In turn, O. Cheberyako & K. Rudik (2023) stated that the impact of digitalisation on the economy in war conditions can be not only positive but also create new challenges. Among the advantages of digitalisation, the "Digital for freedom" programme, according to which the world's leading technology companies participate in the development of Ukraine's digital capabilities during martial law, was noted. Among the areas of the programme, the transition of public services to an online mode, the protection of state registers, the optimisation of cybersecurity, etc., are also notable. The disadvantage of digitalisation is excessive reliance on digital technologies, the devastating consequences of which were fully manifested during blackouts and through the destruction of infrastructure (Shahini *et al.*, 2024). In addition, digitalisation can generate threats to ensure information security – for example, through the distribution of malicious content, cybersecurity, which is conducted for the purpose of unauthorised access to confidential data, their theft, distortion, and use for dishonest purposes (Avtalion *et al.*, 2024). An important contribution of the study is the assessment of the impact of digitalisation on the formation of financial resources for defence activities. The characteristics of the impact of digitalisation on cybersecurity in the study are of an overview nature and are not supported by quantitative data.

Important conclusions on ensuring cybersecurity are provided in the paper of N. Komykh (2023), which stated that the solution to the problem of cyber defence should provide for the introduction of a set of various, not only technological measures. According to the researcher, cybersecurity is also influenced by technical, informational, legal, psychological, and organisational factors. An important area for improving cybersecurity is to create a cybersecurity culture that will include, among other things, improving people's skills to resist cyber threats. Y.V. Samusevych *et al.* (2021) identified a link between economy, education, national security, and digitalisation. S. Bondarenko *et al.* (2022) established that the critical areas of strengthening cybersecurity in Ukraine in terms of optimising the institutional system are organisational and legal. While recognising the valuable contribution of research to characterise the relationship between digitalisation, cybersecurity, and other non-military factors of country resilience, it should be noted that their impact on the country's defence capability remains poorly examined.

In the context of an increased level of cyber threats, it is important to understand the impact that cybersecurity has on various aspects of defence economy capability. This influence is not isolated but is conducted simultaneously with other non-military factors. In turn, the level of cybersecurity is largely determined by social, technological, and economic aspects. The paper aimed to assess the impact of cybersecurity and other non-military factors of countries' resilience on their defence economy capability and analyse the factors that explain the level of cybersecurity. This goal required solving the following tasks: to provide an overview of the state of digitalisation of the defence economy of Ukraine in the context of war, identify key advantages and main problems; to analyse the impact of non-military factors of country resilience, including cybersecurity, on defence capability using the example of a global sample of countries; to evaluate the impact of technological, economic, and social aspects on the level of cybersecurity.

MATERIALS AND METHODS

The statistical analysis allowed to describe the state of digitalisation of the defence economy of Ukraine and assess global trends through the analysis of defence spending indicators, revenue dynamics, and the place of Joint-Stock Company Ukrainian Defence Industry in the ranking of the top 100 companies for the production of weapons and military services in the world, estimates of non-military sustainability indicators, and the global artificial intelligence market in the defence economy (FM Resilience Index, n.d.; SIPRI arms industry database, n.d.; Global AI in defense and security market, 2024; Defence spending and procurement trends, 2025). The comparative analysis allowed determining the place of Ukraine among other states by comparing the indicators of the country's defence capability and non-military factors influencing its defence capability with global averages.

Correlation analysis was used to analyse whether there are statistically substantial relationships between indicators of countries' defence capability and non-military factors of countries' resilience. This allowed forming an initial vision of the problem and identifying potential influencing factors. The purpose of the regression analysis was to analyse what non-military sustainability factors of countries can affect their defence capabilities. Special attention in the context of the research subject is paid to defining the role and impact of cybersecurity on defence capability.

Accordingly, the first group of indicators for regression analysis was formed considering their ability to fully characterise the defence capability of countries. These indicators acted as dependent variables in the analysis. These include military strength, security threats index, armed forces personnel, and military expenditure. Despite the fact that some indicators partially overlap (for example, armed forces personnel and military expenditure are reflected in military strength), their inclusion in the analysis was appropriate because it allowed assessing the impact of sustainability factors on various aspects of defence capability.

The second group of indicators consisted of indicators describing non-military factors that can potentially affect defence capability. The indicators of this group were independent variables. These factors reflect economic, social, environmental, and technological factors, including the level of cybersecurity. This approach to forming a sample of independent variables, among other things, allowed describing the impact of cybersecurity more accurately because it was evaluated in the context of interaction with other indicators.

An additional stage of regression analysis was devoted to assessing the impact of individual indicators on cybersecurity. The criteria for selecting indicators were their potential ability to influence the level of cybersecurity through economic, social, and technological aspects. All indicators that were used in the study are contained in Table 1, with an explanation of their essence and a link to the source.

Table 1. Sample of indicators for the study

Indicator	Source	Entity
Indicators that characterise defence capability and acted as dependent variables in the study		
Military strength score (varies from 0.0744 to 4.3156 for the study period, where 0.0744 indicates high military strength)	Global Firepower (2025 military strength ranking, 2025)	Assessment of countries by available firepower, determined by about 60 factors (number of military units, financial condition, material and technical capabilities, etc.)
Security Threats Index – (varies from 0.2 to 9.7 for the study period, where 0.2 indicates a high level of security)	The Global Economy (Security Threats Index – country rankings, n.d.)	It considers such immediate security threats as explosions, attacks, deaths due to battles, rebel movements, uprisings, coups, and terrorism. The index also reviews substantial criminal factors and perceived public confidence in the internal security system
Armed forces personnel	World Bank (Armed forces personnel, total, n.d.)	Total number of military personnel in the country
Military expenditure	World Bank (Military expenditure (current USD), n.d.)	The country's total defence expenditures, including the maintenance of the army and the purchase of weapons for other purposes
Non-military threat resistance factors that acted as independent variables in the study		
Resilience Index (not directly included in the analysis, its drivers were used; the index, like drivers, is measured from 0 to 100, where 100 is the highest level of stability)	Factory Mutual Insurance Company (FM Resilience Index, n.d.)	The index reflects countries' resilience to various risks through 18 indicators included in it, including productivity, health expenditure, education, inflation, political risk, control of corruption, energy intensity, ghg emissions, water stress, urbanisation rate, logistics, internet usage, climate risk exposure, climate risk quality, climate change exposure, seismic risk exposure, fire risk quality, cybersecurity
Indicators for an additional stage of regression analysis that acted as independent variables that potentially affect cybersecurity		
Overall Global Innovation Index (reflects the position of countries in the ranking, where 1 is the highest level of development)	World Intellectual Property Organization (GII 2024 results, 2024)	It evaluates the effectiveness of innovation in about 130 economies of the world and contains approximately 80 indicators, including political, educational, and infrastructure measures

Table 1. Continued

Indicator	Source	Entity
Human Capital Index (measured from 0 to 1, where 1 is the highest level of development)	World Bank (Human Capital Index (HCI), upper bound (scale 0-1) – East Asia & Pacific (excluding high income), n.d.)	Determines how effectively countries mobilise human capital and realise the economic and professional potential of the population
GDP per capita	World Bank (GDP per capita (current US$), n.d.)	Shows the country's gross domestic product (GDP) divided by the total population

Source: compiled by the authors

Thus, the analysis used 4 indicators of defence capability, 18 indicators of non-military sustainability factors, and 3 indicators of impact on cybersecurity for 91 countries of the world. Such a sample was considered to be sufficient for a study confirming the reliability of the results.

RESULTS

Digital technologies in the defence economy of Ukraine: Effectiveness of digitalisation and cybersecurity

The defence economy is an essential tool for ensuring an appropriate level of national security, increasing the country's defence capability through the efficient use of resources. Defence spending determines the ability of countries to respond to global challenges in the face of instability and escalation of conflicts of various origins. Figure 1 shows the countries that are the leaders in defence spending as of 2024.

Ukraine ranked fourteenth in terms of military spending in 2024, down several positions from 2023, when the country's military spending totalled USD 64.8 billion, and it ranked eighth in the ranking (Countries with the highest..., 2024). Moreover, Joint-Stock Company Ukrainian Defence Industry (Ukroboronprom) has been among the top 100 companies producing weapons and military services in the world since 2011 (Fig. 2).

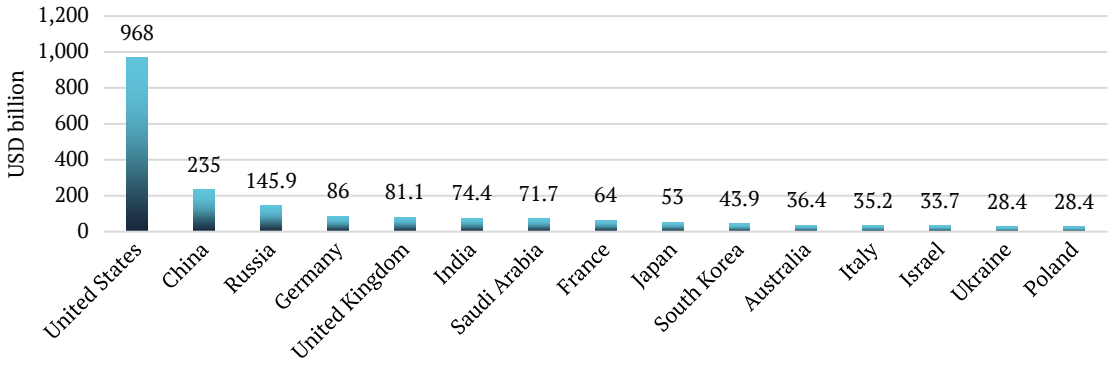

Figure 1. Countries with the highest military spending in 2024

Source: compiled by the authors based on Defence spending and procurement trends (2025)

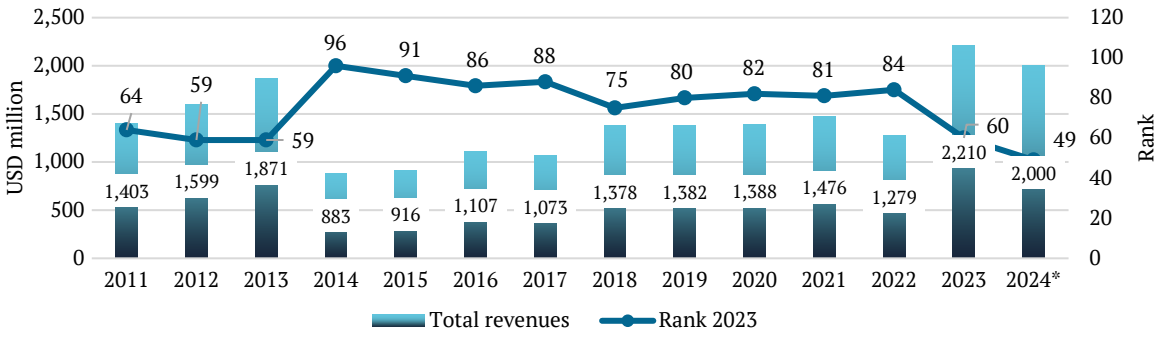

Figure 2. Revenue dynamics and position of Joint-Stock Company Ukrainian Defence Industry in the top 100 companies for the production of weapons and military services in the world

Note: * – as of September 2024

Source: compiled by the authors based on SIPRI arms industry database (n.d.), B. Miroshnychenko (2024)

The military strength indicator in 2025 is 0.3755 for Ukraine, which is quite high compared to the global average value of this indicator, which is about 1.3514. The number of military personnel of Ukraine as of 2025 reaches approximately 800,000 people, another 1,000,000 people are in reserve. Regarding non-military indicators of country resilience, Ukraine's indicators generally adhere to global averages (Fig. 3).

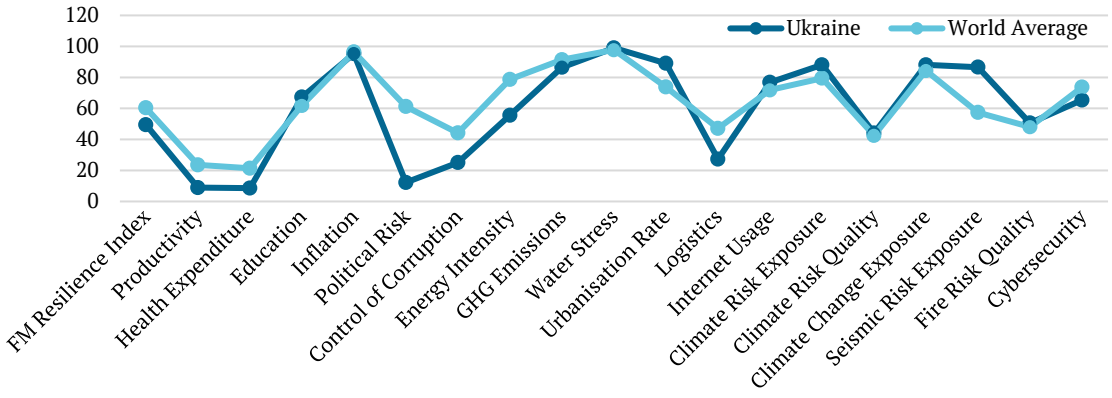

Figure 3. Comparison of non-military indicators of Ukraine's stability and global averages in 2024
Source: compiled by the authors based on FM Resilience Index (n.d.)

For Ukraine, among these non-military sustainability indicators, cybersecurity is of particular importance. In the context of war, given the scale and consequences of Russian cyber-attacks, cybersecurity is one of the most important areas of ensuring defence economy capability. Digitalisation of the defence sector, on the one hand, provides new opportunities for improving protection systems against cybersecurity threats. On the other hand, digitalisation can create new cybersecurity challenges, especially in the case of excessive dependence on information and communication technologies (Metelskyi & Kravchuk, 2023). In war conditions, enemy cyber-attacks can be aimed at obtaining confidential information or disrupting the activities of the military administration (Cherleniak & Tokar, 2024). Therefore, the activity of anticipating, countering and eliminating cybersecurity threats is one of the priorities in the context of armed confrontation.

Current initiatives in the field of digitalisation of the security and defence sector of Ukraine can be divided into several areas. The first concerns direct warfare, and one example of using digitalisation in this process is the introduction of the Delta system, which allows tracking enemy targets. As of January 14, 2025, it was reported that this system helped eliminate Russian equipment worth about USD 15 billion. The second area is material and technical support, which is the responsibility of the procurement agencies of the Ministry of Defence. Digitalisation of procurement processes (in particular, purchases through Prozorro, implementation of the DOT-Chain IT system, optimisation of internal dot processes, etc.) allowed saving about UAH 21 billion for the state budget, improving the food supply cycle, and optimising accounting systems. The third direction concerns human capital and is presented through: the register "Oberig", which contains data on those liable for military service, necessary for military registration; the electronic cabinet Reserve+, which contains the largest database of military vacancies; the application Army+ for military personnel, created to overcome excessive bureaucracy in the army. The last and fourth direction of digitalisation of the security and defence sector concerns resource provision. This area is the least digitalised and requires the introduction of effective tools for translating data work into digital form (Defence Talks, 2025).

The main directions of the state's cybersecurity policy are determined by the Law of Ukraine No. 2163-VIII (2017) and the Cybersecurity Strategy of Ukraine (Decision of the National Security and Defence Council of Ukraine No. n0055525-21, 2021). Coordination between cybersecurity entities is provided by the National Cybersecurity Coordination Centre, established in 2016. In 2020, changes were introduced to the work of the National Cybersecurity Coordination Centre, in particular, private sector specialists were involved. Such initiatives have allowed turning the National Cybersecurity Coordination Centre into a central platform for tracking, predicting, detecting, and eliminating cybersecurity threats in the public and private spheres. In 2024, the Ministry of Defence added another structural unit to improve the state of cybersecurity – the Cyber Incident Response Centre. It is assumed that this unit will have the goal of prompt and effective response to cyber incidents. Another way to improve cyber defence is to standardise information security requirements in the Ministry of Defence systems in accordance with North Atlantic Treaty Organization (NATO) best practices. This applies to the ministry's digital tools, services, applications, and systems. An important area of countering cyber threats is improving the training of specialists in the field of cybersecurity and finding opportunities for information exchange and cooperation with other parties, particularly international partners.

Despite the noted efforts in the field of countering cyber threats, the cybersecurity indicator of Ukraine is below the global average, and spending on digitalisation in the field of defence is only 0.16% of the total spending on the main areas (Cheberyako & Rudyk, 2023). Given the rapid development of technologies and the projected growth of the global artificial intelligence market in defence and security, Ukraine needs to increase attention to cybersecurity issues through improving information security strategies, strengthening the regulatory framework, and financial support (Fig. 4). Assessing the impact of cybersecurity and other non-military resilience factors in countries can help identify which aspects of countries' defence capabilities are most dependent on the level of cybersecurity. Initial conclusions about the relationship between cybersecurity and the defence capabilities of countries can be obtained through correlation analysis. Thereby, it should be considered that the level of cybersecurity is not a separate indicator but has an impact simultaneously with other sustainability factors.

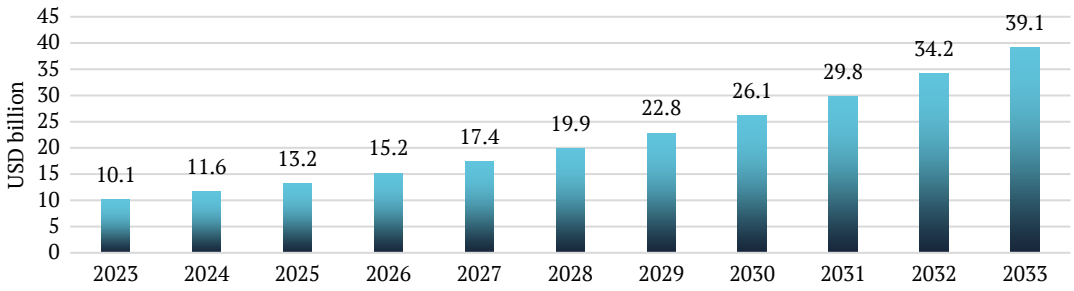

Figure 4. The size of the global artificial intelligence market in defence and security
Source: compiled by the authors based on Global AI in defense and security market (2024)

Regression analysis was used to assess the combined impact of these factors. In turn, it is also important to investigate what factors of the social, economic, and technological environment affect the level of cybersecurity. This will determine the extent to which factors such as human development, well-being, and digitalisation determine cybersecurity.

Impact of digitalisation on global sustainability

Correlation analysis was aimed at identifying the strength and direction of the relationship between the indicators of countries' defence capability and non-military indicators of resistance to threats. Tables 2 and 3 show the results of the correlation analysis between the observed indicators. Table 2 contains the obtained correlations of defence performance indicators with physical scores, Table 3 – with macro scores. Based on the results presented in Table 2, initial conclusions were drawn regarding the presence of a relationship between the examined indicators. The military strength and security threats index indicators correlated with most physical scores, and this relationship was statistically substantial. For military strength, the relationship strength was mostly weak or moderate, for the security threats index – noticeable and strong. For the armed forces personnel and military expenditure indicators, statistically substantial correlations were observed with individual indicators, mainly with weak coupling strength.

Table 2. Results of correlation analysis between indicators of defence capability of countries and non-military indicators of resistance to threats (resilience index drivers – physical scores)

Indicators	Military strength	Security threats index	Armed forces personnel, total	Military expenditure (current USD)
Productivity	−0.28*	−0.69*	−0.09	0.18
Health expenditure	−0.36*	−0.66*	−0.06	0.39*
Education	−0.43*	−0.63*	−0.1	0.13
Inflation	−0.05	−0.22*	0.03	0.06
Political risk	0.03	−0.89*	−0.27*	−0.01
Control of corruption	−0.26*	−0.78*	−0.13	0.13
Energy intensity	0.18	0.05	−0.13	−0.12
GHG emissions	−0.23*	−0.38*	−0.07	0.02
Water stress	0.01	0.08	0.02	0
Urbanisation rate	−0.35*	−0.47*	−0.15	0.05
Logistics	−0.47*	−0.64*	0.07	0.22*
Internet usage	−0.39*	−0.62*	−0.08	0.12

Note: * – statistically substantial relationships at $p < 0.05$
Source: calculated by the authors based on Armed forces personnel, total (n.d.), FM Resilience Index (n.d.), Military expenditure (current USD) (n.d.), Security Threats Index – country rankings (n.d.), 2025 military strength ranking (2025)

Table 3. Results of correlation analysis between indicators of defence capability of countries and non-military indicators of resistance to threats (resilience index drivers – macro scores)

Indicators	Climate risk exposure	Climate risk quality	Climate change exposure	Seismic risk exposure	Fire risk quality	Cybersecurity
Military strength	0.01	−0.431*	−0.069	−0.047	−0.451*	−0.552*
Security threats index	−0.146	−0.653*	−0.218*	−0.154	−0.568*	−0.425*
Armed forces personnel, total	−0.243*	−0.09	−0.199	0.002	0.072	0.23*
Military expenditure (current USD)	−0.119	0.152	−0.065	0.116	0.218*	0.189

Note: * – statistically substantial relationships at $p < 0.05$
Source: calculated by the authors based on Armed forces personnel, total (n.d.), FM Resilience Index (n.d.), Military expenditure (current USD) (n.d.), Security Threats Index – country rankings (n.d.), 2025 military strength ranking (2025)

Regarding the relationship between defence capability indicators and macro scores, a similar trend can be noted: military strength is moderately or noticeably correlated with climate risk quality, fire risk quality, and cybersecurity. The security threats index showed a weak correlation with climate change exposure and a moderate or noticeable correlation with climate risk quality, fire risk quality, and cybersecurity. The armed forces personnel indicator showed a weak association with the climate risk exposure and cybersecurity indicators, while military expenditure – only with fire risk quality indicators. The results showed that the defence capability of countries can be closely linked to a number of non-military indicators. However, the obtained correlations do not prove the direct impact of these indicators on defence capability. For a more in-depth analysis of the ability of the non-military indicators under study to determine the defence capability of countries, a regression analysis was conducted. Regression analysis was performed in several stages, each of which had its own dependent variable. The dependent variables were alternately indicators of the countries' defence capability. The set of independent indicators for regression analysis was common to all stages and consisted of non-military indicators of countries' resilience to threats.

Table 4 shows the results of regression analysis for military strength as a dependent variable and non-military threat resistance indicators as independent. The correlation coefficient for the resulting model was 0.76025834, which indicated a fairly strong correlation between the indicators included in it. The coefficient of determination was 0.57799274, and the updated coefficient of determination was 0.47249092, which showed moderate explanatory ability. The indicator is $p < 0.00000$, and therefore, the results are statistically substantial.

Table 4. Regression analysis results for military strength as a dependent variable and non-military threat resistance indicators

Indicators	Coefficients	Standard error	*t* (72)	*p* value
Intercept	1.714	1.804	0.95	0.345
Productivity	0.401	0.184	2.184	0.032
Health expenditure	−0.364	0.212	−1.716	0.09
Education	0.074	0.202	0.363	0.718
Inflation	0.035	0.091	0.387	0.7
Political risk	0.428	0.129	3.315	0.001
Control of corruption	0.335	0.221	1.519	0.133
Energy intensity	0.091	0.138	0.658	0.513
GHG emissions	−0.018	0.145	−0.123	0.902
Water stress	−0.022	0.089	−0.247	0.805
Urbanisation rate	−0.043	0.145	−0.298	0.767
Logistics	−0.518	0.173	−2.991	0.004
Internet usage	−0.285	0.173	−1.645	0.104
Climate risk exposure	0.222	0.136	1.636	0.106
Climate risk quality	−0.159	0.213	−0.746	0.458
Climate change exposure	−0.137	0.138	−0.989	0.326
Seismic risk exposure	0.058	0.098	0.595	0.554
Fire risk quality	−0.017	0.195	−0.088	0.93
Cybersecurity	−0.354	0.125	−2.838	0.006

Source: calculated by the authors based on FM Resilience Index (n.d.), 2025 military strength ranking (2025)

A statistically substantial impact on military strength was observed from the following non-military indicators: productivity and political risk – direct impact, logistics and cybersecurity – reverse impact. Notably, the growth of the military strength indicator used in the work indicated a lower military power and defence capability, and its approach to zero, on the contrary, indicated substantial defence capabilities of countries. Accordingly, rising levels of productivity and political risk weaken countries' military power. An increase in productivity by 1 was accompanied by an increase in military strength by 0.401 and an increase in political risk – by 0.428. In turn, the development of logistics and a high level of cybersecurity contribute to improving defence and military capabilities. An increase in the logistics indicator by one was associated with a decrease in the military strength indicator by 0.518 and cybersecurity – by 0.354. Conclusions about the inverse effect of productivity on military power may seem continental. However, this state of affairs can be explained by the focus of countries on technological, social, and political aspects of development, with a low focus on defence needs. Table 5 contains the regression results for the model in which the security threats index was the dependent variable. The model is characterised by a high correlation coefficient, which was 0.92801302, and a high explanatory ability, as indicated by the value of the coefficient of determination – 0.86120816 and the refined coefficient of determination – 0.8265102. The results are statistically substantial ($p < 0.0000$).

Table 5. Regression analysis results for the security threats index as a dependent variable and non-military threat resistance indicators

Indicators	Coefficients	Standard error	*t* (72)	*p* value
Intercept	7.837	2.524	3.106	0.003
Productivity	−0.175	0.105	−1.661	0.101
Health expenditure	0.177	0.122	1.452	0.151
Education	−0.026	0.116	−0.226	0.822
Inflation	−0.008	0.052	−0.145	0.885
Political risk	−0.685	0.074	−9.255	0
Control of corruption	−0.292	0.127	−2.309	0.024
Energy intensity	0.006	0.079	0.077	0.939
GHG emissions	0.053	0.083	0.64	0.524
Water stress	0.059	0.051	1.161	0.25
Urbanisation rate	0.098	0.083	1.177	0.243
Logistics	0.129	0.099	1.302	0.197
Internet usage	0.012	0.099	0.117	0.907
Climate risk exposure	−0.094	0.078	−1.203	0.233
Climate risk quality	−0.235	0.122	−1.918	0.059
Climate change exposure	−0.008	0.079	−0.105	0.917
Seismic risk exposure	0.088	0.056	1.563	0.123
Fire risk quality	0.062	0.112	0.557	0.579
Cybersecurity	−0.076	0.072	−1.064	0.291

Source: calculated by the authors based on FM Resilience Index (n.d.), Security Threats Index – country rankings (n.d.)

The security threats index was under the statistically substantial influence of political risk and control of corruption. The growth of the security threats index indicates an increase in the level of threats, so the inverse relationship with indicators indicates that their increase contributes to a decrease in security threats. An increase in political risk by 1 was accompanied by a decrease in the security threats index by 0.685 and the control of corruption indicator – by 0.292. This impact can be considered quite large-scale because the security threats index for the study period ranged from 0.2 to 9.7, and its change by 0.292 and even more so by 0.685 is substantial. Notably, the lowest value of the indicator (9.7) among 91 countries under study is typical for Ukraine. Table 6 shows the results of a regression analysis in which the military expense indicator was the dependent variable. There was a noticeable correlation between the indicators in the model (0.72259235), and it was characterised by moderate explanatory ability because the updated coefficient of determination was 0.40267463. As in previous models, the results are statistically substantial ($p < 0.0000$).

Table 6. Regression analysis results for military expenditure as a dependent variable and non-military threat resistance indicators

Indicators	Coefficients	Standard error	*t* (72)	*p* value
Intercept	217,635,598,285.156	190,205,112,522.16	1.144	0.256
Productivity	−0.668	0.195	−3.419	0.001
Health expenditure	1.714	0.226	7.598	0
Education	−0.36	0.215	−1.67	0.099
Inflation	0.017	0.097	0.179	0.859
Political risk	−0.043	0.137	−0.313	0.755
Control of corruption	−0.608	0.235	−2.588	0.012
Energy intensity	−0.073	0.147	−0.496	0.622
GHG emissions	−0.169	0.154	−1.099	0.276
Water stress	0.059	0.095	0.625	0.534
Urbanisation rate	−0.074	0.155	−0.479	0.633
Logistics	0.064	0.184	0.349	0.728
Internet usage	0.229	0.185	1.239	0.22
Climate risk exposure	−0.292	0.145	−2.019	0.047
Climate risk quality	−0.465	0.227	−2.046	0.044
Climate change exposure	0.227	0.147	1.544	0.127
Seismic risk exposure	−0.028	0.104	−0.264	0.793
Fire risk quality	0.238	0.208	1.145	0.256
Cybersecurity	0.317	0.133	2.387	0.02

Source: calculated by the authors based on FM Resilience Index (n.d.), Military expenditure (current USD) (n.d.)

Military expenditure was inversely affected by productivity, control of corruption, climate risk exposure, and climate change exposure. Military expenditure was directly influenced by health expenditure and cybersecurity. Among the observed indicators, the strongest influence was observed from productivity, an increase of 1 was associated with a decrease in military spending by 0.668, control of corruption, an increase of which by 1 was accompanied by a decrease in spending by 0.608, and health expenditure, an increase of which by 1 increased military spending by 1.714. Given that costs were measured in dollars, the scale of the impact was insubstantial and made no practical sense despite its statistical importance. The results of regression analysis with armed forces personnel as a dependent variable are shown in Table 7. The correlation coefficient shows a noticeable correlation between the model variables (0.67083765), according to the refined coefficient of determination, it has a moderate explanatory capacity (0.31252894), and $p < 0.00018$, which confirms statistical significance.

Table 7. Regression analysis results for armed forces personnel as a dependent variable and non-military threat resistance indicators

Indicators	Coefficients	Standard error	*t* (72)	*p* value
Intercept	1,184,327.619	1,001,958.332	1.182	0.241
Productivity	−0.471	0.21	−2.248	0.028
Health expenditure	0.485	0.242	2.006	0.049
Education	−0.473	0.231	−2.047	0.044
Inflation	−0.033	0.104	−0.314	0.755
Political risk	−0.151	0.147	−1.026	0.309
Control of corruption	−0.293	0.252	−1.161	0.249
Energy intensity	−0.284	0.157	−1.801	0.076
GHG emissions	−0.024	0.165	−0.142	0.887
Water stress	0.097	0.102	0.955	0.343
Urbanisation rate	−0.063	0.166	−0.38	0.705
Logistics	0.426	0.198	2.153	0.035
Internet usage	0.12	0.198	0.605	0.547
Climate risk exposure	−0.446	0.155	−2.879	0.005
Climate risk quality	−0.439	0.244	−1.802	0.076
Climate change exposure	0.231	0.158	1.467	0.147
Seismic risk exposure	−0.094	0.112	−0.839	0.404
Fire risk quality	0.407	0.223	1.826	0.072
Cybersecurity	0.453	0.142	3.181	0.002

Source: calculated by the authors based on Armed forces personnel, total (n.d.), FM Resilience Index (n.d.)

The variables productivity, health expenditure, education, logistics, climate risk exposure, and cybersecurity have a statistically substantial impact on armed forces personnel. However, judging by the regression coefficients, as in the previous model, the impact scale is too small to have practical value. In the context of the subject of study, cybersecurity deserves special attention among the examined indicators. According to the regression analysis, the statistically substantial and largest impact of this indicator was observed relative to military strength. Among the countries considered, the highest military strength value is 0.0744 (for the United States of America) and the lowest is 4.3156 (for Benin). Given that an increase in the cybersecurity indicator by 1 led to an increase in military strength by 0.354, the impact of cybersecurity on military strength can be considered substantial. Therefore, it was advisable to investigate which social, economic, and technological indicators affected the level of cybersecurity, for which regression analysis was also used. The correlation coefficient for the model, where cybersecurity was used as a dependent variable and Overall Global Innovation Index, Human Capital Index, and GDP per capita were independent, is 0.76412146, and indicates a strong relationship. The refined coefficient of determination is 0.5695327, which indicates a noticeable explanatory ability (Table 8).

Table 8. Regression analysis results for cybersecurity as a dependent variable and economic, social, and technological impact indicators

	Coefficients	Standard error	*t* (72)	*p* value
Intercept	163.365	25.505	6.405	0
Overall Global Innovation Index	−1.068	0.154	−6.914	0
Human Capital Index	−0.299	0.15	−1.999	0.049
GDP per capita	−0.078	0.103	−0.759	0.45

Source: calculated by the authors based on GDP per capita (current US$) (n.d.), FM Resilience Index (n.d.), Human Capital Index (HCI), upper bound (scale 0-1) – East Asia & Pacific (excluding high income) (n.d.), GII 2024 results (2024)

According to the results obtained, the impact is reversed; that is, an increase in Global Innovation Index and Human Capital Index is accompanied by a decrease in the level of cybersecurity. The results can be explained by the fact that countries with a high level of innovation and human resource development face more complex cyber threats and have a higher risk due to the active use of new technologies. Accordingly, highly developed countries should pay special attention to preventing and countering cyber threats through government initiatives, educational programmes, strengthening technological characteristics, etc.

Based on the analysis of the state of digitalisation of the defence economy of Ukraine in the conditions of war and the results of regression analysis, the following recommendations can be formed for Ukraine to balance the need to implement digitalisation and ensure an appropriate level of cybersecurity: increase funding for digitalisation of the defence sector of Ukraine, for example, through the development of state co-financing programmes and international initiatives to support digitalisation in Ukraine; expand the use of the latest technologies in the defence sector while ensuring proper control over their development and use, in particular, through the adaptation of NATO standards in the field of cybersecurity, as well as the development of clear requirements for certification of implemented systems; optimise state training programmes in the field of cybersecurity, cooperation with research centres, universities and international partners will be useful; ensure coordination of actions and exchange of information with international partners (through specialised platforms, training, etc.); conduct regular monitoring of cyber threats and the state of cybersecurity, analyse the impact of cybersecurity on defence capability; pay close attention to protecting critical infrastructure objects from cyber threats, for example, through the creation of secure data storage; conduct information campaigns for the population to improve self-defence skills against digital threats.

DISCUSSION

In the course of regression analysis, it was established that the simultaneous impact of cybersecurity and other non-military factors on the level of defence capability of countries is substantial. The statistically important and largest impact on cybersecurity was recorded relative to the military strength indicator. The increase in cybersecurity is accompanied by increased military strength, but it has also been determined that increased Global Innovation Index and Human Capital Index levels can increase cybersecurity threats.

Many of the papers of researchers also analysed the impact of digitalisation on various aspects of countries' resilience to threats. B. Brenner & B. Hartl (2021) investigated how the degree of digitalisation affects sustainability dimensions – economic, social, and environmental. The perception of environmental and economic sustainability was identified to be dependent to the greatest extent on digitalisation. These results are consistent with the results obtained by A. Grybauskas *et al*. (2022), which showed that digitalisation makes a substantial contribution to economic development at the corporate level by increasing the rate of return, reducing the time to market goods and increasing labour productivity. Similar conclusions are observed in the field of environmental sustainability. E.S. Knudsen *et al*. (2021) proved that digitalisation makes competitive advantages more extensive and sustainable. However, these studies focus mainly on the impact of digitalisation on non-military sustainability factors and do not pay enough attention to analysing the relationship between digitalisation and security at different levels.

In different publications, the relationship between digitalisation and security factors is investigated. For example, T.T. Thanh *et al*. (2023) discovered that digital transformation has a positive impact on the sustainability of energy security and ultimately contributes to sustainable economic development. However, their study does not fully disclose what cybersecurity challenges digitalisation poses. Regarding the risks of digitalisation for cybersecurity, S. Kumar & R.R. Mallipeddi (2022) noted that the use of the latest technologies, in particular, cloud technologies, the Internet of things, artificial intelligence, big data, and nanotechnology, creates new risks for organisations in the form of cybersecurity problems. The situation is aggravated by the growing number of cyber-attacks related to these technologies. Based on the results of the study by B. Guembe *et al*. (2022), the capabilities of existing cyber defence infrastructures will not be sufficient in the near future to counter sophisticated cyber-attacks controlled by artificial intelligence. P. Sharma & B. Dash (2023) added that the increase in the number of attacks in the cyber environment has recently led to serious negative consequences for business systems and individuals. The authors analysed how big data analytics and artificial intelligence technologies affect cybersecurity risks. Researchers have found that artificial intelligence-based platforms such as ChatGPT can have both positive and negative effects. On the one hand, these technologies can be used to implement preventive measures, and on the other – promote complex cyber-attacks. These conclusions are confirmed by M. Gupta *et al*. (2023), who noted the use cases of generative artificial intelligence, in particular ChatGPT, in both defensive and offensive cybersecurity strategies. Specifically, the researchers clarified how ChatGPT can be used to develop cyber-attacks, extract malicious information without ethical restrictions, create phishing attacks, social engineering attacks, malicious software, etc.

M. Charfeddine *et al*. (2024) supplemented this list, noting the technology's ability to provide malicious hints, test brute-force attacks, develop ransomware, and more. D. Kalla *et al*. (2023) noted that ChatGPT offers important information for cybersecurity, but its risks and limitations must be considered. M. Alsharif *et al*. (2022) concluded that the active use of technology increases cybersecurity risks. Examples include password attacks, phishing attacks, and social engineering. An important conclusion of the paper is to establish the fact that most successful cyber-attacks can be explained by the human factor – for example, about 95% of attacks were caused by human errors. These conclusions are consistent with the results of the author because the paper determined that the level of digitalisation, which was presented in the paper through the Overall Global Innovation Index indicator, negatively and statistically substantially affects the cybersecurity indicator of the examined countries.

A number of papers analyse successful international practices in countering cyber risks. In contrast to the previous studies reviewed, A.B. Ige *et al*. (2024) suggested that artificial intelligence and machine learning could help overcome information security challenges. The researchers also noted the advantages of international cooperation, implementation of international standards, investment in new technologies and public-private partnerships to increase resilience to cyber threats. M. Abdullahi *et al*. (2022) come to similar conclusions, noting the capabilities of artificial intelligence for continuous compliance monitoring and threat detection. B. Al Kurdi *et al*. (2024), using the example of the United Arab Emirates, established that successful cybersecurity management is impossible without optimising the supply chain, training employees, monitoring and the awareness of protection and security needs. However, these papers do not examine the relationship between the defence economy, cybersecurity, and the introduction of digitalisation. In turn, D. Cai *et al*. (2023) examined how defence science and technological innovation are related using the example of China. Researchers found a stable correlation between the defence sector, technological innovation, and economic development of this state, but it was heterogeneous for different regions of China. Based on the results of the study, the authors propose to balance defence and national construction, optimise the defence strategy in terms of science and technology, and strengthen the efficiency of using industrial advantages.

In turn, E.B. Kania (2022) noted that the effectiveness of China's approach to using new defence technologies will be determined by a clear strategic culture, operational requirements, and organisational characteristics. J. Reis *et al*. (2021) noted the feasibility of developing innovative defence systems based on technologies such as artificial intelligence and robots. The development of the high-tech defence industry requires effective investment of limited resources in the most promising areas (Hysi *et al*., 2024). The authors claimed that the greatest effect can be achieved at the tactical level, when the need for human intervention is minimised. D. Araya & M. King (2022) used the example of Canada to examine the development of military capabilities through the use of artificial intelligence and machine learning. The positive impact of new technologies on the management of military operations was noted. The researchers expressed concern about the security risks associated with the use of network technologies. Therefore, researchers focused on the need to strengthen security and improve data management, the need for new knowledge and experience, and the need for a balance between the rigidity of power and the needs of a changing geopolitical environment.

J.M. Rickli & M. Ienca (2021) examined the security and military implications of the use of artificial intelligence and nanotechnology. They have noticed the great potential of these technologies, which can be realised due to their modifying ability and rapid spread. Therefore, the introduction of technology in the military sector is of great concern due to the possibility of implementing security risks such as data bias, social control and manipulation, the use of weapons, etc. (Lyndyuk *et al*., 2023). Scientists emphasised that because of these dangerous opportunities of technologies, there is an urgent need for appropriate management responses to their distribution, access, and use.

The response should account for the interests of all stakeholders and be diverse and adaptive, which will counter the risks associated with the rapid development of technology. The conclusions are somewhat different from the results of this study on the directions of ensuring cybersecurity in Ukraine through different contexts because the experience of each state is unique and depends on numerous factors – the level of development, financial capabilities, political factors, etc. However, the experience described in the studies can be used in the process of developing cybersecurity strategies in Ukraine, along with the areas covered in the author's paper.

CONCLUSIONS

The results of the work showed that Ukraine has quite high indicators of military strength, military spending, and the number of military personnel. Calculating the average value of these indicators based on the data of the studied countries and comparing it with the indicators of Ukraine allowed confirming that the military potential of Ukraine substantially exceeds the global average. However, the analysis of non-military indicators of Ukraine's resilience and their comparison with the national average demonstrated that, in this case, Ukraine shows quite average results. Indicators of productivity, health costs, political risk, corruption control, and logistics are noticeably lower than average. Non-military sustainability indicators can provide important support for a country's defence capability, as confirmed in the regression analysis.

Regression analysis conducted for indicators of the defence capability of countries as dependent variables and non-military indicators of the stability of countries allowed confirming that the latter are able to partially determine military strength and influence various parameters of defence capability. Thus, productivity and political risk had a statistically substantial direct impact on military strength, while logistics and cybersecurity had the opposite impact. Given that the increase in military strength indicates a lower military strength, it was concluded that increased productivity and political risk weaken the military power of states, and better logistics and a high level of cybersecurity increase defence capabilities. The increase in logistics per unit was accompanied by a decrease in military strength by 0.518, cybersecurity – by 0.354. Given that the military strength indicator for the study period ranged from 0.0744 to 4.3156, where 0.0744 meant the highest military strength, such an impact can be considered substantial.

In addition to the impact on military strength, regression analysis revealed a statistically substantial impact of non-military resilience indicators on the security threats index. This indicator was under the statistically substantial and substantial influence of political risk and control of corruption. The military expense indicator was heavily influenced by productivity, control of corruption, climate risk exposure, and climate change exposure. A direct impact on this indicator was observed on the part of health expense and cybersecurity. Armed forces personnel were substantially affected by the variables productivity, health expenditure, education, logistics, climate risk exposure, and cybersecurity. However, for both the military expense

indicator and armed forces personnel, the scale of impact was insubstantial and did not make practical sense.

Analysis of the impact of economic, technological, and social indicators on cybersecurity displayed that the level of cybersecurity depends on the overall development of innovation and the level of human capital development. Therewith, these indicators have the opposite effect, which indicates an increase in cybersecurity risks with the growth of these variables. Thus, countries with a high level of innovation and human resource development are exposed to more complex cyber threats, which are highly likely to be implemented through the active use of innovative technologies. Based on the results of the study, recommendations were formed for Ukraine on balancing digital development and the need to ensure a high level of cybersecurity. Further research should focus on a comparative analysis of the best practices for ensuring cybersecurity in countries with a high level of innovative development because this can provide new insights to improve the fight against cyber threats in the face of the threat of more complicated and complex risks.

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CONFLICT OF INTEREST

None.

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Вплив цифрових технологій на оборонну економіку України в контексті економічних викликів кібербезпеці

Анотація. Метою дослідження була оцінка впливу кібербезпеки та низки інших невійськових чинників стійкості країн до загроз на їх обороноздатність, а також характеристика факторів, що визначають рівень кібербезпеки. У результаті охарактеризовано стан цифровізації оборонної економіки України через якісні та кількісні показники, що дозволило відзначити значні зусилля держави щодо впровадження цифровізації та забезпечення кібербезпеки. Встановлено, що рівень кібербезпеки країни був нижчим за середньосвітовий, а витрати на цифровізацію в оборонному секторі становили лише 0,16 % від загальних витрат за основними напрямами. Зазначено, що підвищення рівня кібербезпеки в умовах стрімкого впровадження цифровізації є пріоритетом для забезпечення обороноздатності, оскільки цифровізація створює нові виклики для кібербезпеки. Це підтверджується регресійним аналізом, який виявив статистично значущий негативний вплив цифровізації та рівня людського розвитку на кібербезпеку. Крім того, за допомогою регресійного аналізу визначено аспекти обороноздатності країн, на які найбільше впливає рівень кібербезпеки. Виявлено, що збільшення показника кібербезпеки на одиницю спричиняє збільшення військової сили на 0,354. Отже, вплив кібербезпеки на оборонну економіку можна вважати суттєвим. За результатами дослідження сформовано рекомендації для України щодо цифровізації оборонної економіки та підвищення рівня кібербезпеки. Отримані результати можуть бути корисними для розробки стратегій підвищення рівня кібербезпеки в оборонній економіці в умовах стрімкого впровадження цифровізації

Ключові слова: військова міць; фактори стійкості до невійськових загроз; рівень людського розвитку; глобальний індекс інновацій; витрати

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