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# MODELING OF CLUSTER STRUCTURE AND DIGITAL DEVELOPMENT TRAJECTORIES OF EU COUNTRIES USING MACHINE LEARNING METHODS

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**Shabelnyk T. V., Prokopovych S. V., Gvozdytskyi V. S., Teslenko D. A. Modeling of Cluster Structure and Digital Development Trajectories of EU Countries Using Machine Learning Methods**

*The rapid development of digital technologies is fundamentally transforming economic systems, business models and social processes. Digitalization is becoming a key factor in increasing the competitiveness of countries, contributing to innovative growth, more efficient resource management and the formation of new forms of interaction between citizens, business and the State. However, currently the level of digital development among countries within the EU is uneven. Both the digital infrastructure and the level of digital skills of the population and business differ. Therefore, it is becoming relevant to develop and implement a comprehensive approach to the analysis of digital transformation processes and mechanisms of digital evolution, which will allow identifying structural patterns and classifying groups of countries, as well as monitoring how countries move between different levels of digital development and under the influence of which factors. The aim of the work is to identify structural patterns of digital transformation and assess the positioning of countries in the EU digital space, as well as trace the trajectory of the digital evolution of states. The work substantiated that machine learning methods, namely hierarchical clustering methods and the transition matrix method, allow for a comprehensive study of the multidimensional structure of digital transformation, to distribute countries with similar digitalization profiles and to trace the trajectories of countries over time, which, in turn, will allow assessing the efficiency of EU policy within the framework of defined development strategies, to adjust and optimize it. Using the developed cluster analysis model, the differentiation of EU countries by the level of digital development in a defined multidimensional information and digital space was assessed. A model for analyzing the trajectories of digital development in EU countries was implemented based on a study of the cluster structure using a transition matrix, which allows assessing trends, stability and speed of digital change. According to the results of the study, the current state of digital development in EU countries was assessed, both general long-term trends and individual trajectories of particular countries were identified, influencing factors and possible scenarios for further digital evolution were identified, which will allow developing recommendations for increasing the efficiency of State policy in the field of digital development.*

***Keywords:*** *modeling; digitalization; cluster analysis; transition matrix; digital transformation.*
***Fig.:*** *7.* ***Tabl.:*** *3.* ***Bibl.:*** *15.*

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***Шабельник Т. В., Прокопович С. В., Гвоздицький В. С., Тесленко Д. А. Моделювання кластерної структури та траєкторій цифрового розвитку країн ЄС методами машинного навчання***

*Стрімкий розвиток цифрових технологій докорінно трансформує економічні системи, моделі бізнесу та суспільні процеси. Цифровізація стає ключовим чинником підвищення конкурентоспроможності держав, сприяє інноваційному зростанню, ефективнішому управлінню ресурсами та формуванню нових форм взаємодії між громадянами, бізнесом і державою. Проте наразі рівень цифрового розвитку серед країн всередині ЄС є нерівномірним. Відрізняється як цифрова інфраструктура, так і рівень цифрових навичок населення та бізнесу. Тому стає актуальною розробка та впровадження комплексного підходу до аналізу процесів цифрової трансформації та механізмів цифрової еволюції, що дозволить виявити структурні закономірності та класифікувати групи країн, а також проводити моніторинг, як країни переміщуються між різними рівнями цифрового розвитку та під впливом яких факторів. Метою роботи є виявлення структурних закономірностей цифрової трансформації та оцінка позиціонування країн у цифровому просторі ЄС, а також простеження траєкторії цифрової еволюції держав. У роботі було обґрунтовано, що методи машинного навчання, а саме – ієрархічні методи кластеризації та метод матриць переходів, дозволяють комплексно дослідити багатовимірну структуру цифрової трансформації, розподілити країни із подібними профілями цифровізації та простежити траєкторії руху країн у часі, що, своєю чергою, дозволить оцінити ефективність політики ЄС у рамках визначених стратегій розвитку, коригувати та оптимізувати її. За допомогою розробленої моделі кластерного аналізу було оцінено диференціацію країн ЄС за рівнем цифрового розвитку у визначеному багатовимірному інформаційно-цифровому просторі. Було реалізовано модель аналізу траєкторій цифрового розвитку країн ЄС на основі дослідження кластерної структури за допомогою матриці переходів, що дозволяє оцінити тенденції, стабільність і швидкість цифрових змін. За результатами дослідження було оцінено поточний стан цифрового розвитку країн ЄС, виявлено як загальні довгострокові тенденції, так і індивідуальні траєкторії окремих країн, визначено фактори впливу та можливі сценарії подальшої цифрової еволюції, що дозволить розробити рекомендації щодо підвищення ефективності державної політики у сфері цифрового розвитку.*

***Ключові слова:*** *моделювання; діджиталізація; кластерний аналіз; матриця переходів; цифрова трансформація.*
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Within the EU, digitalization is seen as a strategic priority that stimulates economic growth, increases competitiveness, promotes innovation and improves the quality of life of citizens [1]. The EU approach emphasizes a holistic framework that integrates technological, economic, social and regulatory aspects to ensure sustainable digital progress in all Member States [13]. Accordingly, digitalization is seen as a factor in strengthening competitiveness, increasing labor productivity, forming a single European digital market and ensuring a sustainable transition to a knowledge-based economy.

However, digital development is uneven both between countries and between sectors of the economy.

There are significant differences in access to digital infrastructure, the level of digital skills of the population, the pace of business digitalization and the development of the ICT sector. In these conditions, there is a need for a deep quantitative analysis of digital transformation processes, which allows identifying structural patterns, identifying groups of countries with similar digitalization profiles and tracking the dynamics of changes over time. Of particular importance is the study of how countries move between different levels of digital development, what factors influence these changes, and whether there is convergence of digital capabilities within the EU.

Therefore, it is extremely important to further study the mechanisms of digital evolution, using modern digital, IT methods, including machine learning methods. And the distribution of member states by clusters and the comparison of clustering results in dynamics will allow adjusting and optimizing state policy within the framework of the defined strategies Europe 2020, Digital Single Market Strategy, Digital Compass 2030, etc. [1; 2; 13].

**Analysis of scientific research and publications.** Due to the great relevance of digital transformation issues, many Ukrainian and foreign scientists have recently been studying the mechanisms of digital evolution. For instance, J. Huňady, P. Pisár, S. Khawaja, F. H. Qureshi in their work [3] classified EU countries by digital readiness, compared indicators before and during the pandemic. Moreover, as a tool, scientists justified the use of Data Science methods, namely cluster and factor analysis.

Akhnovska I., Bondarenko R. in [4], and Chesnokova N. in [5] analyze scientific and methodological approaches to defining digitalization and digital transformation.

Ratushnyak T. V. et al. in their work [6] analyze the Digital Economy and Society Index (DESI) [2] and investigate its application for assessing the digital development of European countries.

In their studies [8; 10] Khaustova V. E. et al. developed a methodological approach to analyzing the impact of digitalization factors on economic development based on a cognitive approach, and also identified factors for increasing the effectiveness of digitalization process management strategies.

Researchers [9] focus on identifying those factors that have a significant impact on the sustainable economic development of countries, and justify that in modern conditions, sustainable development is possible only with the successful implementation of digitalization processes.

Nevertheless, despite the scientific value of the aforementioned studies, the works do not fully substantiate possible scenarios of further digital evolution, and therefore, studies devoted specifically to tracing both general trends in the development of digitalization and individual development trajectories of individual countries, taking into account the different speeds of digital change, have great theoretical and practical value.

**Aim of the article.** The aim of this article is to to identify structural patterns of digital transformation and assess the positioning of countries in the EU digital space, as well as to trace the trajectories of digital evolution of states using modern methods of Data Science. To achieve this goal, machine learning methods were used, namely hierarchical clustering methods and transition matrix methods. The information base of the study is open Eurostat data [14], which forms a comprehensive system of digitalization indicators within the Science, technology, digital society / Digital economy and society section.

**Results.** Analysis of available multi-year data series allows us to trace a steady increase in the level of digitalization in most EU countries. The most noticeable positive changes are observed in the area of Internet access and digital skills of the population [7; 12]. The latter, to some extent, determines the ability of the economy to adapt to new technological conditions. Most EU countries demonstrate a positive trend in terms of increasing the share of the population with basic or higher digital competencies. At the same time, there is a gap between highly developed countries and countries that are only approaching the average European indicators.

At the same time, the indicators of the ICT sector also demonstrate a gradual increase in the economic role of the digital technology industry. The share of gross value added created by the ICT sector and the share of employment in this area are increasing in most countries. The volume of e-commerce is also growing, and the use of ERP, CRM and BI systems indicates the gradual integration of digital technologies into production and management processes. However, the pace of these changes varies significantly between EU countries: enterprises in Northern and Western European countries are implementing digital management systems much faster, while most Central and South-Eastern European countries are demonstrating moderate progress.

Thus, the dynamics of various indicators indicate a gradual equalization of the levels of digitalization between EU countries, although structural differences persist. Northern and Western countries are steadily maintaining their positions as digital leaders, while Southern and Eastern European countries are demonstrating high growth rates, catching up with Central

European standards. The identified trends confirm the need for further research into the relationships between groups of countries, including identifying factors that determine the differentiation of the pace of digital transformation and analyzing structural transitions in their digital development [15].

To achieve the goal set in the study, clustering methods (in particular, the k-means method, the Ward method) were used to divide countries into typological groups according to their positions in the digital space for several selected time periods. This makes it possible to assess the differentiation of countries within the EU, identify leaders and outsiders, and also trace the dynamics of changes over time. As indicators characterizing digitalization, the indicators described in the previous study [11] were taken, divided into 4 groups: Group 1 – Digital inclusion of the population; Group 2 – Digital skills (competences); Group 3 – Business digitalization; Group 4 – Digital Economy (ICT economy).

The solution of the problem of determining the optimal number of clusters was performed using the following tests: the Elbow Method, the Silhouette Method, and the gap statistics. The results of applying these methods are presented in *Fig. 1*.

As can be seen from Fig. 1, the results of the elbow method show a "bend" for 3 and 6 clusters, so it is not possible to accurately determine the optimal number of clusters. However, the results of the silhouette method and gap statistics show that the maximum coefficient corresponds to the number of clusters equal to 2. However, this division of the EU countries into only two groups according to the level of digital development is not informative, so it is concluded that the optimal division of countries is precisely into 3 clusters.

*Fig. 2* shows the distribution of countries obtained based on the k-means method, implemented in Python, in the space of two principal components found and interpreted in a previous study [11].

An identical result was obtained when using the Ward method (*Fig. 3*).

*Fig. 4* shows graphs of the average values of digitalization indicators for each of the three clusters.

*Fig. 5* shows the members of each cluster and their distance to the center of the cluster.

Cluster 1 with low values of digitalization indicators includes the following 8 countries: Bulgaria, Greece, Croatia, Italy, Cyprus, Poland, Portugal, Romania. Cyprus and Italy have the shortest distance from the center of the cluster.

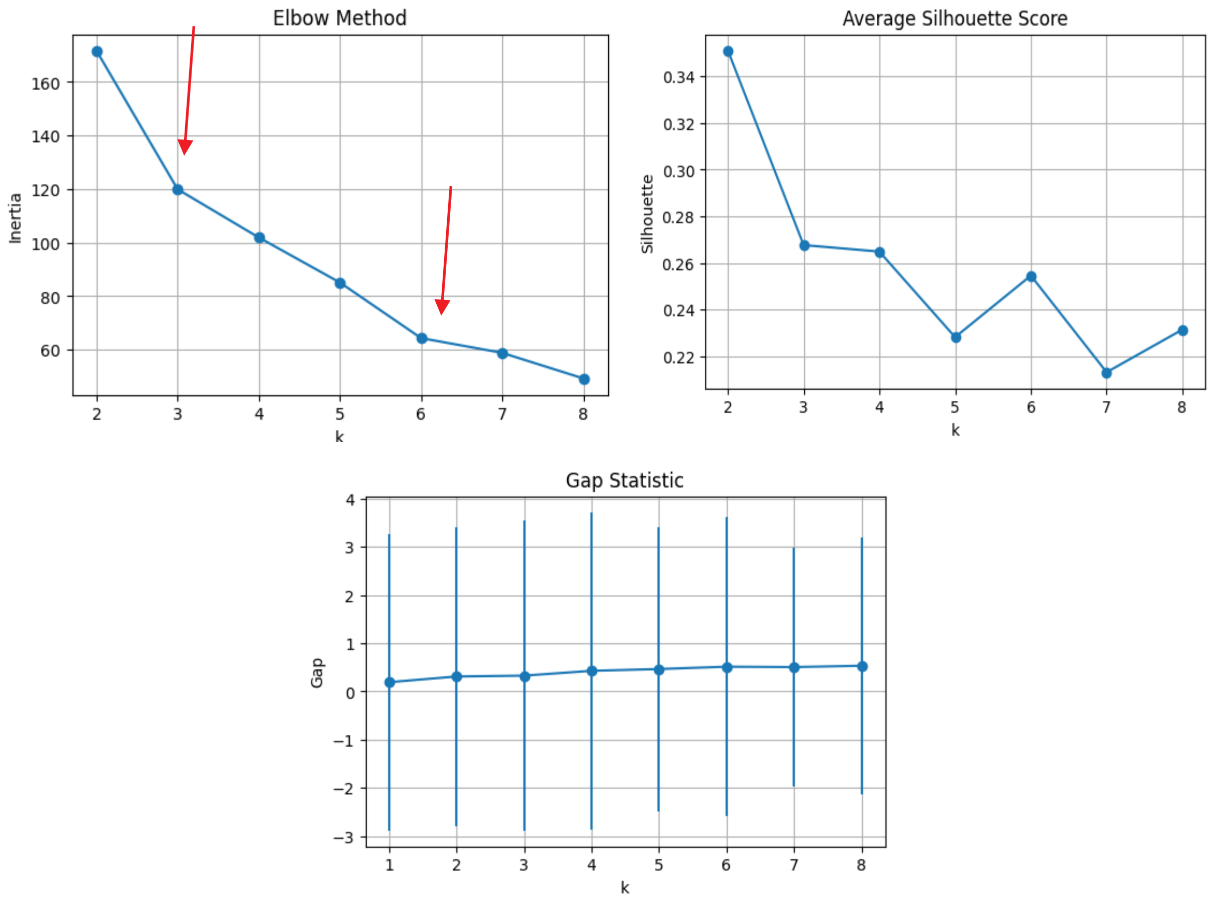


**Fig. 1. Determining the optimal number of clusters using the elbow, silhouette, gap-statistics methods (2013)**

**Source:** compiled by the authors.

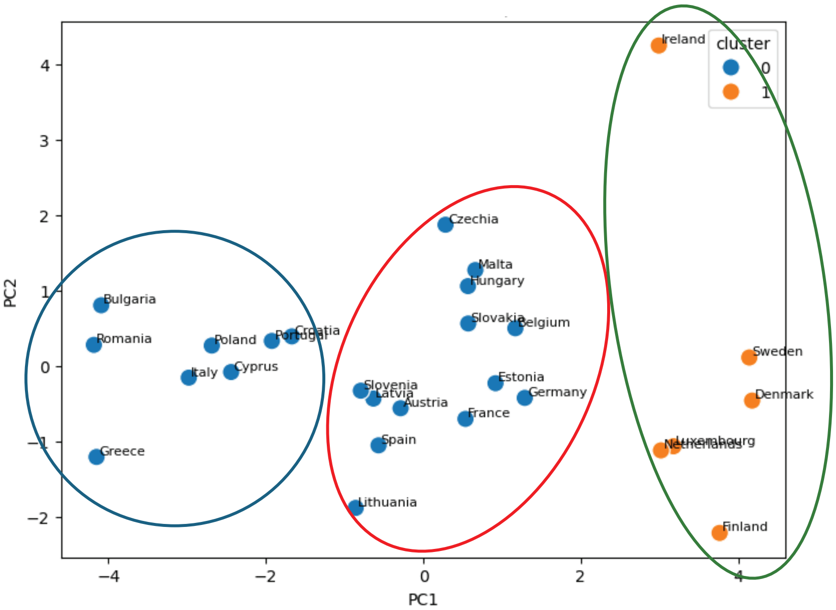


**Fig. 2. Distribution of countries in the space of two principal components (2013)**

**Source:** compiled by the authors.

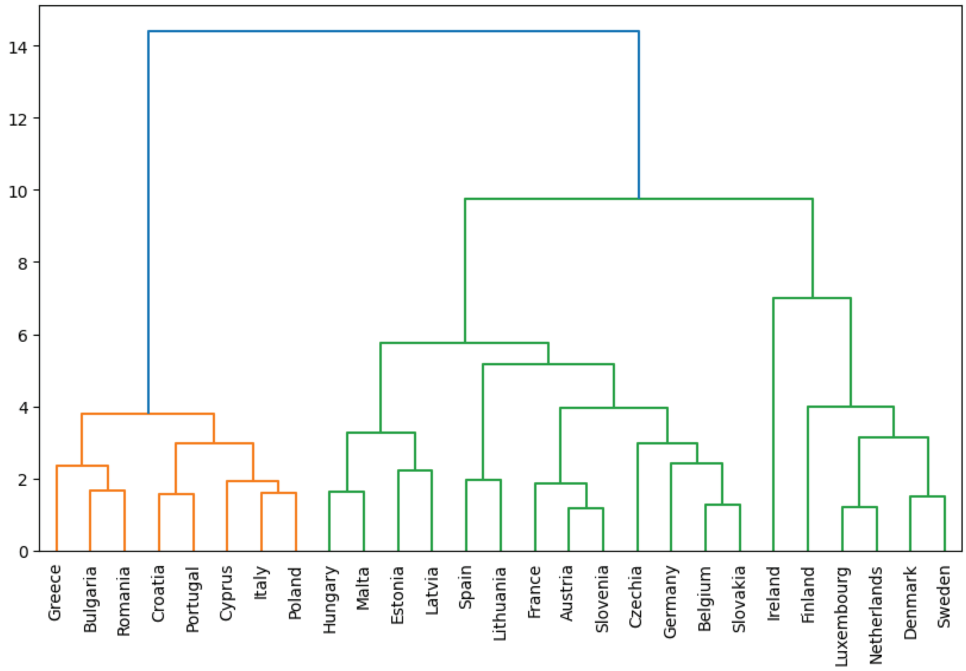


**Fig. 3. Dendrogram by the Ward's method in Python (2013)**

**Source:** compiled by the authors.

Cluster 2 with medium values of digitalization indicators includes the following 13 countries: Belgium, Czechia, Germany, Estonia, Spain, France, Latvia, Lithuania, Hungary, Malta, Austria, Slovenia, Slovakia. Slovakia has the shortest distance from the center of the cluster.

Cluster 3 with high values of digitalization indicators includes the following 6 countries: Denmark, Ireland, Luxembourg, Netherlands, Finland, Sweden. Sweden has the shortest distance from the center of the cluster, and Ireland has the largest distance.

The quality of clustering can be assessed using data from the table of analysis of intra-cluster and inter-cluster variances (*Fig. 6*).

As can be seen from Fig. 6, the division into three clusters is very qualitative. For all indicators, high statistical significance is observed according to the Fisher test. The error level (signif. p) is much lower than the threshold level of 0.05.

Similar calculations were performed for the other three periods of the study (2016, 2020 and 2024). Thus, for all periods, the optimal division was precisely into

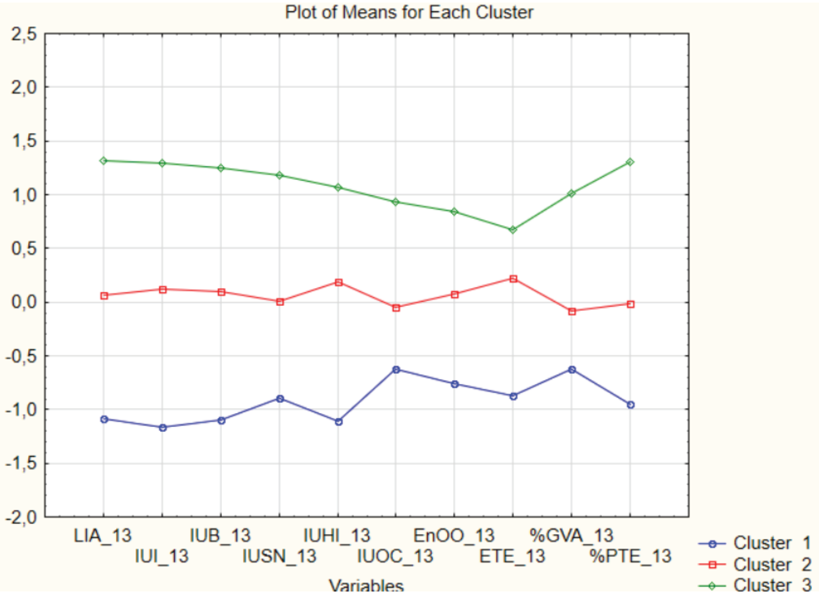


**Fig. 4. Graph of average values of indicators for each cluster (2013)**

**Source:** compiled by the authors.

Members of Cluster Number 1 and Distances from Respectiv Cluster contains 8 cases

| linkage | Distance |
|---|---|
| **Bulgaria** | 0,582234 |
| Greece | 0,564468 |
| Croatia | 0,580047 |
| Italy | 0,400394 |
| Cyprus | 0,382920 |
| Poland | 0,446501 |
| Portugal | 0,515093 |
| Romania | 0,414025 |

Members of Cluster Number 2 and Distances from Respective Cluster contains 13 cases

| linkage | Distance |
|---|---|
| **Belgium** | 0,529010 |
| Czechia | 0,917408 |
| Germany | 0,699175 |
| Estonia | 0,578682 |
| Spain | 0,628574 |
| France | 0,456592 |
| Latvia | 0,732326 |
| Lithuania | 0,959339 |
| Hungary | 0,762999 |
| Malta | 0,727783 |
| Austria | 0,519890 |
| Slovenia | 0,480021 |
| Slovakia | 0,293682 |

Members of Cluster Number 3 and Distances from Respective Cluster contains 6 cases

| linkage | Distance |
|---|---|
| **Denmark** | 0,595523 |
| Ireland | 1,403516 |
| Luxembourg | 0,423522 |
| Netherlands | 0,549108 |
| Finland | 0,901197 |
| Sweden | 0,406431 |

**Fig. 5. Members of each cluster and distances to the cluster center (2013)**

**Source:** compiled by the authors.

3 clusters, and the quality of clustering was very high. It was concluded that for the periods of 2013, 2016, 2020, the clustering results were similar, and the cluster member countries coincided in general. But the results of the division into clusters in 2024 are very different, and the average values of digitalization indicators for each of the three clusters are also different (*Fig. 7*).

*Tbl. 1* shows the results of dividing the EU countries into three clusters in 2024.

Thus, cluster 1 with low values of digitalization indicators in 2024 includes only 2 countries: Bulgaria, Romania.

Cluster 2 with average values of digitalization indicators in 2024 includes the following 11 countries: Germany, Greece, France, Croatia, Italy, Latvia, Lithuania, Poland, Portugal, Slovenia, Slovakia. Slovenia has the smallest distance from the center of the cluster.

| Variable | Analysis of Variance (Digitalisation Normalized Dataset) Between SS | df | Within SS | df | F | signif. p |
|---|---|---|---|---|---|---|
| LIA_13 | 19,92877 | 2 | 6,07123 | 24 | 39,38993 | 0,000000 |
| IUI_13 | 21,20425 | 2 | 4,79575 | 24 | 53,05766 | 0,000000 |
| IUB_13 | 19,17866 | 2 | 6,82134 | 24 | 33,73878 | 0,000000 |
| IUSN_13 | 14,74717 | 2 | 11,25283 | 24 | 15,72637 | 0,000043 |
| IUHI_13 | 17,05958 | 2 | 8,94042 | 24 | 22,89767 | 0,000003 |
| IUOC_13 | 8,32020 | 2 | 17,67980 | 24 | 5,64726 | 0,009773 |
| EnOO_13 | 9,00798 | 2 | 16,99202 | 24 | 6,36156 | 0,006071 |
| ETE_13 | 9,45684 | 2 | 16,54316 | 24 | 6,85976 | 0,004403 |
| %GVA_13 | 9,36823 | 2 | 16,63177 | 24 | 6,75927 | 0,004694 |
| %PTE_13 | 17,48765 | 2 | 8,51235 | 24 | 24,65264 | 0,000002 |

**Fig. 6. Analysis of variance table (2013)**

**Source:** compiled by the authors.

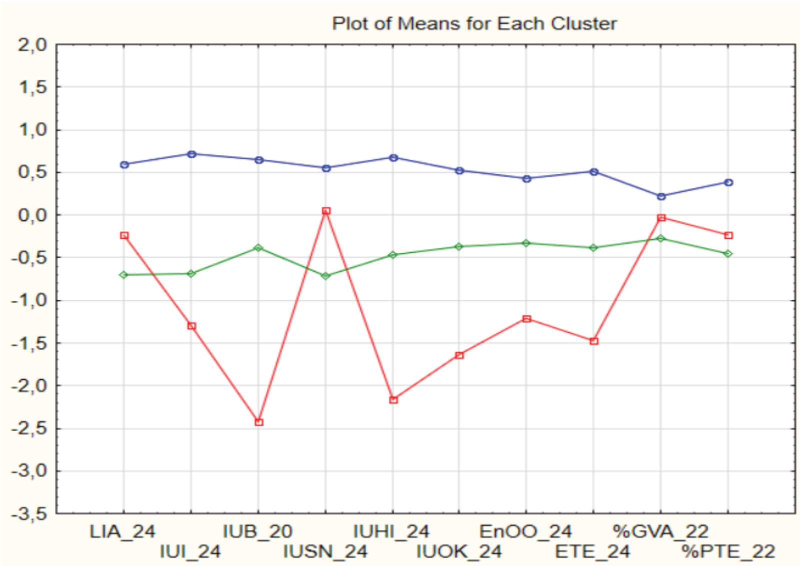


**Fig. 7. Graph of average values of indicators for each cluster (2024)**

**Source:** compiled by the authors.

Cluster 3 with high values of digitalization indicators includes the following 8 countries: Belgium, Czechia, Denmark, Estonia, Ireland, Spain, Cyprus, Luxembourg, Hungary, Malta, Netherlands, Austria, Finland, Sweden. The Czech Republic has the smallest distance from the center of the cluster, and the largest, as always, Ireland.

Thus, within the framework of this study, clustering was carried out according to ten integral indicators of digitalization of the population, business and digital economy based on normalized data for 2013, 2016, 2020 and 2024. The results obtained will allow us to determine the trends of digital transformation based on the analysis of the dynamics of the cluster structure.

And at the next stage of the study, an analysis of the dynamics of the cluster structure was conducted by constructing transition matrices that reflect the movement of countries between clusters over time, which allows us to assess the trends, stability and speed of digital change.

First, the structure of digital inequality in 2013–2020 was analyzed. Thus, in 2013, a classic three-level model of digital development was traced: 1) Cluster 1 (low level): mainly Southern and Eastern European countries (8 countries); 2) Cluster 2 (medium level): the most numerous group of 13 countries; 3) Cluster 3 (high level): 6 technologically advanced countries of the North and Benelux. The same three-layer structure is preserved in 2016 and 2020, although the intercluster distance is gradually decreasing.

The study of the trajectories of countries' movement between clusters was carried out on the basis of constructing a transition matrix. Transition matrix $M = (m_{ij})$ is formed according to the rule:

$$m_{ij} = \text{number of countries that moved from cluster } i \text{ to cluster } j,$$

Table 1

**Results of dividing the EU countries into three clusters in 2024**

| Country | Cluster | Dist. | Country | Cluster | Dist. | Country | Cluster | Dist. |
|---|---|---|---|---|---|---|---|---|
| Bulgaria | 1 | 0.427 | Germany | 2 | 0.424 | Belgium | 3 | 0.628 |
| Romania | 1 | 0.427 | Greece | 2 | 0.982 | Czechia | 3 | 0.381 |
| | | | France | 2 | 0.789 | Denmark | 3 | 0.983 |
| | | | Croatia | 2 | 0.765 | Estonia | 3 | 0.930 |
| | | | Italy | 2 | 0.463 | Ireland | 3 | 1.796 |
| | | | Latvia | 2 | 0.868 | Spain | 3 | 0.710 |
| | | | Lithuania | 2 | 0.768 | Cyprus | 3 | 0.892 |
| | | | Poland | 2 | 0.566 | Luxembourg | 3 | 0.926 |
| | | | Portugal | 2 | 0.365 | Hungary | 3 | 0.636 |
| | | | Slovenia | 2 | 0.382 | Malta | 3 | 0.624 |
| | | | Slovakia | 2 | 0.543 | Netherlands | 3 | 0.779 |
| | | | | | | Austria | 3 | 0.573 |
| | | | | | | Finland | 3 | 0.708 |
| | | | | | | Sweden | 3 | 0.408 |

**Source:** compiled by the authors.

where $i$ – cluster in the previous period, $j$ – cluster in the next period.

Three situations are possible:

– *a country retains its cluster* – elements on the main diagonal of the matrix;

– *a transition to a cluster with higher digitalization parameters* – elements above the main diagonal;

– *a "fall" to a lower cluster* – elements below the main diagonal.

Let us consider the transition matrix for the period 2013–2016, which will allow us to examine the trajectories of countries' movement between clusters (*Tbl. 2*).

As can be seen from Tbl. 2, none of the countries worsened their position over the period from 2013 to 2016. On the contrary, there was an improvement in the positions of the following countries: Croatia, Poland, Portugal, which moved to cluster 2, as well as Belgium and Estonia moved from the second to the third cluster. And none of the countries made a "jump" through the cluster.

Similarly, a transition matrix was constructed for 2016–2020. Thus, during this period, countries are characterized by movements not only "forward", but also "backward". The decrease in the share of "outsider" countries in 2016 (from 8 to 5), as well as its repeated increase in 2020 (to 7) indicates the instability of digital alignment processes at different stages of development of digital services and infrastructure.

*Tbl. 3* presents the transition matrix for 2020–2024.

During the period 2016–2020, a clear stability of the group of digital leaders is recorded: cluster 3 includes Denmark, Finland, Sweden, Netherlands in all years. Sweden has consistently the smallest distance to the center of the cluster, which indicates its status as the "anchor" center of digital progress in the EU. In contrast, Ireland has demonstrated the greatest distance to the center of the high digitalization cluster in all years, which reflects structural disparities between individual components of its digital development (high Internet activity of the population and uneven development of the digital economy).

From Tbl. 3, it can be seen that none of the EU countries worsened its position in terms of digital development during the period from 2020 to 2024. All changes occurred on the main diagonal of the matrix and above it.

Next, an assumption was made about a structural break in the digital development of the EU countries in 2024. Thus, in 2024, a qualitative transformation of the cluster structure is observed, which is significantly different from previous periods. The cluster with low digitalization values is reduced to two countries (Bulgaria, Romania), which indicates a sharp decrease in digital inequality in the lower segment. At the same time, the cluster with an average level of digital development decreases to 11 countries, while the cluster with high digitalization increases to 15 countries.

Thus, in 2024, a massive shift of countries from the average level of digitalization to the group of lead-

**Table 2**

**Transition matrix (2013–2016)**

| | **Cluster 1 (2016)** | **Cluster 2 (2016)** | **Cluster 3 (2016)** | **Previous number of countries** |
|---|---|---|---|---|
| **Cluster 1 (2013)** | 5 countries remain: Bulgaria, Greece, Italy, Cyprus, Romania | 3 countries moved: Croatia, Poland, Portugal | – | 8 |
| **Cluster 2 (2013)** | – | 11 countries remain: Czechia, Germany, Spain, France, Latvia, Lithuania, Hungary, Malta, Austria, Slovenia, Slovakia | 2 countries moved: Belgium, Estonia | 13 |
| **Cluster 3 (2013)** | – | – | 6 countries remain: Denmark, Ireland, Luxembourg, Netherlands, Finland, Sweden | 6 |
| Actual number of countries | 5 | 14 | 8 | 27 |

**Source:** compiled by the authors.

**Table 3**

**Transition matrix (2020–2024)**

| | **Cluster 1 (2024)** | **Cluster 2 (2024)** | **Cluster 3 (2024)** | **Previous number of countries** |
|---|---|---|---|---|
| **Cluster 1 (2020)** | 2 countries remain: Bulgaria, Romania | 5 countries moved up: Greece, Croatia, Italy, Poland, Portugal | – | 7 |
| **Cluster 2 (2020)** | – | 6 countries remain: Germany, France, Latvia, Lithuania, Slovenia, Slovakia | 7 countries moved up: Belgium, Czechia, Spain, Cyprus, Lux-embourg, Hungary, Austria, | 13 |
| **Cluster 3 (2020)** | – | – | 7 countries remain: Denmark, Estonia, Ireland, Malta, Netherlands, Finland, Sweden | 7 |
| Actual number of countries | 2 | 11 | 14 | 27 |

**Source:** compiled by the authors.

ers is noted, confirming the effect of technological leveling, the accumulation of digital competencies of the population, and the growth of digital business activity.

It should be noted that Poland, Portugal, Italy and Croatia, which in 2013–2020 were in the "lower" cluster, rise to the middle in 2024. At the same time, the Czech Republic, Estonia, Spain, Cyprus, Malta and Austria move to the high digitalization cluster.

The dynamics of distances to the cluster centers was also analyzed, which allows us to examine changes in the internal homogeneity of clusters:

- Stable "cluster anchors" are observed: Sweden – in the leader cluster; Slovakia and Austria – in the medium-level cluster; Romania and Bulgaria – in the low-level cluster.

- A decrease in inter-cluster dispersion by 2024, which indicates the convergence of digital development.
- The increase in Ireland's distance in the leader cluster (to 1.796 in 2024), indicating a disproportionate growth of individual digital economy indicators compared to other components of inclusion and business digitalization.

Thus, the general trends of the digital transformation of the EU countries were identified:

- *convergence of digital development:* by 2024, almost all EU countries demonstrate convergence in terms of the level of digitalization, as evidenced by a sharp reduction in the "lower" cluster;
- *expansion of the group of digital transformation leaders:* in 2024, the high digitalization cluster became the largest for the entire period;
- *strengthening the role of digital inclusion:* almost all "new leaders" (Czech Republic, Spain, Malta, Austria, Cyprus) made a breakthrough precisely due to the widespread use of the Internet by the population and the growth of digital competencies;
- *the lag of the digital economy from the pace of digitalization of the population and business:* the indicators of %GVA and %PTE indicators demonstrate the least sensitivity to structural changes, which may indicate a slower transformation of the labor market and the structure of added value;
- *stability of the Nordic countries as the undisputed leaders of the EU digital ecosystem.*

## CONCLUSIONS

Thus, the paper systematizes the theoretical foundations of digital transformation and outlines its role in the socio-economic development of countries. It is shown that digitalization is the basis for increasing the competitiveness, productivity and innovative activity of the economy.

The study implemented a cluster analysis model, which allowed grouping EU countries by the level of digital development based on the k-means and hierarchical clustering methods. This model provides a division of countries into typological groups according to their positions in the digital space, which makes it possible to assess the differentiation of countries within the EU, identify leaders and outsiders of digital development, and also trace the dynamics of changes over time.

The implementation of a model for analyzing the trajectories of digital development of EU countries based on a study of the cluster structure made it possible to track the movement of countries between clusters in dynamics using a transition matrix, which allows assessing trends, stability and speed of digital changes.

Thus, the proposed comprehensive model allows us to assess not only the current state of digital development of EU countries, but also to identify long-term trends, influencing factors and possible scenarios for further digital evolution. Comparing the cluster structure in dynamics made it possible to trace both changes in digital development trends common to all EU countries and individual trajectories of countries. ■

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