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ECONOMIC-MATHEMATICAL MODEL OF FORMATION OF INNOVATION AND ENGINEERING INDUSTRIAL CLUSTER

The subject of the article is the use of industrial clusters as tools for innovative economic growth. **The purpose** of the article is to develop an economic-mathematical model of the formation of an industrial cluster, and to create an algorithm for cluster zoning of the economy. **Tasks to be solved** – analysis of the principles of innovative growth, development of a model of an innovation-engineering industrial cluster, formulation of a methodology for the formation of a regional innovation-engineering cluster, analysis and assessment of the features that arise in clusters, use of cluster analysis for systematization, classification and reduction of the number of features. Applied **methods**: system analysis, project approach, institutional theory, clustering methods, Bartlett's sphericity criterion and Kaiser–Meyer–Olkin sampling adequacy criterion, multivariate regression analysis, Fisher's F-test. **The results obtained**: it was determined that the best approach to unification of the main components of innovative development, namely state bodies, business and development institutes, is the creation of innovation and engineering clusters. The principles of creation and functioning of such clusters are described. It is shown that the basis of the cluster construction algorithm of regions is the integration of quantitative and qualitative methods of identification and clustering of the economy. This makes it possible, in contrast to existing approaches, not only to identify cluster elements, but also to model the levels of interaction between them. It is proposed to use the synergistic effect from the use of the newly formed structure as an assessment of the efficiency of the cluster. **Conclusions**: the use of regional innovation and engineering clusters allows for the formation of an effective strategy for the development of the region's economy. The developed algorithm of cluster zoning integrates quantitative and qualitative methods of determining the clustering possibilities of the region's economy. The complex interaction of economic and political factors leads to a synergistic effect and allows modeling cluster formation with the identification of the composition of participants and the level of interaction between them.

Keywords: innovation-engineering industrial cluster, synergistic regional effect, factor analysis, cluster analysis.

Introduction

The modern innovation economy (sometimes also called the "knowledge economy") is a subtype of economy where knowledge plays a major role. In addition, an important feature of the innovation economy is the natural process of accumulating an idea and then implementing it in all areas of human activity, which leads to the growth of the knowledge-intensive sector, increased labour productivity, reduced material costs of production, its energy intensity and labour force [1].

Innovative growth is fundamentally different from other types of economic growth and has undeniable advantages. First, it is based on profound transformations of the entire production base, but without increasing the need for raw materials. Secondly, since reengineering is one of the main areas of innovative development, its use contributes to the formation of technological platforms and the connection of cluster formations of other industries to them. This will create preconditions for cooperation and compatibility of technological processes. Thirdly, the use of reengineering makes it possible to form promising production bases of enterprises, which creates long-term opportunities for their improvement due to relatively small investments, flexibility of technologies and modular construction. Fourthly, the introduction of innovations tends to be vertical and ultimately affects the entire economy. Thus, the innovative transformation of the enterprise's production base within technological platforms through reengineering is an economic category and technological diffusion.

Analysis of recent research and publications

If we consider the restoration of Ukraine's industry after Russia's full-scale invasion and the integration of our country into the global economy, the issue of adopting European technology platforms (ETPs), which have proven their effectiveness, is once again relevant. Strategically, this means the need to create new innovative re-engineering programmes based on platforms that are aligned with the ETP. However, in the current environment and given the structure of ownership and cluster distribution of enterprises in the basic industries, it is impossible to manage and coordinate innovation processes without government involvement. The most

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effective way to solve this problem is through institutional means in the regional context (this is due to the difference in economic development of regions, unequal concentration of industrial production, relocation of various enterprises due to full-scale invasion), as well as through the use of new technological platforms of a new level – European Technology Innovation Platforms (ETIPs).

European and global experience in the use of technology platforms confirms the effectiveness of the public-private partnership mechanism in the field of scientific, technical, information and industrial development. Ukraine now has the opportunity to apply the best practices in this area and avoid the mistakes made by the world's leading countries in this field. Experience has shown that the availability of technology, even if it is the most advanced, is not enough to effectively implement innovative ideas, reengineering and technological growth. The skills of business leaders to understand and create mechanisms for implementing such technologies are also important.

The issue of creating and using technology platforms has been studied by many scholars, including M. Porter, L. Anderson, O. Fedirko, I. Balanchuk, N. Chukhraeva, and others.

The aim of the article

The purpose of the study is to create a structural, economic and mathematical model of an innovation and engineering cluster, assess the synergistic effect of its use and develop an algorithm for cluster zoning of the regional economy. The paper proposes to use innovation and engineering clusters as tools for effective innovation development. In addition, it is necessary to analyse the impact of the main factors on the formation of these clusters.

Materials and methods of the study

In order for the process of recovery and further growth of industry and the economy on an innovation basis to be effective, it must involve all parties – government agencies, business and development institutions. In this regard, we propose a model of an innovation and engineering industrial cluster (Fig. 1), which demonstrates the interconnectedness of government agencies, business, investors, innovation development structures, and society. Such interaction will contribute to the growth of industry and will allow for a synergistic effect from the use of the investment and engineering industrial cluster.

The proposed model is based on a new institutional theory, according to which the institutional environment and the government are of primary importance in ensuring innovative transformations, and the role of participants in economic interaction in the implementation of technological reengineering is considered from the point of view of the spread of innovations. We proceed from the fact that the root cause of economic problems that arise on the way to solving innovation problems is institutional imperfection.

In the course of their evolution, territorial and industrial units (predecessors of modern clusters) have gone through several stages, each of which has had a certain effect on the development of industry and regions (Table 1).

At the initial stages of their functioning, the main suppliers of innovations were state sectoral institutions that provided solutions to the tasks required at that time. However, the lack of competition and low level of motivation prevented such entities from making technological breakthroughs. In today's environment, there is a vital need to create a new model of institutional development that would meet the challenges of not only the fundamental transformations taking place in Ukraine's economy, legal framework and territorial structure, but also be able to orient the vector of the state's development towards integration with the global environment as a full-fledged European country. The Regional Innovation and Engineering Cluster (RIEC) could be used as such a model.

In the post-industrial economy, characterised by the presence of various information and technology transfer networks in the economic space, it is necessary to use an institutional approach to explaining the essence of clusters as a form of integration of capital, business, government, technology and informatics. The new institutional theory is based on the postulate that all these elements of integration exist in the form and forms that have been tested in different socio-economic conditions and environments, in regions with different levels of development and concentration of production. The new institutional theory complements the neoclassical analysis of the processes of formation and development of an innovation cluster by analysing the institutional environment of network interaction of all its actors.

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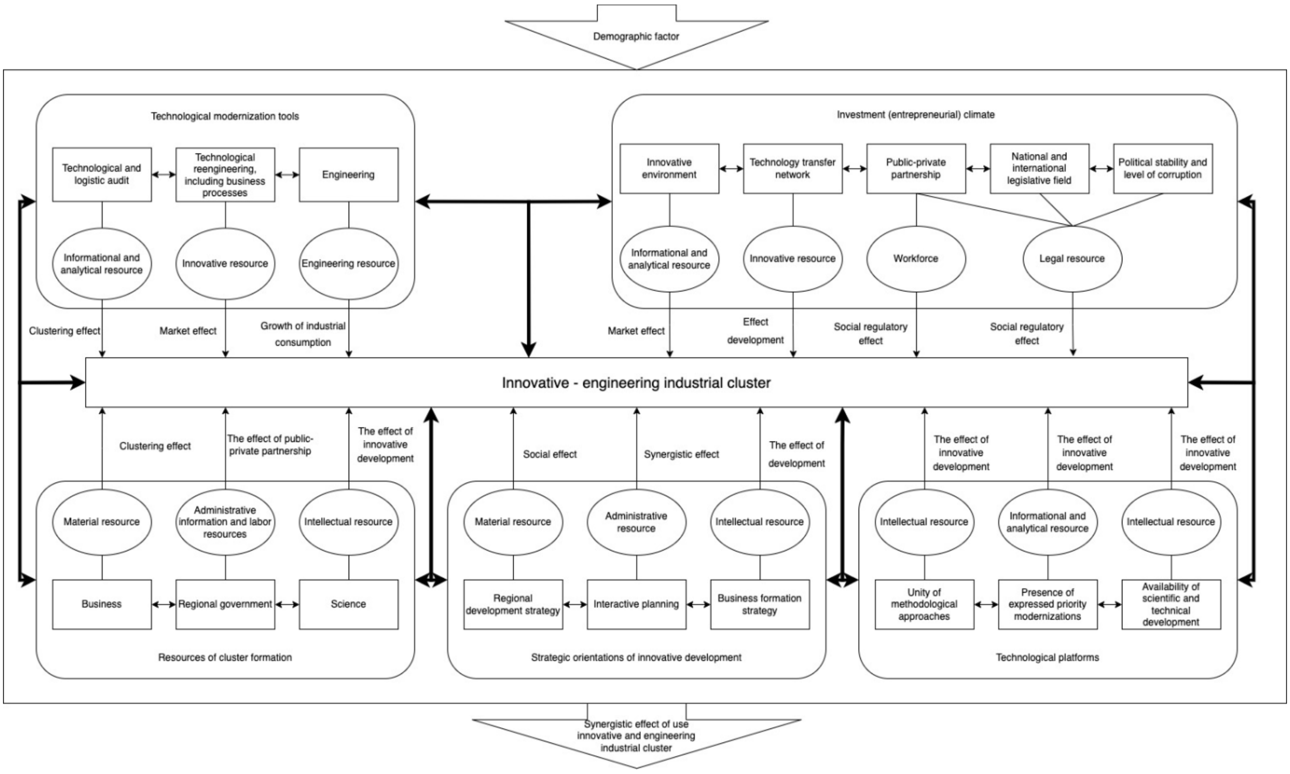

Fig. 1. Model of an innovation and engineering industrial cluster

Table 1. *Factors of competitiveness of territorial-industrial units in the process of their evolution*

Stages of evolution of territorial-industrial formations	Factors of competitiveness of territorial-industrial units in the process of their evolution
Territorial and industrial complexes	Advantages of cooperation, reduction of transaction costs, solving problems of socio-economic development of the region
Industrial agglomerations of industry	Transport and logistics advantages, reduced uncertainty and transaction costs in geographical concentration, quick response to competitors' innovations
Innovative industrial zones	Human and infrastructural benefits of innovative development, reduction of uncertainty and transaction costs through formal institutions and explicit contracts with participants of integrated education on cooperation (technology transfer)
Territorial innovation networks	Information benefits, reduction of uncertainty and transaction costs through the use of informal institutions (formation of social capital, diffusion of managerial innovations)
Innovative industrial clusters	Innovative advantages of joint activities within the framework of network mechanisms (formation of an institutional environment for innovative development, partnership with public authorities and the local community)
Innovative technological clusters	Innovative advantages of joint activities within network mechanisms of scientific and technical cooperation and technology transfer
Regional innovation and engineering industrial clusters	Innovative advantages of joint activities within the framework of network mechanisms of scientific and technical cooperation between business entities and regional authorities on the basis of common technological platforms and intensification of engineering activities (formation of institutional and innovative environment in the context of global technology transfer networks based on public-private partnership and new instruments of innovative development; global technological modernisation of industrial enterprises with active participation of small and medium-sized businesses; coordinated development of social programmes in the regions with programmes of technological modernisation of industrial enterprises)

Realisation of the advantages of the clustering model with the use of institutions to ensure the effective functioning of new instruments of innovative development creates preconditions for resolving contradictions in the cooperation between business, science and the state, primarily in the processes of territorial and intra-cluster development.

The cluster approach is actively used in the current processes of transformation of the regional economy. This is due to the need to update and improve

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the effectiveness of regional policy instruments in wartime, financial crisis and budget shortages to support regional enterprises and increase their competitiveness. At the same time, the most progressive regions have realised, based on an analysis of successful international experience, that the cluster approach is one of the most effective tools for modernising enterprises and ensuring the development of innovative sectors of the economy.

Socio-economic objects are usually quite complex and diverse. This is due to the fact that their formation is usually conditioned by the influence of a large number of different factors. A regional innovation and engineering cluster is a new entity whose main task is to provide organisational and economic conditions for the modernisation of industrial enterprises in order to build an export-oriented economy. The formation of such a cluster in the current conditions in Ukraine is due, on the one hand, to the realities of the existing divisional structure, currently one of the main concerns – SC "Ukroboronprom", and the urgent need for technological and innovative reengineering of the enterprises that belong to it. On the other hand, the formation of the RIEC is due to the influence of a significant number of factors not only on the process of organisational and economic formation of the cluster itself, but also on all mechanisms for managing the effectiveness of the cluster strategy.

Global corporate experience shows that there are several approaches to assessing the effectiveness of a cluster. One of the simplest but most effective approaches is to assess the synergistic effect of the cluster, when the total value of the cluster's members is greater than the sum of the values of these organisations. However, this approach is only possible in stable conditions and if there are sufficiently regular assessments of the business value of the cluster's enterprises. In modern conditions, when it is impossible to regularly assess the value of a business for various reasons, the methodology for forming the RIEC has been formulated.

At the preliminary stage, it is proposed to analyse and evaluate the following features that arise in the process of RIEC formation (except for the geographical one): V_1 – technological audit; V_2 – technology transfer network; V_3 – technological re-engineering; V_4 – engineering; V_5 – innovation environment (including regional governance institutions); V_6 – public-private partnership; V_7 – indicative planning of cluster development; V_8 – technological platforms; V_9 – regional authorities (a team of professional public managers who clearly represent and support cluster policy); V_{10} – strategic guidelines of business formations; V_{11} – political stability and level of corruption; V_{12} – business (industrial enterprises represented by their top managers); V_{13} – scientific potential (research and design institutes, universities, technology parks, business incubators, IT hubs); V_{14} – strategic guidelines for regional development; V_{15} – national and international legislative framework.

Such a large number of factors significantly complicates the final result. Therefore, it is advisable to use a class of factor analysis methods that allow to reduce the number of variables and their generalisation [2, 3]. In our case, to systematise and classify the features, we conducted a factor analysis of the following features $V_i\left(i=1,...,15\right)$ [4, 5].

The initial data for the calculation of a number of the described indicators are aggregated official statistics. For example, such indicators of scientific potential as the Share of Industry Enterprises Engaged in Innovations and the Share of Industry Employees Engaged in R&D, indicators of the technology transfer network, and the business indicator are calculated on the basis of indicators from a sample survey of enterprises. Other indicators were built using the expert evaluation method based on statistical indicators of municipalities and processing the results of the expert survey. The expert assessment is determined on a scale from 0 to 10, where a higher value corresponds to a better value of the factor [12]. To determine the feasibility of performing factor analysis, the statistical programme for social sciences SPSS (Statistical Package for Social Sciences) was used. It was used to calculate Bartlett's criterion of sphericity and the Kaiser–Meyer–Olkin criterion of sample adequacy.

The Kaiser-Meyer-Olkin sample adequacy criterion is a value that determines the degree to which factor analysis can be applied to this sample. In our case, the value of this criterion was 0.519, which indicates low adequacy, but confirms the possibility of using factor analysis.

Bartlett's Sphericity Criterion is an indicator of multivariate normality for the distribution of variables. The criterion checks whether the correlations are different from 0. For our study, the indicator was 0.000, which indicates that the data are suitable for factor analysis.

As we can see, the value of the calculated indicators allows us to conclude that factor analysis is an acceptable method for analysing the correlation matrix [6]. According to the Kaiser criterion, we obtain five principal components (factors).

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The first factor "Entrepreneurial climate" includes:
– innovation environment (including institutions);
– technology transfer network;
– public-private partnerships;
– national and international legal framework;
– political stability and the level of corruption.

The second factor "Cluster formation resources" includes the following features:
– regional authorities
– business
– science.

The third factor "Strategic guidelines for innovative development" includes:
– regional development strategy;
– strategy of business formations located in the region;
– indicative planning based on intensive ideology.

The fourth factor "Tools of technological modernisation" includes:
– technological audit;
– technological reengineering;
– engineering.

The last, fifth, factor contains only one variable – technological platforms, which will be considered as a separate factor in the further study.

Finally, we have five main factors that determine the synergistic regional effect of an industrial cluster: F1 – resources of cluster formation; F2 – technological platforms; F3 – tools of technological modernisation; F4 – entrepreneurial climate; F5 – strategic guidelines for innovative development. The values of the factors and their sequence were determined on the basis of a regression equation in the form of a linear combination of the values of the attributes and the value of the factor load.

Thus, factor analysis resulted in data reduction, after which the number of variables was reduced by three times (while maintaining their descriptive power). The calculated values of the five factors will be used in further analysis and are the basis for the formation of the RIEC in the regions. In addition to the selected five factors $F_i\left(i=\overline{1,5}\right)$, the factor of geographical location was also added as a key factor, especially now. This factor influences the formation of an innovation and engineering industrial cluster.

Taking into account all these factors makes it possible to identify potential opportunities for the formation of an innovation and engineering industrial cluster in a particular territory.

The factors of RIEC influence are shown in Fig. 2 [7–9]. In the process of cluster analysis, we will take into account that each cluster may contain a different number of enterprises. Therefore, the weighted pairwise average method was chosen as the clustering criterion. The problem of determining the most probable number of clusters was solved by hierarchical analysis with a randomly selected sample of observations [10].

Table 2 shows excerpts of the agglomeration table obtained using the aforementioned SPSS software. The columns provide an overview of the membership, which can be used to determine the order of cluster formation and the optimal number of clusters. As you can see, the first significant jump (from 4,995 to 5,475) occurred at iteration 113. Thus, the optimal number of clusters in this case is $134-113=21$. However, when analysing the table, we observe another significant jump in the coefficient – at the 123rd iteration (from 8.340 to 9.277). In this case, the rational number of clusters would be $134-123=11$.

Table 2. *Data agglomerations (excerpt)*

Stage	Cluster combined		Coefficients
	Cluster 1	Cluster 2	
1	20	49	0,550
2	15	37	0,693
3	11	47	0,697
4	23	41	0,700
5	20	34	0,728
6	31	44	0,811
7	19	29	0,846
8	36	48	0,931
9	10	35	0,957
10	13	24	0,984
…	…	…	…
110	20	71	4,536
111	10	16	4,696
112	30	130	4,879
113	39	43	4,995
114	15	31	5,475
115	23	36	5,739
116	6	14	5,957
…	…	…	…
121	22	73	7,456
122	2	4	7,701
123	6	10	8,340
124	20	61	9,277
125	2	6	9,402
126	12	62	9,984
127	20	22	10,030
128	7	20	10,857
129	2	7	11,706
130	17	30	13,546
131	2	17	15,625
132	2	12	16,813
133	1	2	17,368

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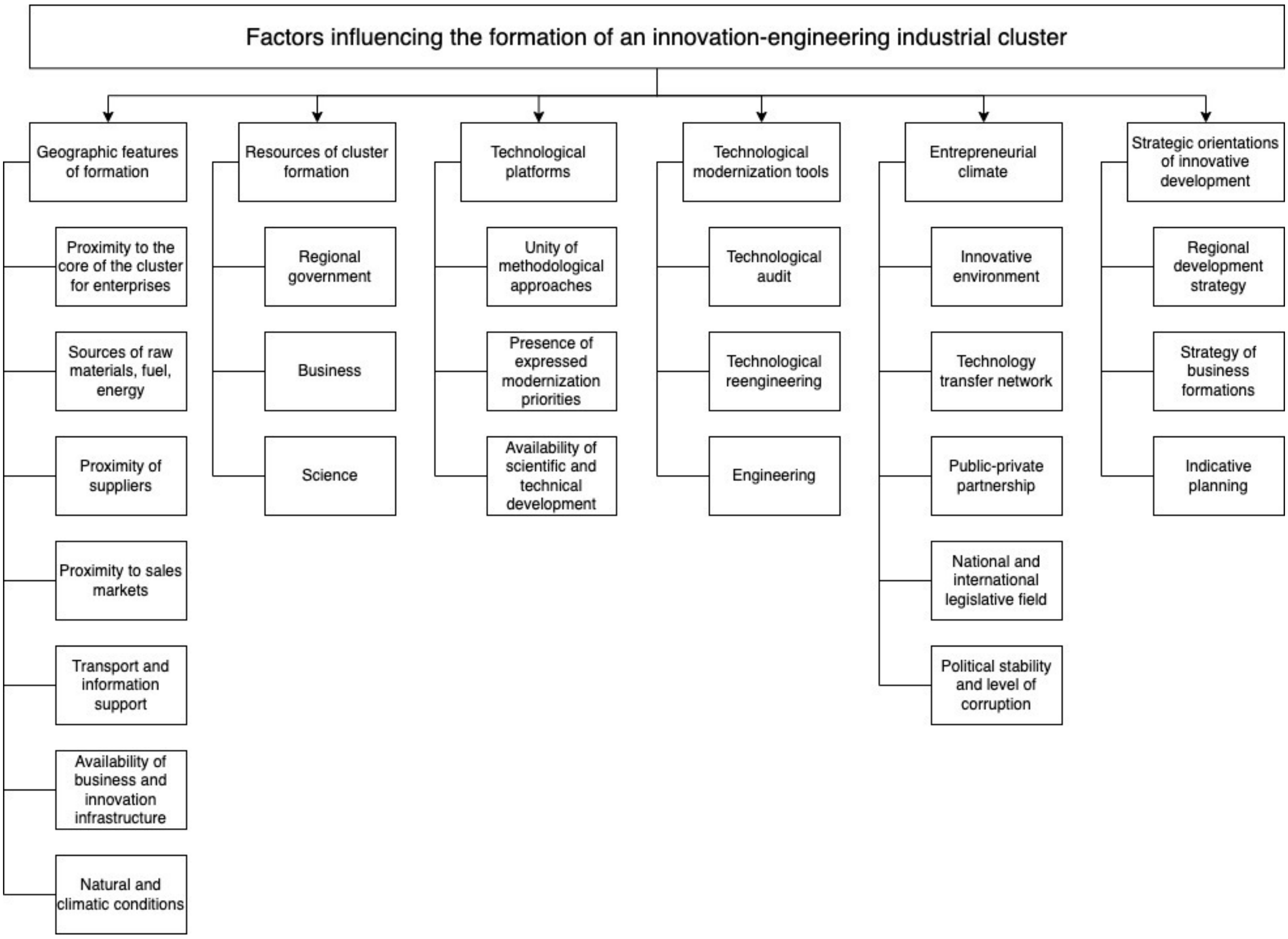

Fig. 2. Key factors influencing the formation of an innovation and engineering industrial cluster

Using the k-means method, we can see that with the number of clusters to be distributed at 21, some clusters are too small. Given the current state of the economy, this is not appropriate. When we choose the number of clusters to be 11, there are no small clusters. This suggests that it makes sense to divide the enterprises belonging to the military-industrial complex into 11 innovation and engineering clusters.

Thus, the proposed scheme of the algorithm for cluster zoning of the region integrates quantitative and qualitative methods for determining the clustering opportunities based on the enterprises of the military-industrial complex. Unlike existing approaches, the use of this algorithm allows not only to determine the clustering potential of the region, but also to model cluster formation with the identification of the composition of participants and the level of interaction between them. In addition to these tasks, the introduction of a cluster into the territory's economy requires an assessment of the actual or potential efficiency of its interaction with other economic entities in the region. In this regard, let us consider the issue of determining the level of clustering in the region.

The effectiveness of cluster formation is a fundamentally new type of effectiveness based, as it was justified earlier, on the integration of business, science and regional authorities. Cluster effects are understood as the result of the impact of a targeted and coordinated cluster policy on various performance indicators of industrial enterprises, scientific and educational institutions, indicators of socio-economic development of regions, including the standard of living and quality of life of its population. The cluster's activities are associated with the synergistic regional effect of the industrial cluster (SRE), which is due to the fact that within the cluster structures, the relations between the participants are streamlined and developed, becoming closer and more productive. As a result, firstly, clusters facilitate the exchange of resources and their joint use to increase efficiency; secondly, information circulates faster within the cluster network, which allows cluster members to respond quickly and adequately to external and internal changes, and make more informed and effective decisions; third, the developed relationships of cluster members in the production, sales,

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financial, scientific and technical spheres help to implement joint projects that strengthen the position of enterprises in the occupied markets and facilitate entry into new ones. Having SREs and the ability to manage them creates a special competitive advantage.

As shown earlier, in addition to the geographical factor, five other major economic and political factors influence the formation of a cluster $F_i\left(i=\overline{1,5}\right)$. The complex interaction of these factors contributes to the emergence of the synergistic effect of SRE in the innovation and engineering industrial cluster, which allows the use of standard approaches to multivariate regression analysis [11].

Using the standard approach of calculating the determinant of the matrix of pairwise correlation coefficients between factors, it is not difficult to show the absence of multicollinearity between them. Since it is impossible to use statistical hypotheses about the density of distribution, in this case we will apply the method of group consideration of the argument, which belongs to the evolutionary algorithms of artificial intelligence [12, 13].

Let's divide the available data sample for 2009–2021 (W) into three subsamples (as proposed by O. Ivakhnenko, Academician of the Institute of Cybernetics of the National Academy of Sciences of Ukraine):

G – training subsample (data taken for 2009–2014);

C – test subsample (data taken for 2014–2019);

B – examination subsample (data taken for 2020–2021).

Using the training subsample *G*, we adjust the model parameters.

$$\varepsilon_G^2=\left|\left(SRE\right)_G-W_G\times\overline{\alpha_G}\right|^2, \qquad (1)$$

where W_G – subsample matrix *G*;

$\overline{\alpha_G}$ – is the value of the parameter vector G, which was found by the least squares method (LSM):

$$\overline{\alpha_G}=\left[W_G^T\times W_G\right]^{-1}\times\left[W_G^T\times\left(SRE\right)_G\right]. \qquad (2)$$

To determine the degree of functional range, a combined external criterion of model optimality is considered, built on the basis of combining the criterion of model consistency, as a criterion of bias and the criterion of predictability:

$$k^2=\overline{\mu_b}\times s^2+\Delta^2\left(B/W\right), \qquad (3)$$

where:

$$\overline{\mu_b^2}=\left(\overline{\alpha_G}-\overline{\alpha_C}\right)^T\times W^T\times W\times\left(\overline{\alpha_G}-\overline{\alpha_C}\right), \qquad (4)$$

$$\Delta^2\left(B/W\right)=\frac{\left|\left(SRE\right)_W-W_G\times\overline{\alpha_B}\right|^2}{\left|\left(SRE\right)_W-\overline{\left(SRE\right)_G}\right|^2}. \qquad (5)$$

Since the minimum of the external criterion (3) is achieved on a second-degree polynomial, we introduce a Kolmogorov–Gabor polynomial for the relationship (SRE) and the available factors, which is linear in parameters and nonlinear in factors:

$$\left(SRE\right)=\alpha_0+\sum_{i=1}^{5}\alpha_iF_i+\sum_{i=1}^{5}\sum_{j=1}^{5}\alpha_{ij}F_iF_j. \qquad (6)$$

To calculate the coefficients of the regression equation (6), we use the least squares method, taking into account the orthogonality of the columns of the new matrix of elements of the orthogonal central compositional plan.

The reliability of the obtained results was assessed using Fisher's F-criterion. The obtained SREs in accordance with the data of the test sample using the proposed model (6) exceeded the real indicators provided. This suggests the existence of an effective interaction of the factors of the proposed methodology for building RIEC (Fig. 1).

Conclusions

Thus, the paper scientifically substantiates and proposes a structural model of an innovation and industrial cluster and defines the principles of functioning of its clusters, which will allow forming an effective strategy for the development of the regional economy. The approach to cluster zoning developed by the authors integrates quantitative and qualitative methods for determining the possibilities of clustering the regional economy, which creates a synergistic effect. This makes it possible not only to determine the potential for clustering in the region, but also to model cluster formation with the identification of the composition of participants and the level of interaction between them. A comprehensive indicator for assessing the importance of a cluster for the development of the territory is the increase in SRE due to the creation and development of this structure. Based on the developed model describing the SRE of RIEC, the article shows the positive role of regional clusters in identifying strategic niches of regional development, which determine the priorities and mechanisms of regional cluster policy.

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СТРУКТУРНА МОДЕЛЬ ІННОВАЦІЙНО-ІНЖИНІРИНГОВОГО ПРОМИСЛОВОГО КЛАСТЕРУ Й АЛГОРИТМ ЙОГО ФОРМУВАННЯ

Предметом дослідження є використання промислових кластерів як інструментів для інноваційного зростання економіки. **Мета статті** – розроблення структурної, економіко-математичної моделі формування промислового кластеру та створення алгоритму кластерного зонування економіки. **Завдання,** що вирішуються: аналіз принципів інноваційного зростання; розроблення моделі інноваційно-інжинірингового промислового кластеру; опис методики формування регіонального інноваційно-інжинірингового кластеру; аналіз і оцінювання ознак, що виникають у кластерів; використання кластерного аналізу для систематизації, класифікації та зменшення кількості ознак. **Застосовані методи**: системний аналіз, проєктний підхід, інстуціональна теорія, методи кластеризації, критерій сферичності Бартлетта та критерій адекватності вибірки Кайзера-Меєра-Олкіна, багатофакторний регресійний аналіз, F-критерій Фішера. **Здобуті результати**: визначено, що найкращим підходом до об'єднання основних складників інноваційного становлення, а саме державних органів, бізнесу та інститутів розвитку, є створення інноваційно-інжинірингових кластерів. Описано принципи створення та функціонування зазначених кластерів. Показано, що в основі алгоритму кластерної побудови регіонів лежить інтеграція кількісних і якісних методів ідентифікації та кластеризації економіки. Це дає змогу, на відміну від наявних підходів, не тільки ідентифікувати елементи кластеру, а й змоделювати рівні взаємодії між ними. Для оцінювання ефективності роботи кластеру запропоновано застосовувати синергетичний ефект від використання новоутвореної структури. **Висновки**: застосування регіональних інноваційно-інжинірингових кластерів дає змогу сформувати ефективну стратегію розвитку економіки регіону. Розроблений алгоритм кластерного зонування інтегрує кількісні та якісні методи визначення можливостей кластеризації економіки регіону. Комплексна взаємодія економіко-політичних чинників призводить до синергетичного ефекту й дає змогу моделювати кластерне утворення з виявленням складу учасників і рівня взаємодії між ними.

Ключові слова: інноваційно-інжиніринговий промисловий кластер; синергетичний регіональний ефект; факторний аналіз; кластерний аналіз.

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