UDC 330.46:332.1:334.7
JEL Classification: C38, C63, R11, R58
DOI: 10.15587/2706-5448.2026.366137

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DEVELOPMENT OF A MULTI-LEVEL APPROACH TO MODELLING THE DEVELOPMENT OF CLUSTER ASSOCIATIONS IN THE REGIONAL ECONOMY

The object of research is the process of cluster association development in the regional economy and the economic-mathematical tools used for its modelling.

The research problem lies in the lack of methodological justification for multi-level modelling of the development of cluster structures in the context of contemporary economic transformations, regional differentiation and growing existential challenges.

The methodological foundations and mathematical tools for modelling the development of cluster structures have been defined, based on a functional-structural approach, with its phased implementation in accordance with the structural-analytical, evaluative-analytical, predictive-modelling, and monitoring-and-adjustment levels.

The results of matrix analysis revealed both restrictive factors and risks, as well as favorable conditions for cluster development depending on the type of Ukrainian region. Using the Lviv IT Cluster, which includes 461 participants and represents one of the largest cluster structures in Ukraine, as a case study, an econometric model was developed to analyze the relationship between its activities and the GRP per employed person of the Lviv region. Based on multiple linear regression modelling implemented in EViews software, statistically significant effects of profitability, return on equity, capitalization level, financial risk, and cluster sales dynamics on regional economic development were identified. The significance and adequacy of the model are confirmed by the coefficients of determination ($R^2 = 0.819$) and the Durbin-Utson coefficient (2.081). Key areas for the provision of resources to cluster associations have been identified, and on this basis, optimistic, baseline and pessimistic scenarios for their development have been formulated. Based on a SWOT analysis, scenario modelling was carried out to identify existential challenges and advantages in the projected development of cluster associations within Ukraine's regional economy.

The findings have practical value for central and regional government bodies, local authorities, cluster associations and research and analysis centers in terms of studying clustering processes and developing and implementing strategies for regional economic development.

Keywords: *cluster policy, regional development, functional-structural approach, econometric modelling, scenario modelling, IT cluster, digital transformation, resource provision.*

Received: 02.07.2026
Received in revised form: 22.09.2026
Accepted: 20.10.2026
Published: 30.10.2026

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How to cite
Kutsyk, P., Lupak, R., Proskurina, N., Artemenko, A., Protsykevych, A., Gryn, V. (2026). Development of a multi-level approach to modelling the development of cluster associations in the regional economy. Technology Audit and Production Reserves, 5 (4 (91)), 15–28. https://doi.org/10.15587/2706-5448.2026.366137

1. Introduction

In a highly dynamic business environment, economic entities organized into clusters have greater opportunities to adapt and implement innovative developments and technologies with a view to ensuring stable and sustainable operation and growth. Conversely, in the context of a full-scale war, the cluster approach should be regarded as a priority tool for addressing spatial and territorial economic imbalances in Ukraine, particularly in ensuring post-war reconstruction. In particular, the development of cluster associations is of significant importance in the context of attracting foreign investment, stimulating high-tech exports and building innovative capacity. At the same time, the significance of such trends is confirmed by the need to enhance the economic efficiency of enterprise through the creation of high-caliber clusters, the development of which takes place via joint, investment-active and innovation- and technology-driven business networks. At the same time, cluster associations play an important role in expanding cooperation between local businesses, research and educational establishments, and state institutions. It is becoming increasingly important to identify the patterns governing the functioning and development of cluster associations, the results of which could lead to the development of new approaches to enhancing the effectiveness of socio-economic policy, particularly at the regional level.

Cluster associations are characterized by their active involvement in ensuring the competitiveness and economic security of regions. Thanks to the scale of their activities, members of cluster associations are able to influence the use of regional resources and ensure a high level of efficiency in their utilization. Consequently, the involvement of clusters is particularly important in regions requiring socio-economic recovery and the elimination of spatial and economic imbalances.

ISSN-L 2664-9969; E-ISSN 2706-5448

Another important area for the development of cluster associations is their role in promoting regional decentralization. In Ukraine, decentralization processes are a key aspect of reforming the system of state regulation, aimed at providing regions with more resources to expand local economic cooperation. At the same time, the lack of a clear strategy for managing cluster processes creates additional risks of a deterioration in the resource base of regional economies, as it becomes difficult to maintain a sufficient level of resource renewal and efficiency of use. Consequently, there is a growing need to develop and implement tools to support management decisions by members of cluster associations, aimed at expanding their activities, thereby ensuring that the regional economy receives the necessary resources to guarantee its own stability and sustainability.

At the same time, economic and mathematical modelling is regarded as one of the key scientific and applied approaches to analyzing and forecasting the development of cluster associations. It is precisely these economic and mathematical tools that make it possible to reliably assess, both qualitatively and quantitatively, the dynamics of interaction between cluster participants, to take into account the influence of internal and external factors, and to identify optimal paths for development. The use of economic and mathematical tools is a priority given their ability to comprehensively cover the processes of developing and implementing management mechanisms, the great importance of which stems from the need to strengthen managerial control over the development of cluster associations in order to ensure the stability and sustainability of the regional economy.

The fundamental principles of the spatial concentration of economic activity within cluster associations are set out in [1], which substantiates the role of technology clusters in shaping the competitive advantages of national economies through the mechanisms of specialization, talent mobility and the dissemination of knowledge. A further exploration of the theory of agglomeration effects – defining the spatial scales of cluster development and the formation of sectoral agglomerations by these clusters – is presented in [2]. However, such approaches mainly focus on spatial and agglomeration effects without taking into account the challenges of comprehensive modelling of cluster development, particularly at the level of the regional economy, and the combination of econometric and scenario-based tools within a single methodological and applied approach.

Further development of the issue of modelling the development of high-tech clusters is linked to a systemic-functional and strategic analysis of their activities. In particular, [3] demonstrates the positive impact of clusters on the productivity of innovators and the concentration of human capital. The author of [4] has empirically confirmed the link between cluster specialization and the socio-economic development of cities and regions. Other scientific researches have demonstrated that the implementation of cluster models enhances the innovative and investment potential of businesses [5], as well as the effectiveness of managing their sustainable development [6], knowledge transfer between universities and SMEs [7].

At the same time, the practical aspects of modelling the strategic development of clusters are summarized in [8], the authors of which emphasize the need to combine analytical tools, institutional support and long-term strategic planning. Modelling partnership relationships within clusters is also of significant importance for the implementation of joint projects between businesses and research institutions [9]. Nevertheless, such researches leave unresolved the issues of quantitatively assessing the functioning of clusters and their impact on the development of the regional economy. Therefore, it is of great importance to combine tools for assessing the interrelationships between participants in cluster associations, taking into account regional trends, and subsequently to define scenarios for their further development.

An important area of contemporary scientific research is the modelling of cluster integration into entrepreneurial and innovation ecosystems – environments in which sustainable links are formed between business, academia and financial and investment organizations. In [10], it is demonstrated that entrepreneurial activity within ecosystems has a direct positive impact on the socio-economic growth of regions. In contrast, the authors of [11] substantiate the role of knowledge and innovation as fundamental drivers of regional development, since it is intellectual capital and researchers' ability to commercialize innovations that determine the long-term competitiveness of regions. The research findings presented in [12] confirm the importance of the network centrality of regional "dealmakers", who act as intermediaries between entrepreneurs, investors and development institutions. Despite the results obtained, the researchers were unable to adequately address the issue of developing methodological guidelines for the quantitative assessment of the integration of cluster associations into ecosystems at regional level.

Some researches demonstrate the importance of taking into account the sector-specific nature of innovative ecosystem formation when modelling the development of cluster associations. For instance, [13] presents the results of an analysis of the development of fintech clusters as an example of the latest forms of financial agglomeration, which combine digital technologies and financial services. The author of [14] emphasizes the priority of digitization processes in innovation hubs in the context of Industry 4.0, the effectiveness of which depends to a large extent on government support and the development of an institutional environment conducive to the formation of cluster associations.

Considerable attention is paid to the issue of modeling the economic resilience of regional economies and their ability to adapt to external and internal challenges, as this helps define the prerequisites for the functioning and development of cluster associations. The authors of [15] argue that the creation of innovation and technology networks promotes the regional economy's adaptability to contemporary challenges and enables the formation of the necessary potential for its recovery and structural restructuring. This issue is also examined in the context of identifying the interrelationships between clustering and the financial and investment flows of enterprises [16].

Researchers have empirically demonstrated the impact of innovation clusters on the socioeconomic stability of regions; in particular, [17] substantiates the significance of innovation-driven cluster development in the context of building the long-term competitiveness of the regional economy. At the same time, it is worth noting the importance of financial agglomeration [18] as an additional factor in improving the resilience of the regional economy [19]. Conversely, the results of the research in [20] confirm the priority for the regional economy of integrating clusters in addressing social and labor-related challenges-expanding employment opportunities for the local population, improving working conditions, and ensuring the intellectualization and productivity of labor, among other things. For the most part, researchers focus on individual aspects of the impact of clustering on the regional economy without analyzing its full scope and subsequently developing scenario-based forecasts.

Scientific research is increasingly focusing on the use of economic-mathematical approaches, which enable a qualitative transition from description to formalized modelling of processes of spatial and sectoral interaction. For example, [21] substantiates the importance of accounting for uncertainty and the dynamics of the regional economy by applying fuzzy clustering algorithms to the modelling of spatial development.

In the context of refining the methodology for economic and mathematical modelling of the development of cluster associations, the importance of using standard machine learning algorithms is growing. For example, in [22], the practical value of applying the K-means algorithm to establish an objective assessment of regional economic development and its potential in the context of creating cluster associations has been demonstrated. It is also important to emphasize the significance of taking into account additional conditions for the clustering of the regional economy, which requires the use of economic-mathematical algorithms with a focus on identifying mechanisms and tools to support the functioning of cluster associations [23].

Researchers are also devoting considerable attention to the development of clustering mechanisms and the identification of internal factors influencing the functioning and development of clusters. Thus, [24]

investigates the interrelationships between knowledge spillover effects and the technological structure of clusters. The authors of [25] focus on assessing the digital potential of innovation-active clusters, [26] – on production ability and economic growth of clusters, whilst [27] – on practical approaches to analyzing regional logistics within clusters. Although such researches provide a thorough analysis of the internal organizational characteristics of cluster associations' development, this does not allow for the formulation of a comprehensive scientific and methodological approach to the quantitative assessment of their impact on the regional economy.

Among Ukrainian researchers, the issues of economic modernization and the development of cluster associations are being actively studied in the context of determining the adaptability of regions to contemporary transformations. In [28, 29], attention is focused on aligning structural changes with digital transformations as a systemic factor in enhancing the economy's competitiveness. At the same time, the sustainability of such transformations is largely linked to financial and economic security. In [30], the importance of establishing cluster linkages between economic sectors is demonstrated as a tool for ensuring the financial and economic security of priority sectors, including with due regard for regional characteristics. In other researches [31], the issue of modelling the development of cluster associations and the regional economy encompasses the processes of innovation and marketing initiatives by enterprises engaged in core economic activities, the results of which form the gross regional product.

At the same time, the effective functioning of clusters requires appropriate organizational and accounting support. It is precisely these aspects that are highlighted in researches examining the specific characteristics of IT clusters [32] and cluster structures in general [33]. Attention should also be paid to the practical aspects of applying cluster analysis, in particular the use of its tools to improve the efficiency of managing commercial [34], manufacturing [35] and other areas of business activity and solving organizational and economic problems at enterprises [36].

A synthesis of the results of the analysis of scientific research provides grounds for noting the existence of conceptual and practical contradictions in approaches to modelling the development of cluster associations and assessing their impact on the socio-economic growth of regions and the state. In this regard, this research puts forward the hypothesis that the effectiveness of cluster development in the regions of Ukraine is determined by the multilevel interaction of numerous factors. At the same time, the application of economic and mathematical tools makes it possible to quantitatively assess these interrelationships and forecast potential scenarios for the development of clusters within the regional economy.

The object of research is the process of cluster association development in the regional economy and the economic-mathematical tools used for its modelling.

The aim of research is to develop and justify a multi-level approach to modelling the development of cluster associations in the regional economy, based on the application of economic and mathematical tools.

To achieve the stated aim, the following objectives have been identified:
– to analyze the potential of regions and the sectoral specialization of cluster associations;
– to carry out econometric modelling of the impact of cluster associations on the development of the regional economy;
– to formulate scenarios for the provision of resources to support the development of cluster associations in the regional economy;
– to carry out scenario-based modelling of the impact of existential challenges and advantages on the development of cluster associations within the regional economy.

2. Materials and Methods

Based on the synthesis of theoretical and methodological foundations of modelling cluster development within the regional economy, the necessity of adopting a multilevel approach has been established. Each stage of this approach requires the selection and application of appropriate mathematical tools, taking into account the specific objectives and research tasks (Fig. 1).

The systemic nature, precision, and flexibility of modelling are ensured through the application of diverse mathematical tools. At the structural-analytical level, this enables comprehensive identification of cluster participants, their structural classification, and analysis of internal interactions. At the evaluative-analytical level, the focus shifts to assessing the state and performance of the cluster association and identifying reserves for its dynamic growth. At the forecasting and modelling level, it is crucial to develop alternative scenarios for the development of cluster associations that take into account the specific characteristics of the regional economy. Conversely, at the monitoring and adjustment level, it is appropriate to monitor, promptly identify, and adjust management decisions in order to maintain the stability and sustainability of cluster development within the regional economy.

Stages of Modelling	Methodological tools	Objectives and Application Tasks
Structural-Analytical Level		
Identification and structural analysis of participants	– matrix analysis; – data typology; – structural analysis	– identification of regional types with key challenges and favourable conditions for the development of cluster associations; – identification of differences and interdependencies between the characteristics of regional economies
Selection of the object of empirical modelling	– comparative analysis; – structural-dynamic analysis; – complementary analysis	– characterisation of the structure and dynamics of cluster associations' functioning; – selection of a specific cluster association as the object of economic-mathematical modelling
Evaluative-Analytical Level		
Assessment of state and performance	– structural-temporal analysis; – comparative analysis; – comparative analysis	– comparative assessment of the performance of a cluster association; – identification of factors influencing the development of a cluster association
Scenario modelling of development	– regression analysis; – statistical estimation of model parameters; – residual analysis	– quantitative assessment of the interrelationships between the performance indicators of a cluster association and the development of the regional economy; – forecasting the performance and economic impact of a cluster association in the region; – characterisation of development scenarios for a cluster association
Evaluative-Analytical Level		
Monitoring and model adjustment	– scenario analysis; – SWOT analysis	– assessment of the impact of external and internal factors on the development of cluster associations; – refinement of scenarios and adjustment of the directions for implementing cluster initiatives

Fig. 1. The methodological basis for modelling the development of cluster associations in the regional economy: an applied perspective

ISSN-L 2664-9969; E-ISSN 2706-5448

For the purpose of a comprehensive analysis of the regional economy, it is appropriate to integrate quantitative methods with elements of scenario modelling. Accordingly, there is a growing need to study internal linkages within a cluster and to take into account the impact of external trends, in particular the state and dynamics of the regional economy. Economic-mathematical modelling makes it possible to objectively draw conclusions about the intensity of the impact of internal and external factors on the development of cluster associations, which can serve as a basis for developing strategic programs for their operation, taking regional aspects into account. At the same time, the identification of such factors must be accompanied by the determination of indicators, which values make it possible to identify expected positive or negative changes (Table 1).

Table 1

A list of factors influencing the development of a cluster association: an applied perspective

Factors	Indicators	Impact (PST/NEG)
Profitability of business processes	Profitability of activities	PST
Efficiency of resource utilization	Asset utilization ratio	PST
Stability of cash flows	Financial stability ratio	PST
Independence from external financing	Autonomy ratio	PST
Level of business activity	Current assets turnover ratio	PST
Return on invested capital	Return on equity	PST
Development of internal resource potential	Current assets to equity ratio	PST
Investment activity	Capitalization level	PST
Level of unpredictability and risk resilience	Financial risk ratio	NEG
Development of the customer base	Product sales index	PST
Efficiency of organization and work standards	Labor productivity	PST

Note: PST – positive; NEG – negative

This list of factors makes it possible to reliably substantiate the specific characteristics of the regional economy, which stability and sustainability are primarily determined by profitability, investment and business activity, and other performance indicators of local businesses. Undoubtedly, creating the necessary infrastructure to increase the volume of entrepreneurial activity and foster cooperation not only has a positive impact on the state of local business but also establishes the necessary conditions for forming associations within the regional economy that are capable of flexibly adapting to existential challenges and maintaining the competitiveness of the region. Combining this approach with economic and mathematical tools creates the necessary foundation for the well-founded development and implementation, at the regional economic level, of a cluster policy that clearly defines scenarios and response measures for the aforementioned changes.

3. Results and Discussion

3.1. Analysis of regional potential and sectoral specialization of cluster associations

The matrix analysis carried out not only made it possible to compare the potential of individual groups of regions in Ukraine with factors that either facilitate or hinder the development of cluster associations, but also established that the effectiveness of clustering is determined by the complex interplay of a region's resource potential, institutional environment and level of development of its innovation infrastructure (Table 2).

Table 2

Matrix-based assessment of cluster association development in Ukraine: alignment of regional typologies with key challenges and enabling conditions

Barriers and Challenges		Types of Regions	Favorable Preconditions for Development	
– Insufficient funding for research activities	H	Regions specializing in innovation and technological development	H	– Presence of universities and research centers
– Outflow of young professionals	H		M	– Active participation in international projects and partnerships
– Fragmentation of innovation initiatives	M		L	– Growing interest of small businesses in innovation
– Limited suitability of material and technical resources	H	Regions with industrial potential	H	– Developed production infrastructure
– High level of energy dependence	M		H	– Presence of technoparks and industrial zones
– Difficulties in modernization and innovation implementation	H		H	– High qualification of technical personnel
– Insufficient integration with small businesses	L		L	– Availability of local innovation initiatives
– Limited access to investment resources	H	Regions with agro-industrial potential	H	– Access to raw materials and land resources
– Underdeveloped processing infrastructure	M		M	– Development of agricultural cooperatives
– Volatility of the local agricultural market	M		M	– State support for the agro-industrial complex
– Bureaucratic and regulatory barriers	H	Regions with cross-border and logistics potential	H	– Favorable geographic location
– Incomplete infrastructure projects	M		H	– Presence of transport corridors and logistics hubs
– Elevated security risks	H		M	– Developed cross-border cooperation
– Insufficient local support for small logistics and transport businesses	L		L	– Presence of local small business potential for logistics sector development
– Seasonality of tourist flows	H	Regions with tourism and recreational potential	H	– Diversity of natural and recreational resources
– Insufficient diversification of tourism clusters	M		H	– Significant historical and cultural heritage
– Low quality of local services and weak territorial marketing	M		M	– Development of creative economy sectors
– Insufficient coordination among small businesses in the tourism sector	L		L	– Individual local initiatives of entrepreneurial cooperation

Note: Impact levels **H** – high, **M** – moderate, **L** – low

An advantage of this matrix analysis is that it takes into account different types of regions – those specializing in innovation and technological development, industrial potential, agro-industrial potential, cross-border and logistical potential, and tourism and recreational potential – which enables a comprehensive characterization of clustering processes in the regional economy in terms of identifying the constraints and favorable conditions for their formation and implementation.

It is noteworthy that, within the structure of cluster associations in Ukraine's regional economy, IT clusters specializing in the digital transformation of local businesses play a key role (Table 3). Given the number of participants, it is worth highlighting the active development of the Lviv IT Cluster, the Ivano-Frankivsk IT Cluster, the Kharkiv IT Cluster and the Kyiv High-Tech Cluster, which focus on various sectors of the economy – medicine, education, financial technologies and others. At the same time, their activities are closely linked to the development and implementation of smart city projects, in which significant importance is attached to the deployment of intelligent systems for the purpose of monitoring, analyzing and controlling urban infrastructure.

In addition, these clusters actively implement smart city initiatives aimed at improving the quality of the urban environment through the deployment of intelligent systems for transportation management, energy consumption optimization, and public utilities administration.

In Ukraine, regions are developing industrial and agro-industrial clusters; however, the pace of their development depends on the specific characteristics of local economies and the availability of appropriate infrastructure. One of the most illustrative examples of successful cluster development is the IT cluster in Lviv, which integrates IT companies, educational institutions, and local authorities to advance digital technologies and create favorable conditions for entrepreneurs and investors. Lviv IT Cluster has become a prominent example of cooperation among academia, business, and local government, contributing to talent development and increasing regional income. The results obtained are fully consistent with recent research on cluster policy, which emphasizes the key role of IT clusters in ensuring the competitiveness of regions.

The limitations of research relate to the use of generalized regional characteristics and the available information on the functioning and development of cluster associations; as a result, it is not possible to fully account for intra-regional differences in clustering processes. Therefore, further research should focus on expanding the spatial-territorial analysis of network interactions among members of cluster associations, which will require the application of spatial econometrics and network modelling.

3.2. Econometric modelling of the impact of cluster associations on the development of the regional economy

A comparative and structural-temporal analysis of the activities of the Lviv IT Cluster in 2020–2024 has established that the gross regional product (GRP) of the Lviv region is largely shaped by the development of cluster associations. This confirms that the IT cluster acts as a regional econometric multiplier – not only driving growth in the IT sector but also stimulating the development of related industries in the region.

The modelling results presented in Table 4 show that operating profitability, return on equity, capitalization ratio, financial risk level and sales growth rate have a substantial and statistically significant positive impact on GRP per employed person in the region. By contrast, other factors exhibit a lower level of statistical significance ($p > 0.10$), which is attributable to the specific characteristics of internal financial and economic processes within the cluster association; the dynamics of these processes across different time periods lead to either a weakening or a strengthening of their impact on the regional economy. Consequently, there is increased uncertainty in the organization of joint projects between public authorities and cluster associations, the expected outcomes of which may not be achieved.

Based on the calculations performed using EViews software, the following multiple linear regression equation was obtained

$$GRP/E_t = \underset{(2.251^{**})}{1.571} PROF_t + \underset{(5.480^{*})}{0.451} ROE_t + \underset{(3.988^{*})}{2.508} CL_t - \underset{(-4.967^{**})}{0.899} FRR_t + \underset{(2.455^{**})}{1.918} PSI_t, \quad (1)$$

$$R^2 = 0.819;\ Fstatistic = 25.505;\ p < 0.0001;\ Std.Error = 4.882;\ DW = 2.081$$

where GRP/E_t – gross regional product per employed person in period t; $PROF_t$ – profitability of activities in period t; ROE_t – return on equity in period t; CL_t – capitalization level in period t; FRR_t – financial risk ratio in period t; PSI_t – product sales index in period t.

Table 3

Cluster associations in the regional economy of Ukraine as of January 1, 2025

Cluster Name (Year of Establishment)	Number of Members	Key Specializations	Region
All-Ukrainian Association of Innovation and Space Clusters (2014)	130	Aerospace development, defense-related innovation	Odesa Region
IRON Lviv Tech Cluster (2021)	71	Aerospace technologies, engineering and hardware startups	Lviv Region
Lviv IT Cluster (2011)	461	Development and implementation of regional educational innovation projects, smart city initiatives, digital infrastructure	Lviv Region
Ukrainian dual-use technologies cluster (2022)	12	Dual-use technologies for defense and civilian sectors	Kyiv (city)
International Agricultural and Tourists Cluster "Dniester 1362" (2018)	35	Agro-food sector, rural green tourism	Chernivtsi Region
Interregional union of poultry breeders and fodder producers (2016)	41	Poultry farming, animal feed production	Multiple regions
Ukrainian food association "U-food" (2015)	92	Food industry, innovation in the agro-industrial complex	Nationwide
Ivano-Frankivsk IT Cluster (2017)	47	Software development, development of local IT community	Ivano-Frankivsk Region
Ukrainian industrial cluster (2020)	12	Digital transformation of industry	Kharkiv (city)
Kharkiv IT Cluster (2015)	617	Information technologies, educational initiatives, smart city projects	Kharkiv Region
Kyiv high-tech cluster (2021)	12	Innovative technologies, consulting, creative economy	Kyiv (city)

Note: compiled based on [37–39]

ISSN-L 2664-9969; E-ISSN 2706-5448

Table 4

Results of the multiple linear regression model assessing the impact of Lviv IT Cluster on the economy of Lviv Region (Ukraine), 2020–2024

Variables	Coefficient	Standard Error	*t*-Statistic	*p*-Value
PROF – profitability of activities	1.571	0.606	2.591	0.031**
AE – asset efficiency	0.750	0.195	3.840	0.897
FS – financial stability	–0.125	0.045	–2.764	0.623
AR – financial autonomy	0.344	0.050	6.907	0.390
CAT – current asset turnover	0.100	0.014	7.020	0.382
ROE – return on equity	0.451	0.082	5.480	0.074*
OFCA – own funds coverage of current assets	0.143	0.017	8.202	0.544
CL – capitalization level	2.508	0.629	3.988	0.024**
FRR – financial risk ratio	–0.899	0.191	–4.697	0.081*
PSI – product sales index	1.981	0.807	2.455	0.029**
LP – labor productivity	0.054	0.013	4.017	0.882
Model Summary Statistics				
Coefficient of Determination				0.819
Adjusted Coefficient of Determination				0.752
Root Mean Squared Error of the Regression				1.905
Standard Deviation				4.882
Fisher's F-statistic				25.505
Akaike Information Criterion				3.066
Schwarz Information Criterion				3.201
Durbin-Watson Test Statistic				2.081

Note: The sample includes the largest enterprises which combined share in total cluster output exceeds 50%; **, * – statistical significance at the 1%, 5% and 10% levels respectively. Author's calculations based on EViews software (IHS Markit, USA)

It is worth noting that the multiple regression model developed takes into account the specific characteristics of the regional industrial environment, in which the role of the IT sector is becoming increasingly significant. Unlike most researches, which primarily analyze individual indicators of cluster performance or their sectoral structure, the proposed approach enables a comprehensive assessment of the effect of clustering by integrating the cluster's financial indicators with the region's economic indicators.

Fig. 2 indicates that the model residuals do not exhibit pronounced autocorrelation or abnormal structural patterns, thereby confirming the adequacy of the applied model for assessing the impact of Lviv IT Cluster's activities on the gross regional product of Lviv Region. The majority of residual values are concentrated near zero, within the interval from –0.1 to 0.1, while extreme values occur infrequently. Both the mean and median of the residuals are close to zero, suggesting the absence of systematic bias in terms of overestimation or underestimation of the modeled results.

Furthermore, the residual distribution of the model assessing the impact of Lviv IT Cluster's activity on the gross regional product of Lviv Region exhibits slight positive skewness (skewness = 0.1089), indicating an almost symmetric distribution. The kurtosis value (kurtosis = 2.2567) falls within acceptable recommended limits, confirming the relatively uniform distribution of the modeled variables. The Jarque-Bera normality test indicates no statistically significant deviation from normality of the residuals.

Based on Table 5 and 6, it can be concluded that the constructed factor model assessing the impact of Lviv IT Cluster on the gross regional product of Lviv Region demonstrates an adequate level of goodness of fit and provides a satisfactory correspondence with the observed data.

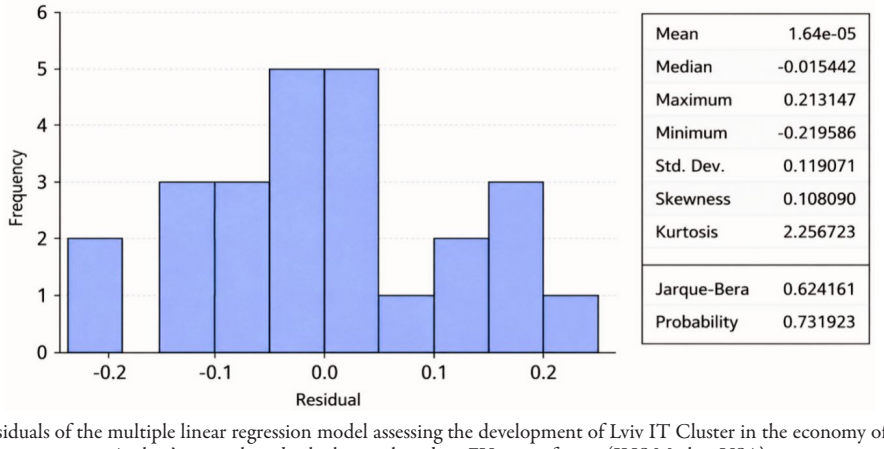

Fig. 2. Histogram of residuals of the multiple linear regression model assessing the development of Lviv IT Cluster in the economy of Lviv Region, Ukraine. Author's research and calculations based on EViews software (IHS Markit, USA)

Table 5

Absolute model fit indices of the multiple linear regression specification assessing the impact of Lviv IT Cluster on regional economic performance in Lviv Region, Ukraine

Indicators	Baseline Regression Model	Standard Regression Model with Independent Variables	Full Model Considering All Possible Relationships
Variance	2.455643	48.87186	0.000000
Statistic χ^2	58.935440	1172.925	–
Probability χ^2	0.000100	0.000000	–
Bartlett's Statistic χ^2	40,51812	936.7106	–
Bartlett's Probability	0.018800	0.000000	–
Root Mean Square Residual (*RMSR*)	0.002171	0,893064	0.000000
Akaike Information Criterion	0.437418	41.63698	0.000000
Schwarz Information Criterion	–0.732703	38.41918	0.000000
Hannan–Quinn Criterion	0.112876	40.74449	0.000000
Expected Cross-Validation Index (*ECVI*)	6.955643	49.87186	6.500000
Goodness-of-Fit Index (*GFI*)	0.796679	0.102321	1.000000
Adjusted *GFI*	0.339207	–1.917458	–
Non-Centrality Parameter	34.93544	1106.92500	–
Gamma Hat	0.578763	0.041561	–
McDonald's Non-Centrality Index	0.482960	9.66E-11	–
Root Mean Square Error of Approximation (RMSEA)	0.246276	0.838952	–

Note: Author's research and calculations based on EViews software (IHS Markit, USA)

Table 6

Incremental model fit indices of the multiple linear regression model assessing the impact of Lviv IT Cluster on the economic performance of Lviv Region, Ukraine

Fit Indices	Baseline Regression Model	Standard Regression Model with Independent Variables	Full Model Considering All Possible Relationships
Relative Fit Index (*RFI*)	0.861822	–	–
Normed Fit Index (*NFI*)	0.949753	–	–
Non-Normed Fit (Tucker–Lewis) Index (*NNFI*)	0.913208	–	–
Incremental Fit Index (*IFI*)	0.969593	–	–
Comparative Fit Index (*CFI*)	0.968439	–	–

Note: Author's research and calculations based on EViews software (IHS Markit, USA)

The probability of χ^2 (0.0001) indicates statistically significant deviations of the model from an optimal variable specification, while the Bartlett test probability value (0.0188) confirms the model's suitability for practical application in supporting cluster development. In addition, the low value of the Root Mean Square Residual (*RMSR* = 0.0217) suggests a satisfactory level of parameter estimation quality within the mathematical modelling framework of regional economic clusterization.

Fig. 3 demonstrates that the development model of Lviv IT Cluster in the economy of Lviv Region adequately captures the dynamic influence of the selected actors, while forecasting errors appear to be randomly distributed. The deviations between actual and estimated values, reflected in the fluctuations of the residual line, do not exhibit a systematic pattern. This confirms the absence of a pronounced trend in the forecasting errors and supports the reliability of the model in assessing the development of Lviv IT Cluster within the regional economic context.

It is noteworthy that the actual and predicted value trajectories appear largely parallel, demonstrating a similar upward trend throughout most of the analyzed period. This indicates a relatively high level of predictive accuracy of the model describing the development of Lviv IT Cluster within the economy of Lviv Region. The obtained results further confirm that the multiple linear regression specification constitutes an appropriate analytical instrument for assessing the impact of Lviv IT Cluster development on key economic indicators of Lviv Region. The corresponding residual and difference matrices provide additional evidence of the statistical reliability and robustness of the selected mathematical modelling framework. This supports the applicability of the model for subsequent forecasting of cluster development dynamics and regional economic performance.



Fig. 3. Comparison of actual and predicted values and residuals of the multiple linear regression model evaluating the development of Lviv IT Cluster in the economy of Lviv Region, Ukraine. *A*uthor's research and calculations based on EViews software (IHS Markit, USA)

ISSN-L 2664-9969; E-ISSN 2706-5448

The results obtained, on the one hand, are consistent with the findings of many researches regarding the positive impact of IT clusters on regional economic growth, and, on the other hand, update the conceptual understanding of the significance of cluster development in the regional economy, as confirmed by econometric calculations using EViews software.

At the same time, the researches is limited to a sample of the largest cluster in the region and the period under consideration; consequently, applying the proposed approach in the context of other regions or clusters may prove challenging. It is therefore advisable to direct further research towards expanding the sample of cluster associations and assessing the long-term effects of clustering in the context of Ukraine's post-war economic recovery.

3.3. Scenarios for the provision of resources to support the development of cluster associations in the regional economy

Given these considerations, the modelling results for the development trajectory of Lviv IT Cluster are presented in Fig. 4.

According to the optimistic scenario, the impact of clustering on regional economic development is projected to increase through higher investment activity, the expansion of modernization efforts, and the active implementation of a collaborative approach to business development. Under this scenario, a 10% increase in the profitability of the Lviv IT cluster is statistically linked to a 0.045% increase in the GRP per employed person of the Lviv region. Conversely, a 1% increase in the cluster's return on equity is statistically associated with a 0.013% decrease in GRP per employed person. Conversely, a 1% increase in the cluster's financial stability is statistically associated with a 0.07% increase in GRP per employed person. These scenarios confirm the significance of these interrelationships in the context of creating an integrated IT ecosystem on the scale of the regional economy.

With regard to the pessimistic scenario, concerns arise regarding a decline in the IT cluster's performance and a deterioration in the quality of relationships among its participants. Thus, a decline in the profitability of the Lviv IT cluster could reduce the Lviv region's GRP per employed person by 0.023%. A decrease in GRP per employed person (by 0.012%) can also be expected in the context of a 3% decline in the IT cluster's ability to finance its current assets with its own funds. Financial risks are increasing in the region's economy as the cluster's autonomy deteriorates; specifically, for every 2% decline in this indicator, GRP per employed person decreases by 0.066%. An additional factor slowing the economic development of the Lviv region is the decline in the asset turnover ratio of the Lviv IT cluster; specifically, every 1% decrease in this ratio causes a 0.018% decline in GRP per employed person.

It has also been established that the key financial indicators of the Lviv IT Cluster's operations have a significant impact on GRP per employed person. Specifically, a 1% increase in corporate profitability leads to a 0.045% increase in GRP per employed person, while an increase in the autonomy ratio results in a 0.033% increase. The high significance of the ratio of equity to current assets (impact of 0.040%) underscores the importance of liquidity in an unstable environment.

The results of the comprehensive scenario-based modelling of cluster development in Ukraine's regional economy suggest that strategic assessment should be grounded in the evaluation of key resource dimensions, including financial-investment, intellectual-human capital, infrastructural, innovation-technological, institutional-regulatory, and socio-partnership components (Table 7). Thus, identifying several scenarios for the development of cluster associations – optimistic, baseline and pessimistic – makes it possible, on the one hand, to project the dynamics of the creation and operation of clusters and, on the other, to identify potential risks and threats to the regional economy. Accordingly, the advantage of this approach is that it facilitates the high-quality development and implementation of regional strategies and programs for the development of cluster associations in Ukraine.



Fig. 4. Scenario-based forecast of performance indicators of Lviv IT Cluster in the Economy of Lviv Region, 2025–2027: *a* – Profitability of activities; *b* – Return on equity; *c* – Capitalization level; *d* – Financial risk ratio; *e* – Sales Performance Index (*The sample includes the largest enterprises, which combined share in the total cluster sales volume exceeds 50.0%. Author's research and calculations based on EViews software (IHS Markit, USA))

Table 7

Scenarios and expected results of modelling resource provision for the development of cluster associations in Ukraine's regional economy

Resource Provision Dimension	Modelling Scenario			Expected Outcomes		
	Optimistic	*Baseline*	*Pessimistic*	*Optimistic*	*Baseline*	*Pessimistic*
Financial-Investment	High financial-investment activity	Moderate financial-investment activity	Insufficient financial-investment activity	↑ increased innovation activity among local businesses; ↑ increased modernization of business processes in the local market; ↑ expansion of the cluster association's areas of activity	↔ stable development of the regional economy ↔ support for the cluster association's local business projects; ↔ maintaining the cluster association's competitive position	↓ slowdown in the development of the regional economy; ↓ limitations on the scope of modernization in the local market; ↓ decline in the cluster association's investment activity
Intellectual-Human Capital	Intensive development and attraction of personnel	Preservation of current professional qualification level	Outflow of qualified personnel; reduction of staffing levels	↑ increasing the level of intellectualization of the regional economy; ↑ improving the professional skills and abilities of cluster personnel; ↑ building a pool of intellectual and human resources to implement innovative cluster initiatives	↔ supporting the stability and sustainability of the local labor market; ↔ retaining highly qualified personnel within the cluster association; ↔ gradual renewal of the cluster association's intellectual and human resources	↓ decline in the intellectual and human resource potential of the regional economy; ↓ slowdown in the professional development of the cluster association's personnel
Infrastructural	Modernization and development of local infrastructure	Maintenance of existing infrastructure	Deterioration of local infrastructure	↑ improvement in the quality of business services in the region; ↑ expansion of the local network of warehouses and retail spaces; ↑ creation and modernization of local logistics and transportation hubs	↔ maintenance of current logistics and transportation capacities in the region; ↔ support for the stable operation of regional infrastructure facilities; ↔ limited modernization of the region's infrastructure facilities	↓ decreased availability of local logistics and retail space; ↓ decreased functionality of regional infrastructure facilities; ↓ increased logistics and transportation costs for local businesses
Innovation-Technological	Active implementation of new technologies	Moderate implementation of innovations	Absence of technological renewal	↑ development of innovative and high-tech local businesses; ↑ adoption of innovations and technologies by cluster associations; ↑ strengthening of innovation and technology integration within cluster associations	↔ limited modernization of the region's innovation and technology infrastructure; ↔ maintaining the current level of innovation and technology activity in cluster associations; ↔ supporting the stable and sustainable operation of cluster associations without innovation and technology breakthroughs	↓ worsening of the regional economy's innovation and technology gap; ↓ weakening of the innovation and technology potential of cluster associations; ↓ decrease in the attraction of innovation and technology resources by cluster associations
Institutional-Regulatory	Favorable regulatory and institutional support	Moderate state support	Absence of effective institutional support	↑ expansion of areas of partnership between the state, local governments, and business; ↑ ensuring transparency in regulatory processes in the region; ↑ simplifying procedures for conducting business	↔ moderate improvement in cooperation between business, central government, and regional authorities; ↔ moderate stability of the system of government regulation of business	↓ increased administrative barriers to the development of cluster associations; ↓ increased corruption risks in the region; ↓ deterioration in the quality of public services in the region
Socio-Partnership	Active expansion of areas of collaboration and cooperation	Maintenance of stable cooperative ties	Absence of coordination and partnership linkages	↑ establishing new partnerships and expanding areas of cooperation in the regional economy; ↑ developing a cluster ecosystem in the region; ↑ increasing the level of trust and social interaction among members of cluster associations	↔ maintaining a stable level of cooperation in the regional economy; ↔ moderate exchange of knowledge and experience among participants in cluster associations; ↔ support for existing partnership-based cluster initiatives	↓ limitation of potential and loss of opportunities for the development of cluster associations; ↓ decrease in the social activity of cluster associations in the regional economy

The results of the scenario analysis of cluster associations in Ukraine's regional economy have confirmed the importance of investment activities aimed at building up innovation and technological potential and expanding areas of cross-sectoral cooperation. At the same time, it is important to take into account the significance of state support and the involvement of local authorities, particularly at all stages of cluster development – from initiation to scaling up.

Unlike other approaches, which primarily focus on assessing the impact of individual factors, the results of the scenario enable to simultaneously take into account the specific characteristics of various areas of cluster development within the regional economy – financial and investment, intellectual and human resources, infrastructure, innovation and technology, institutional and regulatory, and social and partnership.

A significant practical outcome of such modelling is the development of tools for monitoring and evaluating the strategic management system. Consequently, it is possible to draw conclusions regarding the extent to which clustering objectives have been achieved; these serve as a basis for revising the associations' development plans and can be used by regional authorities to adjust the direction of economic development policy.

Furthermore, the results obtained are consistent with contemporary concepts of scenario modelling for the development of cluster associations within the regional economy. The key distinction of the author's approach lies in conducting a comprehensive analysis of the resource base for the development of a cluster association; based on the results of this analysis, it is possible to develop scenarios for the

ISSN-L 2664-9969; E-ISSN 2706-5448

adaptation of the regional economy in the context of information and technology trends.

At the same time, scenario modelling is of paramount importance in the context of long-term planning for the development of cluster associations in the regional economy. This involves the preparation of analytical reports and their continuous updating to take account of internal and external factors, with the main emphasis placed on comparing the current state with expected outcomes. Accordingly, it is possible to identify both missed opportunities for accelerating the growth of cluster associations and reserves that are important in the context of adapting to new existential challenges.

However, the results of scenario modelling do not take into account the impact of a significant number of possible external changes – frequent reforms of state regulatory policy, the unpredictability of the geopolitical situation, and so on – the impact of which is quite difficult to predict, as the effects are only evident in the long term. As a result, cluster associations often have to update their mechanisms for adapting to external trends and adjust their risk resilience policies, particularly to prevent a decline in performance.

Looking ahead, it is worth considering the integration of scenario modelling with agent-based models and digital platforms, which significantly simplify the processes of gathering and processing information; in this context, cluster management is able to promptly adjust management decisions and respond swiftly to changes in the regional economy.

3.4. Scenario-based modelling of the impact of existential challenges and advantages on the development of cluster associations within the regional economy

The simulation-based analysis of existential challenges and advantages in the projected development of cluster associations can serve as a basis for formulating a comprehensive strategy for the socio-economic development of Ukraine's regions (Table 8). In particular, the use of the SWOT analysis methodology has made it possible to identify key existential challenges and existential advantages, a list of which is of great value in the context of implementing joint projects involving clusters, public authorities and representatives of other forms of business. The results obtained demonstrate that the development of cluster associations is linked to the ability of their members to adapt to contemporary challenges on the basis of available resources and existing market opportunities.

The scenarios developed to minimize risks and strengthen the development potential of cluster associations form a set of scenario-based optimization measures which take into account a range of interrelated factors and various possible options for striking a balance between risks and opportunities, and are geared towards maintaining the socio-economic stability and sustainability of the regions. A key stage of simulation modelling is to analyze the impact of scenario-based optimization measures on the key performance indicators of clusters. The main areas of such planning include crisis-response scenarios, the retention and return of specialists, human capital and staff qualifications, public-private partnership and funding mechanisms, educational programs, and so on.

At the same time, the results of simulation modelling of cluster associations in the regional economy depend on the comprehensiveness of the information available, the relevance of expert assessments and assumptions regarding trends in the external environment. Therefore, further research should focus on expanding the simulation model of cluster development in the regional economy through the use of artificial intelligence and big data technologies.

Table 8

Simulation-based framework of existential challenges and strategic advantages in the projected development of cluster associations in the regional economy of Ukraine

SWOT Analysis Results			*Recommendations for Mitigation / Strengthening*	*Expected Outcomes for the Regional Economy*
Existential Challenges	Threats	* geopolitical fluctuations and loss of external markets; * inflationary pressure and macroeconomic instability; * demographic decline and labor migration abroad; * significant technological breakthroughs of competitors and limited competitive advantages; * deterioration of environmental conditions	⁕ development and implementation of anti-crisis cluster development scenarios; ⁕ creation of conditions for retention and return of professionals to the region; ⁕ investment in human capital development and workforce upskilling; ⁕ active implementation of modern environmental standards and technologies	⁂ reduction of socio-economic risk exposure; ⁂ preservation and strengthening of local intellectual and human capital; ⁂ increased resilience and adaptability of local businesses; ⁂ reduction of economic losses from external shocks
	Weaknesses	* territorial and sectoral imbalance in cluster development; * shortage of managers with strategic cluster management experience; * obsolete material and technical base; * limited resources for innovation and modernization	⁕ introduction of public-private partnership mechanisms for financing innovation and technological activities; ⁕ implementation of targeted training programs for cluster managers; ⁕ modernization of production and technological infrastructure	⁂ reduction of interregional socio-economic disparities; ⁂ improvement of cluster governance quality; ⁂ strengthening of production base and growth of regional investment attractiveness
Existential Advantages	Opportunities	* market and product diversification; * strengthening international cooperation with research and educational institutions; * development of green technologies and sustainable production	⁕ integration into international value-added chains; ⁕ support of cluster initiatives in global markets; ⁕ enhancement of innovation and environmentalization of production	⁂ creation of new jobs in local markets; ⁂ attraction of investment to local innovation projects; ⁂ increased resilience of the regional economy to crises
	Strengths	* expansion of communication and cooperation networks among business, research institutions, educational institutions, and public authorities; * regional support for cluster initiatives; * development of export potential; * active implementation of digital technologies	⁕ expansion of intersectoral cooperation and integration into high value-added sectors; ⁕ acceleration of commercialization of research outcomes; ⁕ creation of local high-tech hubs supporting cluster initiatives; ⁕ promotion of digital transformation among cluster participants	⁂ increase in innovation and technological activity of local businesses; ⁂ formation of competitive sectors within the regional economy; ⁂ growth in export volumes of local products

3.5. Discussions

Interpreting the results of the multilevel modelling of cluster development in the regional economy of Ukraine, it is appropriate to conclude that the proposed hypothesis has been confirmed regarding the decisive role of the integrated interaction among financial-investment, institutional, innovation-technological, and other determinants. The results obtained confirmed that the functioning and development of clusters depend on sectoral specialization, the quality of the institutional environment, the number of participants, and the status and trends of their activities.

The conclusions drawn complement the findings of other scientific researches. Thus, the scientific and methodological provisions developed are consistent with researches [1, 2], which emphasize the importance of expanding the scope of clustering and the concentration of business associations from various sectors within specific territories. In this context, it has been demonstrated that in regions with a high concentration of research centers, technology parks, and other associations, the economy develops quite dynamically. However, in the Ukrainian context, this is insufficient to form a stable and sustainable regional economy based on the potential of cluster associations. The full-scale war prevents regions from fully reaping all the benefits of cluster development.

The results obtained are consistent with researches [4, 20], which have demonstrated the interrelationships between the specialization of cluster associations and increases in productivity and employment among the local population. At the same time, clusters are capable of encompassing various types of economic activity and facilitating the creation of new jobs within them. Conversely, the correlation between the development of human capital in the regional economy and the performance of a cluster association is exacerbated by a significant shortage of skilled workers and specialized professionals. This imbalance has a significant cumulative effect – slowing the development of clusters, worsening the state of the regional economy, and fueling uncontrolled structural transformations.

The author's proposals are consistent with the findings of researches [3, 5, 11], which highlight the challenges of creating high-tech clusters capable of forming innovation ecosystems, particularly at the regional economic level. In particular, Ukraine's IT clusters possess sufficient experience in initiating the implementation of entirely new types of business processes characterized by a high level of innovation and technological sophistication, which serve as the basis for increasing the number of competitive advantages for the regional economy. On a national economic scale, the priority of innovation and technology development is growing significantly in sectors that have limited potential for producing high-value-added goods and are dependent on imported technologies.

Certain elements of the proposals and recommendations are consistent with the conclusions of scientific researches [14, 15] regarding the importance of establishing and expanding the scope of activities of innovation and technology networks at the regional and interregional levels. Establishing horizontal and vertical partnerships is viewed as a key means of creating integrative associations, which potential enables them to support the regional economy amid uncertainty and unpredictability. At the same time, the scale of activity is one of the key indicators for assessing the development of cluster associations and the strategic directions for implementing dynamic regional policy.

This research builds upon the research in [21, 22] regarding the development of new methods and tools for analyzing and designing clustering processes, taking into account the characteristics of economic activity, the state and trends of the regional economy, and other factors. The use of modern software tools for economic-mathematical modelling is a key condition for determining the prerequisites for creating and ensuring the stability of cluster associations. At the same time, the author's assumptions are distinguished by a focus on the issues of dividing economic-mathematical tools into separate groups, each of which emphasizes the specific characteristics of cluster association development.

Furthermore, the results obtained from testing the author's methodology for economic and mathematical modelling of the development of cluster associations complement the works [13, 18, 32], which scientific value lies in identifying and studying the degree of influence of security factors. This involves specifying analysis indicators, substantiating scenarios of their impact, providing predictive assessments, and solving other tasks; by addressing these, it is possible to objectively determine the basic principles of a policy for the sustainable development of clustering processes.

Unlike many researches, the results obtained provide a sufficient foundation for the applied implementation of economic-mathematical modelling in cluster associations focused on the creation and implementation of innovative technologies. In such associations, great importance is placed on ensuring the objectivity and reliability of data, and to achieve this, it is necessary to implement methodologies based on specialized software developments. The conclusions drawn from this approach have high scientific and methodological value, as they serve as a basis for presenting updated scenarios and project calculations for the development of cluster associations within the regional economy.

The practical significance of the results obtained lies in expanding the analytical capabilities of cluster association management with regard to the application of a multilevel economic-mathematical approach to development modelling. Furthermore, the conclusions drawn have significant practical value for national and regional government bodies, local governments, and regional development agencies in the context of developing and implementing development strategies aimed at establishing partnerships with the business sector. The practice of cluster association development demonstrates the priority of cluster initiatives for the regional economy; to effectively implement these initiatives, which require a reliable information base, it is appropriate to apply economic-mathematical tools.

The methodological and scientific value of the presented indicators for assessing the development of a cluster association lies in conducting a comprehensive economic and statistical verification of the objectivity and adequacy of the constructed regression model. The use of the coefficient of determination, Fisher's F-test, t-statistic, p-value, Durbin-Watson statistic and other criteria made it possible to assess the statistical validity and suitability of the regression model of cluster association development for its subsequent scenario-based modelling.

The limitations of this research stem from the use of statistical data on the activities of a cluster association in a specific industry, which do not account for the specific characteristics of different types of clusters. At the same time, econometric and scenario modelling is based on the assumptions of adherence to the principles of statistical significance and reliability, whereas the impact of existential challenges is primarily driven by highly dynamic and unpredictable structural shifts. Another limitation of the research is its time frame, which is characterized by significant structural changes in the Ukrainian economy brought about by the COVID-19 pandemic and the full-scale military invasion. A further limitation is the research reliance on the selected set of indicators and the availability of information required for their calculation.

Prospects for further research involve integrating economic and mathematical tools, big data technologies, and scenario planning into management decision-making processes regarding the long-term development of cluster associations. It would be appropriate to supplement the research information base with a comparison of trends in the development of cluster associations in Ukraine and EU countries in order to study their practices for adapting to the impact of geopolitical hybrid threats and shocks.

ISSN-L 2664-9969; E-ISSN 2706-5448

4. Conclusions

1. Based on the results of an analysis of regional potential and the sectoral specialization of cluster associations in Ukraine, a matrix comparison was carried out between different types of regions (innovation and technology, industrial, agri-industrial, cross-border and logistics, tourism and recreation) and the key factors for the development of cluster associations. Using a matrix approach, this research systematizes the constraints (challenges) and favorable conditions for the development of cluster associations in Ukraine's regional economies, categorizing their impact into high, medium, and low levels. The results obtained are of great practical value in the processes of developing and implementing regional policies for the development of cluster associations, as they take into account the specific characteristics of each type of region.

It has been established that, as at 1 January 2025, the largest cluster associations in Ukraine include clusters specializing in the development and implementation of information technologies – the Kharkiv IT Cluster (617 members) and the Lviv IT Cluster (461 members).

2. An econometric model analyzing the impact of cluster associations on regional economic development was constructed using the Lviv IT Cluster and the Lviv region as case studies. Using EViews software, a multiple linear regression model was developed to examine the relationships between the performance indicators of the Lviv IT Cluster and the GRP per employed person of the Lviv region. It has been concluded that the development of cluster associations has a statistically significant regression effect on the dynamics of the regional economy.

Unlike typical econometric approaches, the developed model makes it possible to comprehensively determine the interrelationships between indicators of cluster association development and key changes in the regional economy. The practical significance of the authors' methodology lies in its application to the analysis of the current state and development trends of cluster associations, which impact on the regional economy is growing ever stronger.

The adequacy and reliability of the proposed methodology are confirmed by statistical indicators (R^2 = 0.819; adjusted R^2 = 0.752; F = 25.505; DW = 2.081) and high goodness-of-fit indices (NFI = 0.950; CFI = 0.968; IFI = 0.970).

3. Scenarios for the resource provision required for the development of cluster associations within the regional economy have been identified – optimistic, baseline and pessimistic – covering the financial and investment, intellectual and human resources, infrastructure, innovation and technology, institutional and regulatory, and social partnership areas.

Unlike other researches of this kind, the proposed scenario-based approach comprehensively covers the key processes of resource provision and assesses their mutual influence with a view to establishing forecast benchmarks for the functioning and development of cluster associations in the regional economy.

The practical value of the results obtained lies in their application to the development of regional cluster policy, in which priority is given to defining investment priorities, establishing monitoring and control mechanisms for the implementation of strategic measures, and improving the efficiency of resource management.

The results of forecasting the development indicators for the Lviv IT Cluster showed that, under an optimistic scenario, a 10% increase in its profitability leads to a 0.045% rise in the Lviv region's GRP per employed person, whilst a 1% increase in financial stability results in a 0.070% rise in GRP per employed person. Under a pessimistic scenario, a 5% decrease in the IT cluster's profitability would lead to a 0.023% fall in GRP per employed person, whilst a 3% deterioration in the coverage of current assets by own funds would result in a 0.012% fall in GRP per employed person.

4. Scenario modelling of the challenges and advantages of developing cluster associations in the regional economy was conducted based on the results of a SWOT analysis. Groups of factors influencing the development of cluster associations were systematized; for each group, a set of recommendations was formulated to strengthen competitive advantages, and the expected socioeconomic outcomes of their implementation were identified.

The key distinguishing feature of the authors' approach lies in the combination of SWOT analysis tools with scenario modelling, which makes it possible to simultaneously identify the risks and potential benefits of developing cluster associations, whilst providing a predictive assessment of their impact on the regional economy.

The practical value of this approach is confirmed by the provision of well-founded recommendations to cluster management regarding the formulation of crisis-response development scenarios, which can serve as a basis for the development and implementation of regional cluster policy.

The results obtained from scenario modelling are characterized by scientific and methodological soundness, which is marked by the simultaneous incorporation of the conclusions of SWOT analysis, expected effects and directions for managing cluster development.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing

The research was performed without financial support.

Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that no artificial intelligence technologies were used during the research, with the exception of the presentation of selected results of economic and mathematical modelling in Fig. 2, 3 and 4.

Model and AI identification: ChatGPT (GPT-5).

Section of the article where AI was used: the sections presenting the residuals of the multiple linear regression model (Fig. 2), a comparison of actual and predicted values and model residuals (Fig. 3), and the forecast of the cluster's performance indicators (Fig. 4).

Specific tasks performed with AI tools: using ChatGPT, it was possible to improve the visualization of individual results of econometric modelling obtained using EViews software, in terms of graphical representation, organization of elements and the layout of the figures.

Verification of AI-generated results: the figures produced were compared with the fundamental principles of econometric modelling; figure labels and captions were refined in accordance with academic standards; and graphical editing was carried out.

Impact on research conclusions: the use of ChatGPT was of a supporting nature; the clarity, precision and comprehensibility of the presentation of the material were enhanced.

Authors' contributions

Petro Kutsyk: Conceptualization, Methodology, Resources, Writing – original draft, Writing – review and editing, Supervision, Project administration, Funding acquisition; ***Ruslan Lupak***: Conceptualization,

Methodology, Software, Validation, Investigation, Resources, Writing – original draft, Writing – review and editing, Supervision, Project administration, Funding acquisition; ***Nelia Proskurina***: Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Visualization, Funding acquisition; ***Andrii Artemenko***: Methodology, Software, Validation, Formal analysis, Investigation, Resources, Writing – original draft, Visualization, Funding acquisition; ***Arsen Protsykevych***: Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Visualization, Funding acquisition; ***Viktoriia Gryn***: Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Visualization, Funding acquisition.

All authors have read and agreed to the published version of the article and are jointly responsible for the reliability, accuracy, and integrity of the data and research results presented in the article.

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