“Clustering EU countries by the level of information and communication technologies development”

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ARTICLE INFO	Vladimir Bilozubenko, Maxim Korneyev, Serhii Ivantsov, Vadym Yakovenko, Fedir Zhuravka, Dmytro Shchytov and Mykola Nahorianskyi (2025). Clustering EU countries by the level of information and communication technologies development. *Problems and Perspectives in Management*, *23*(2), 862-874. doi:10.21511/ppm.23(2).2025.63
DOI	http://dx.doi.org/10.21511/ppm.23(2).2025.63
RELEASED ON	Friday, 27 June 2025
RECEIVED ON	Monday, 21 April 2025
ACCEPTED ON	Monday, 23 June 2025

JOURNAL	"Problems and Perspectives in Management"
ISSN PRINT	1727-7051
ISSN ONLINE	1810-5467
PUBLISHER	LLC “Consulting Publishing Company “Business Perspectives”
FOUNDER	LLC “Consulting Publishing Company “Business Perspectives”

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
38	0	3

BUSINESS PERSPECTIVES

LLC "CPC "Business Perspectives"
Hryhorii Skovoroda lane, 10,
Sumy, 40022, Ukraine
www.businessperspectives.org

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CLUSTERING EU COUNTRIES BY THE LEVEL OF INFORMATION AND COMMUNICATION TECHNOLOGIES DEVELOPMENT

Received on: 21st of April, 2025
Accepted on: 23rd of June, 2025
Published on: 27th of June, 2025

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Abstract

The development and wider use of information and communication technologies (ICT) are at the core of the EU's strategic course to intensify digital transformation. This is complicated by significant differences between EU member states in this area, the alignment of which is becoming an important task for supranational policy. The paper, therefore, aims to cluster EU countries by their ICT development level and identify key differences. A dataset was generated based on 18 relative ICT development indicators used in the ICT Development Index and the Digital Economy and Society Index. In the first stage, based on the k-means method, the EU countries were divided into three clusters, which characterize their differences in the ICT development level. Then, using the decision tree method, indicators were identified that absolutely distribute the resulting clusters, confirming their specificity. The parameters that reflect the most significant differences between EU countries in ICT development include individuals using the Internet, active mobile broadband subscriptions per 100 inhabitants, mobile data and voice high-consumption basket price, fixed-broadband Internet basket price, ICT graduates, fiber to the premises coverage, mobile broadband take-up, and 5G spectrum. This has demonstrated the critical importance of the spread and availability of the Internet, mobile technologies, and human resources for intensifying digital transformations within the EU. The results can be used in supranational policies to support the development of ICT and digital transformations and also serve as a guide in ensuring digital progress in individual member countries.

Keywords EU countries, ICT development indicators, clustering, classification analysis, differences, supranational policy, digital transformation

JEL Classification C38, O30, O52

INTRODUCTION

The rapid progress and use of information and communication technologies (ICT) in various sectors of the economy observed in recent decades have brought about significant structural and functional changes, stimulated economic activity, innovation, and investment, and contributed to overall economic growth. Digitalization, aimed at enhancing efficiency and improving production chains, logistics, and management systems, increases the global competitiveness of national economies. Therefore, digital transformations have become a global trend of socio-economic modernization.

The EU is implementing an ambitious Digital Decade policy aimed at the transition to a digital economy. It is focused on four main areas: digital skills, digital infrastructure, digital transformation of business and public services, and support for the green transition (European Commission, n.d.). In the context of the intensification of digital transformations envisaged by this policy, attention to ICT develop-

Conflict of interest statement:
Author(s) reported no conflict of interest

http://dx.doi.org/10.21511/ppm.23(2).2025.63

ment and, accordingly, to overcoming significant differences between member states in this area that hinder the achievement of common goals is naturally increasing. From a supranational policy perspective, this poses the challenge of assessing the similarities and key differences between EU countries in terms of ICT development. This will enable a more rational prioritization of support for the digital sector, particularly for lagging member states.

1. LITERATURE REVIEW

ICT has become one of the most powerful drivers of economic dynamics and transformation in the modern economy. The positive impact of digitalization on economic growth has been empirically confirmed in both the old (EU-15) and new (EU-12) member states (Mura & Donath, 2023). With the development of the digital economy, the importance of ICT as a factor of economic growth is increasing (Magoutas et al., 2024). Therefore, countries are trying every possible way to promote the progress and use of ICT and increase their network readiness and digital competitiveness (Savulescu, 2015). At the same time, as the European experience shows, the impact of ICT on the economies of different countries has significant features and differences (Fernández-Portillo et al., 2020), which is fundamentally important, given the EU's unified course toward building a digital economy. Implementing the large-scale Digital Compass strategy in the EU involves assessing the progress of digitalization processes in member states, the level of achievement of established target indicators, etc. This also requires a comparative analysis of digital transformations in different EU countries (Małkowska et al., 2021).

The deployment of large-scale digital transformations requires taking into account the diverse impacts of ICT, including the decisive importance of the modernization of industry and infrastructure (Fura et al., 2024), stimulating economic activity, innovation, increasing productivity, reducing social inequality (Cioacă et al., 2020), improving environmental quality, mitigating the effects of climate change, and promoting human and financial development (Arshad et al., 2024). Given this, the development of ICT is given one of the central roles in ensuring positive structural changes in national economies in the context of the green transition, in particular, promoting the development of a circular economy (Nguyen & Le, 2022; D'yakonova et al., 2018), increasing the level of environmental friendliness, and reducing the energy intensity of production (Matthess et al., 2023). Digitalization aims to increase overall efficiency in the context of ensuring sustainability (Bocean & Vărzaru, 2023; Zhuravka et al., 2019), increasing productivity, and creating new opportunities for businesses (Ghazy et al., 2022; Zhuravka et al., 2023). In the EU, harnessing the benefits of ICT is seen as a prerequisite for the dual (green and digital) transition and for achieving global leadership, especially digital leadership (Gao, 2024). Increased attention is being paid to ICT development, as digitalization allows for the simultaneous restructuring of the economy in line with sustainability requirements and an increase in economic efficiency. One of the important effects of digitalization is the stimulation of various innovations. Therefore, ICT progress is closely viewed as one of the conditions for increasing digitalization and, consequently, innovation capacity (Marti & Puertas, 2023). In this context, the EU seeks to promote the success of member states in the field of innovation, especially helping those that are lagging behind, to increase overall competitiveness. Given this, assessing the relationship between digitalization and innovation is a separate area of research (Hernández de Rojas et al., 2024; Brodny & Tutak, 2024).

The need to develop ICT is due to the growth of not only economic effects but also the social significance of these technologies and digitalization based on them (Novikova et al., 2020). In the EU, digital transformation is viewed as a crucial step in enhancing healthcare systems and ensuring equitable access to medical services for all populations (Majcherek et al., 2024; Chatti, 2020). ICT and advanced digital technologies (Internet of Things, machine learning, blockchain, etc.) allow for significant improvements in healthcare value chains (Mauro et al., 2024). In addition, ICTs are increasingly used to improve education and training systems and digitalize the delivery of relevant services, which has a significant positive impact on human capital and a corresponding effect on employment growth and the well-being of the population (Laitsou et al., 2025). Digitalization also significantly changes the conditions under which civil society operates, which is particularly important for the EU given its political, legal, and spatial specificities. ICTs are transforming the way citizens communicate, participate in political processes, utilize services, and interact with organizations operating within the EU. This includes, in particular, the implementation of e-government (Golob et al., 2024).

Given the importance of digitalization for the green transition, economic growth, increased efficiency and competitiveness, and its significant social impacts, the EU prioritizes supporting digital transformation. The basis for this is the progress of ICT (Quaglio et al., 2016). To formulate the relevant EU policy, it is important to monitor the achievements of individual member states, their characteristics, the gaps between them, the lag of individual countries behind the leaders, and the average level in the EU. Moreover, it is essential to understand the key indicators that, at a certain point, most significantly differentiate countries in terms of ICT development.

ICT development has become an important independent object of socio-economic research. To assess differences between countries, special international indices that summarize various indicators are widely used in addition to traditional statistical monitoring. The ICT Development Index has long been one of the most authoritative globally (James, 2012). Another special index used by the EU is the Digital Economy and Society Index (Bruno et al., 2023). This index measures the level and dynamics of digitalization and is also used to assess the convergence of EU countries in the digital sphere (Szajt et al., 2024).

Analyzing ICT development, digitalization processes, and their consequences at the macro level involves the use of a large set of indicators (Perumal et al., 2024). Accordingly, this complicates comparisons between countries, although in the EU, this is critical for understanding national characteristics and differences (Zhuravka et al., 2021; Biernacki et al., 2023), identifying leaders in building a digital economy to share experiences and ensure common progress in the EU (Kiseľáková et al., 2022; Palale & Ishida, 2024).

Given the multifaceted and multifactorial nature of ICT development, its study at the EU level requires specific methodologies for comparison across member countries (Bánhidi & Dobos, 2023; Hunady et al., 2022). Therefore, there is a need to improve the methods for conducting international comparisons, a generalized analysis by groups of countries, particularly the EU, covering a specific set of indicators for assessing ICT development. In addition to defining leadership, these methods should identify key parameters that differentiate countries. This is important for justifying decisions supporting technological change and individual countries within supranational policies.

This paper aims to cluster EU countries by ICT development level and to identify key differences between them, considering the strategic course for intensifying digital transformations.

2. METHODS

To conduct the study, a set of quantitative indicators was formed that is used in two authoritative international indices designed to assess ICT development at the national level, namely, the ICT Development Index (IDI) (International Telecommunication Union, 2025) and the Digital Economy and Society Index (DESI) (European Commission, n.d.).

Eight relative indicators were taken from the IDI in unnormalized values. Two indicators (mobile broadband Internet traffic per mobile broadband subscription and fixed broadband Internet traffic per fixed broadband subscription) were excluded from the analysis because they are presented in absolute values.

Ten relative indicators from the Digital Skills Indicators and Digital Infrastructure Indicators sections (except for the "5G SIM cards share of population" indicator, for which there is not much data) were taken from DESI, which directly involves the development of ICT and does not directly duplicate the IDI components.

A dataset was formed for further analysis based on the indicators selected from the IDI and DESI (Table 1).

http://dx.doi.org/10.21511/ppm.23(2).2025.63

Table 1. General list of indicators selected from IDI and DESI characterizing ICT development at the national level

Source: ICT Development Index 2024 (International Telecommunication Union, 2025) and DESI indicators 2024 (European Commission, n.d.).

Variable	Indicators
	1. Indicators included in the IDI
x_1	Individuals using the Internet, %
x_2	Households with Internet access at home, %
x_3	Active mobile broadband subscriptions per 100 inhabitants
x_4	Population covered by at least a 3G mobile network, %
x_5	Population covered by at least a 4G/LTE[1] mobile network, %
x_6	Mobile data and voice high-consumption basket price, as % of GNI[2] per capita
x_7	Fixed-broadband Internet basket price, as % of GNI per capita
x_8	Individuals who own a mobile phone, %
	2. Indicators included in the DESI
x_9	ICT specialists, % of total employment
x_{10}	ICT graduates, % of graduates
x_{11}	Share of fixed broadband subscription >= 100 Mbps, % of fixed broadband subscriptions
x_{12}	Share of fixed broadband subscription >= 1 Gbps, % of fixed broadband subscriptions
x_{13}	Fixed Very High-Capacity Network coverage, % of households
x_{14}	Fiber to the Premises coverage, % of households
x_{15}	Mobile Broadband take-up, % of individuals aged 16–74
x_{16}	5G coverage, % of households
x_{17}	5G coverage in the 3.4-3.8 GHz band, % of households
x_{18}	5G spectrum, % of harmonized spectrum assigned

Note: [1] LTE – Long-Term Evolution; [2] GNI – Gross National Income.

When assessing the formed set of parameters, it should be noted that they are heterogeneous and specific. The groups of indicators for IDI and DESI complement each other, expanding the range of analysis areas. The full list of indicators (see Table 1) does not contain completely duplicated or mutually exclusive indicators. The data distribution nature for each indicator is not taken into account. Also, possible relationships and mutual influence between different indicators are not taken into account; they are considered independent. The same significance is attributed to the indicators, and their contribution to ICT development is assumed. In terms of change, all indicators do not have a minimum value. The desired change for most indicators is to maximize their value, except for price indicators x_6 and x_7. Some indicators can potentially saturate at 100% (this is clearly visible at x_4 and x_5). At the same time, even in indicators with potential saturation, significant differences are observed between countries. In general, it can be said that the resulting set of indicators satisfies the conditions of systematicity, completeness, and diversity in characterizing such a complex phenomenon as the development of ICT at the country level, covering its various aspects. Given the above and the authority of IDI and DESI, the dataset presented in Table 1 can be used to compare EU countries in the ICT area (the initial data and the results of the first stage of calculations are presented in Table A1, Appendix A). Identifying key parameters of differentiation of EU countries by ICT development level will take place in two stages.

The first stage involves dividing EU countries into clusters based on ICT development indicators. The indicators presented in Table 1 form a feature space, i.e., an "object-property" table for clustering, in which the objects are countries, and the features are indicators (parameters), the values of which characterize the ICT sphere. As a result of clustering, the countries in the set are divided into clusters based on ICT development parameters, i.e., into distinct natural classes. Countries assigned to a certain cluster are relatively similar to each other, and countries from different clusters are relatively different. This will serve as the basis for determining the key parameters that differentiate countries in the future.

The possibility of clustering is preliminarily assessed using 2D and 3D visualization based on the existing dataset. The optimal number of clusters is determined based on the dendrogram and special indices (Sum of Squared Error Index, Davies-Bouldin Index, Trace Index, Calinski-Harabasz Index, Dunn Index, and PBM Index). Given the nature of the data, it is planned to use the generally accepted k-means method (Euclidean distance metric) for clustering, which is widely used in socio-economic research. The methodology for calculating the k-means method is well-known and does not require additional explanations. Tools for visualization, dendrogram construction, index calculation for determining the optimal number of clusters, as well as performing calculations directly on clustering, are available on the ScienceHunter web portal.

The second stage is the selection, through classification analysis, of information groups of features (IGFs) that most distinguish the obtained clusters. The basis for the classification analysis is the training sample (the "object-class" table), constructed according to the list of indicators (together with empirical data) given in Table 1, with the division of EU countries into classes, which are recognized as clusters obtained in the first stage.

Based on the compactness hypothesis, IGFs are relatively small combinations of indicators with the maximum, if possible absolute, discriminatory (separating) ability or informativeness, as close as possible to the informativeness of the entire training sample. IGFs indicate the most significant differences between clusters and, accordingly, the parameters by which all countries from the population included in different clusters differ from each other. Therefore, the indicators included in the IGF are key parameters for differentiating EU countries by ICT development level.

The IGFs are determined based on the mathematical processing of the obtained training sample, for which the logical-combinatorial decision tree method is used. As a result of processing, one or several IGFs can be identified. Their information content is compared with the information content of the entire training sample, based on which the most suitable combinations for analysis are selected. Based on the study's objective, not only the IGFs are important, but also the indicators included in them. Therefore, in the case of identifying several highly informative IGFs, all indicators from these combinations can be considered key parameters for differentiating EU countries.

The information content of the training sample, each of the indicators included in it, as well as their various combinations for finding the highest quality IGFs, is assessed using the formula:

$$V\left(x_{i1},\ldots,x_{ij}\right)=\frac{1}{k}\sum_{\Delta\in\Gamma}\max_{Y}\left(\frac{m_{\Delta Y}}{m_{Y}}\right), \quad (1)$$

where k is the number of classes (clusters), m_Y is the number of objects belonging to a class (cluster) Y, $\Delta = t_{i1}, t_{i2}, \ldots, t_{ij}\left(0 \le t_{ij} \le k_{ij}-1\right)$, $j = 1,\ldots,\Gamma$ means the arbitrary set of parameter values $x_{i1},\ldots,x_{ij}\left(1 \le \Gamma \le n\right)$, $m_{\Delta Y}$ denotes the number of sampling sets of the m class, for which the relation $x_{ij} = t_{ij}\left(j = 1,\ldots,\Gamma\right)$ is performed, t_{ij} are the values of parameters x_{ij} in the set of Δ, Γ means variety of all sets of parameter values $x_{i1},\ldots,x_{ij}$. With complete separation of classes, this estimate acquires a limiting value of 1. It is important to note that such an estimate is calculated directly from the training sample data.

3. RESULTS

The proposed methodology, based on Data Mining methods, is applicable to international studies, where new non-obvious patterns are sought in multidimensional data sets for a set of countries. Specifically, this concerns the definition of key parameters for differentiating EU countries based on their ICT development level.

Based on the list of indicators given in Table 1, a set of empirical data for EU countries was compiled. Using 3D visualization, dendrograms, and special indices, it was determined that clustering can be carried out based on the existing dataset, and the optimal number of clusters into which the set of EU countries is best divided is three. This is the exact quantity that is specified for mathematical processing, which resulted in the following distribution:

1. Cluster I: Austria, Denmark, Estonia, Finland, Ireland, Luxembourg, the Netherlands, and Sweden;

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2. Cluster II: Belgium, Cyprus, France, Hungary, Latvia, Lithuania, Malta, Poland, Portugal, Romania, Slovenia, and Spain;

3. Cluster III: Bulgaria, Croatia, the Czech Republic, Germany, Greece, Italy, and Slovakia.

Primary data, the results of dividing EU countries into clusters based on ICT development indicators, as well as calculated additional analytical estimates for clusters and the entire set of countries, are presented in Table A1 (Appendix A). The calculation of median values of indicators showed conditional leadership of Cluster I over both other clusters, in particular, for x_1, x_2, x_3, x_8, x_9, x_{10}, x_{13}, x_{14}, x_{15}, x_{16}, x_{17}, and x_{18} (the absolute maximum was achieved for x_4); for the remaining indicators, Cluster I is somewhat inferior to Clusters II and III. At the same time, in terms of maximum values, Cluster I is ahead of both other clusters also in many indicators, in particular, x_1, x_2, x_3, x_9, x_{10}, x_{15}, and x_{17} (the absolute maximum was reached for x_4, x_5, and x_{16}). Each cluster naturally has its own leading and outsider countries, which can be a separate aspect of analysis. The difference between each indicator's minimum and maximum values shows a different range. The coefficient of variation for the set of countries exceeded the conditional threshold of 33% for the following indicators: x_6, x_7, x_{10}, x_{12}, and x_{17}, and for several others (x_9, x_{11}, x_{14}, and x_{18}) it came significantly closer to this threshold. The coefficients of variation for each cluster are often naturally lower than for the entire set, although they are also high, in particular in Cluster I for x_6, x_{12}, and x_{17}; in Cluster II for x_6, x_7, x_{12}, x_{17}, and x_{18}; and in Cluster III for x_6, x_7, x_{12}, and x_{14}. This reveals significant differences between countries in individual indicators, primarily concerning prices and the parameters of using new ICT.

After obtaining the division of countries into clusters (classes), a training sample was compiled and mathematically processed to classify these clusters to find differences between them. Checking the training sample's total separating power (information content), i.e., the quality of the available data set, showed a value of 1, interpreted as the possibility of absolute separation of all classes. The assessment of the informativeness of individual features fluctuates from 0.4 to 0.7 (Table 2). This indicates the absence of any indicator that would, separately from others, absolutely or at a high level, separate all classes. This confirmed the need to search for certain combinations of indicators with higher informativeness than individual indicators.

Given the assessment of the separating power of the training sample and individual indicators, an attempt was made to find the IGFs whose information content would be absolute or as close as possible to the complete separation of classes. Initially, two-feature IGFs were tested, but their informativeness turned out to be insignificant. By testing three-feature combinations, one IGF with an information content of 0.94 was obtained, which included the x_1, x_3, and x_{14} indicators. The other two combinations (x_6, x_{14}, x_{17} and x_{10}, x_{14}, x_{17}) had significantly lower separating power. An attempt was then made to find combinations of four features. As a result, five IGFs were identified, the information content of which was 1: 1) x_1, x_3, x_7, x_{14}; 2) x_1, x_3, x_{14}, x_{18}; 3) x_3, x_7, x_{14}, x_{15}; 4) x_3, x_{10}, x_{14}, x_{15}; and 5) x_6, x_{10}, x_{14}, x_{15}. These IGFs not only have absolute informativeness in class recognition but also combine indicators from both data sources (IDI and DESI), further confirming the reliability. Considering that the obtained IGFs of four indicators were sufficient for the complete distribution of classes, the search for combinations of five or more indicators was not conducted.

Thus, IGFs (four indicators each) were invented, which completely distinguish between clusters and, accordingly, EU countries. Given this, all in-

Table 2. Assessment of the information content of individual indicators included in the training sample

Variable	Information content assessment	Variable	Information content assessment	Variable	Information content assessment
x_1	0.67	x_7	0.45	x_{13}	0.49
x_2	0.69	x_8	0.48	x_{14}	0.54
x_3	0.58	x_9	0.50	x_{15}	0.70
x_4	0.42	x_{10}	0.51	x_{16}	0.48
x_5	0.40	x_{11}	0.59	x_{17}	0.49
x_6	0.53	x_{12}	0.40	x_{18}	0.52

dicators included in the selected combinations can be attributed to the key parameters of differentiating EU countries by ICT development level at the time of the study since they most determine the positions of countries in the entire set, that is, they are the most significant factors of their differentiation by ICT. It should be noted that most of the indicators in the obtained IGFs are repeated (x_1 – 2 times, x_3 – 4 times, x_7 – 2 times, x_{10} – 2 times, x_{14} – 5 times, and x_{15} – 3 times), which also confirms the correctness of the result obtained. Considering the significance of each indicator within different IGFs to be the same and taking into account duplication, it is possible to compile the following complete list of selected key parameters for differentiating EU countries by their ICT development level:

- x_1 "Individuals using the Internet, %" (the IDI indicator) is one of the basic indicators that reflects the scale of ICT use in public life and generally assesses the level of economic digitalization. Increasing the share of individuals using the Internet is a prerequisite for increasing other indicators reflecting the state of ICT.

- x_3 "Active mobile broadband subscriptions per 100 inhabitants" (the IDI indicator) can be called an infrastructure parameter. It focuses on the scale of the population's use of not just broadband but mobile technologies, which are of particular importance in modern conditions, particularly in terms of perspective. The spread of mobile broadband is a condition for expanding the range and improving the quality of digital services, increasing data traffic, and creating new opportunities for users. The indicator reflects the new quality of ICT, as well as the inclusion of the population in these processes.

- x_6 "Mobile data and voice high-consumption basket price, as % of GNI per capita" (the IDI indicator), like the previous indicator, focuses on using mobile technologies, but from the point of view of their availability to the population. Given the growth of mobile data traffic and the intensive consumption of certain digital services, a decrease in the price level is generally positive, which increases the availability of ICT and its use by the population. However, it is also necessary to consider the change in the quality of digital services, which is becoming increasingly significant.

- x_7 "Fixed-broadband Internet basket price, as % of GNI per capita" (the IDI indicator), like x_6, assesses the affordability of the Internet, but fixed broadband, which is already an established element of the digital infrastructure for both the population and businesses. Broadband is often more widespread in more developed countries, but given its importance, the price should be leveled out within the EU. Additionally, when the price increases, it will be necessary to consider the impact of these changes on the quality of such communication.

- x_{10} "ICT graduates, % of graduates" (the DESI indicator) – the inclusion of this indicator in the list is logical due to the critical importance of specialists for the development of ICT and the intensification of digital transformations. Countries strive to increase the absolute number and share of ICT graduates in the employment structure; however, as the study shows, there are significant differences between EU countries in this parameter, which are reflected in the functioning of the digital sector.

- x_{14} "Fiber to the Premises coverage, % of households" (the DESI indicator) – this indicator shows the spread of this new type of ICT, which provides higher quality and speed of the Internet. The increasing use of fiber optics is a prerequisite for increasing Internet usage as data traffic volumes and technical requirements increase.

- x_{15} "Mobile broadband take-up, % of individuals aged 16–74" (the DESI indicator), like x_3, reflects the population's involvement in the digital environment based on the use of mobile broadband. As noted earlier, the indicator reflects the innovative direction of progress and use of ICT.

- x_{18} "5G spectrum, % of harmonized spectrum assigned" (DESI indicator), i.e., the share of available harmonized radio spectrum allocated for 5G networks, distributed among telecom operators in a given country. The inclusion of this indicator in this list once again

http://dx.doi.org/10.21511/ppm.23(2).2025.63

highlights the importance of mobile technologies, particularly their new generation, which expands the possibilities for digitalization and leverages the advantages of ICT.

Thus, the selected indicators reflect different aspects of ICT development and, accordingly, the differentiation of EU countries in this area. They also characterize the conditions for intensifying digital transformations. In addition to x_1 and x_{10}, which have a common meaning, the list includes four indicators (x_3, x_{14}, x_{15}, and x_{18}), characterizing the level of digital infrastructure. In particular, three indicators relate to mobile technologies, the importance of which is constantly increasing for providing digital services. The scale of Internet use (x_1), the percentage of ICT graduates (x_{10}), and infrastructure capacity parameters (x_3, x_{14}, x_{15}, and x_{18}) show characteristic growth patterns that combine business actions with national and supranational policy measures. Two additional indicators (x_6 and x_7) relate to the price aspect, which is also crucial for expanding the use of ICT. Identifying all these parameters of differentiation among EU countries by ICT development level allows for a more targeted allocation of resources.

There is a significant difference between EU countries for most selected indicators. It is characteristic that the list of selected indicators included those that have a variation coefficient (CV) close to or exceeding the conditional threshold of 33%, namely, x_3 – 26.1%, x_6 – 51.8%, x_7 – 34.2%, x_{10} – 35.6%, x_{14} – 28.00%, and x_{18} – 32.8%. At the same time, the coefficient of variation of x_1 and x_{15} is low (5.4% and 5.5%, respectively) since their influence was manifested precisely in combinations. On the other hand, for some indicators not included in the selected IGFs, the coefficient of variation is close to or significantly greater than 33%, namely, x_9 – 28.8%, x_{11} – 28.5%, x_{12} – 117.9%, and x_{17} – 47.1%, but they were not included in the selected IGFs (although x_{17} was included in combinations with three features). This also speaks to the value of combinations and encourages research into the relationships between the individual indicators. For example, x_{12} with a high coefficient of variation did not fall into any of the selected IGFs (four indicators), apparently due to the lack of empirical connection, and therefore, cumulative information content, with other indicators.

4. DISCUSSION

The proposed methodology is a simple, reliable, and practically universal approach to conducting comparative analysis when a specific set of objects, such as countries, exists and a system of features characterizes these objects within a particular subject area, in this case, ICT development. The methodology can be effectively applied independently or as part of more complex methods for comparing countries. In general, this approach is one of the multivariate analysis methods that allows for obtaining qualitative results that can be interpreted to explain the cause-and-effect relationships of certain phenomena. The apparatus of international comparisons is particularly important for the EU since the implementation of its strategies, including in the area of digital transformation, presupposes an increase in the level of convergence (gaps minimization) between member countries for overall progress. In the context of resource constraints, this requires focusing on priority indicators of progress and the use of ICT, which is especially important for lagging countries and for more effective support from the EU.

The proposed methodology and the obtained results have theoretical significance and potential for practical use, expanding analytical capabilities and complementing various areas of research, namely:

1) A study of the main factors of ICT development at the national level allows them to be identified not by expert means (Palale & Ishida, 2024) but empirically based on international comparisons.

2) Analysis of the competitiveness of countries by comparing them using a system of indicators and creating a synthetic indicator measuring digitalization level (Marti & Puertas, 2023). A logical continuation of this is the identification of key parameters for differentiating these countries, in particular by ICT development level.

3) Ranking of the digital development of EU countries (Bánhidi & Dobos, 2023). The proposed method for assessing the informativeness of ICT development indicators is a qualitative al-

ternative to other methods for determining the overall weights of indicators for ranking.

4) Assessing the dynamics of ICT development in EU countries (Savulescu, 2015). Given the complex nature of network readiness, it is advisable to use the proposed methodology to identify those components in which the greatest differentiation between countries is observed.

5) Assessing the level of the digital economy in EU countries (Kiseľáková et al., 2022). In this approach, which covers a large number of indicators, the proposed methodology aims to identify the strengths and weaknesses of individual countries in ICT development.

6) A study of the differentiation of digital economic development in the EU and differences between member states in developing the digital economy (Biernacki et al., 2024). For this purpose, a taxonomic index was used, which has shortcomings in establishing the weights of indicators. The proposed methodology establishes the configuration of gaps between countries and empirically assesses the information content, i.e., the significance of indicators in differentiating countries, i.e., their weights.

7) Measuring the impact of digital transformation on the economies and societies of EU countries enables the identification of their cohesion and recognition of the digitalization gap between them (Małkowska et al., 2021). This can be supplemented by classification analysis to determine the key parameters of differentiation between different groups of EU countries in ICT development, which is also a characteristic of the digital divide.

8) Identifying differences between EU country groups, particularly their subregions, based on multivariate comparison of digital readiness, clustering, and ranking through factor analysis (Hunady et al., 2022). The proposed methodology can be an alternative approach to international comparison by examining differences between EU subregions and assessing the informativeness of indicators for ranking countries by ICT development level.

To summarize the above, the obtained results can be used to formulate the EU ICT support policy (Quaglio et al., 2016), making it possible to justify its priorities not only based on an expert survey but through empirical research. The indicators thus identified can also serve as benchmarks for individual EU countries to accelerate the improvement of their positions relative to others.

CONCLUSION

The EU's strategic course to accelerate digital transformation requires special attention to ICT development. However, the implementation of this course is complicated by significant differences between member states. Therefore, the aim of this study was to identify the main parameters of differentiation among EU countries according to their level of ICT development. For this purpose, a set of 18 indicators (from IDI and DESI) and a corresponding data set were formed. Based on this, the EU countries were divided into three clusters using the k-means method based on the similarity of ICT development indicators. Then, using the logical-combinatorial method of the decision tree, five combinations of indicators (four parameters in each) were identified, according to which the resulting clusters were completely different. Taking into account the duplication, a general list of indicators has been formed that is included in these combinations and which, accordingly, are key parameters for differentiating EU countries by ICT development, namely: individuals using the Internet (%), active mobile broadband subscriptions per 100 inhabitants, mobile data and voice high-consumption basket price (% of GNI per capita), fixed-broadband Internet basket price (% of GNI per capita), ICT graduates (% of graduates), fiber to the premises coverage (% of households), mobile broadband take-up (% of individuals aged 16-74), and 5G spectrum (% of harmonized spectrum assigned). Thus, it has been empirically confirmed that these parameters are of operational importance for the intensification of digital transformations at the EU level. At the same time, their development is a priority for accelerating ICT development in the member states and ensuring con-

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vergence. This can be used to justify decisions within the framework of supranational digital policy. In addition, the highlighted parameters can serve as benchmarks for lagging member states since their increase will facilitate faster overcoming of the gap with the leading countries. In the future, it is planned to test an approach to studying global asymmetry in the development of ICT.

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APPENDIX A

Table A1. EU country clusters by ICT development indicators

Countries	Indicators (the numbering corresponds to Table 1)																	
	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}	x_{17}	x_{18}
Cluster I																		
Austria	93.6	93.2	121.3	98.0	98.0	0.2	0.7	97.0	5.3	5.3	41.52	0.00	67.62	40.97	94.21	96.03	79.10	99.17
Denmark	97.9	95.2	142.7	100.0	100.0	0.4	0.7	97.9	5.9	5.5	82.05	29.33	97.19	84.04	97.61	100.00	85.00	99.17
Estonia	91.0	95.0	209.6	100.0	99.0	0.5	0.8	98.6	6.7	9.6	35.50	0.17	76.94	76.94	90.29	87.47	43.68	99.17
Finland	93.0	97.6	160.5	100.0	100.0	0.7	0.9	98.2	7.6	8.1	51.62	4.02	77.72	61.15	97.70	98.35	89.72	99.17
Ireland	95.6	94.5	118.6	95.0	90.0	0.4	1.5	96.6	6.2	8.2	61.04	9.48	86.99	78.47	93.07	85.32	56.68	62.50
Luxembourg	98.2	97.6	115.7	100.0	100.0	0.2	0.7	98.6	8.0	8.6	78.81	9.86	94.70	78.90	97.02	99.60	63.10	60.83
The Netherlands	92.5	95.6	123.3	99.0	99.0	0.5	1.1	87.4	6.9	4.4	72.03	4.13	98.33	77.66	98.73	100.00	0.00	33.33
Sweden	95.0	92.7	132.4	100.0	100.0	0.5	1.1	88.5	8.7	6.8	93.42	7.53	88.46	83.92	96.53	90.28	64.50	83.89
Min	91.0	92.7	115.7	95.0	90.0	0.2	0.7	87.4	5.3	4.4	35.50	0.00	67.62	40.97	90.29	85.32	0.00	33.33
Median	94.3	95.1	127.9	100.0	99.5	0.5	0.9	97.5	6.8	7.5	66.53	5.83	87.72	78.06	96.78	97.19	63.80	91.53
Max	98.2	97.6	209.6	100.0	100.0	0.7	1.5	98.6	8.7	9.6	93.42	29.33	98.33	84.04	98.73	100.00	89.72	99.17
CV[1], %	2.5	1.8	21.1	1.7	3.2	36.7	28.2	4.5	15.4	24.5	29.8	108.9	12.0	18.9	2.8	6.0	44.6	29.2
Cluster II																		
Belgium	94.0	94.4	94.9	100.0	100.0	0.6	0.7	90.0	5.4	3.0	72.25	5.44	95.95	25.00	92.61	40.35	14.24	65.83
Cyprus	89.6	94.0	86.1	100.0	100.0	0.5	0.9	98.0	5.4	2.3	63.64	2.07	77.07	77.07	91.09	100.00	35.00	66.67
France	85.3	87.3	107.0	99.0	99.0	0.6	1.2	94.9	4.7	4.1	65.39	51.57	81.40	81.40	90.29	93.21	64.78	59.17
Hungary	89.1	91.4	81.6	99.2	99.2	1.1	0.7	94.5	4.2	6.8	84.07	37.19	84.13	76.16	89.13	83.70	37.70	60.28
Latvia	91.0	91.4	120.1	99.0	95.0	0.4	1.4	96.7	4.4	5.4	70.81	4.66	71.45	61.88	90.17	53.11	39.00	66.67
Lithuania	87.7	87.7	133.3	100.0	100.0	0.4	0.8	95.7	4.9	5.0	67.10	2.56	78.06	78.06	86.43	98.87	61.44	47.22
Malta	91.5	93.4	123.7	100.0	100.0	0.5	0.9	96.2	4.7	5.8	70.61	11.69	100.00	69.60	91.73	100.00	24.66	25.00
Poland	86.9	93.3	202.7	100.0	100.0	0.5	1.1	95.7	4.3	4.3	74.20	5.29	81.09	75.43	85.70	71.92	0.00	33.33
Portugal	84.5	88.2	95.7	100.0	100.0	0.7	1.5	97.1	4.5	2.5	89.74	9.07	94.17	92.32	85.19	98.09	65.17	61.11
Romania	85.5	89.4	93.6	100.0	98.6	0.6	0.6	98.0	2.6	6.8	94.04	30.45	94.99	94.99	88.62	32.75	28.92	38.33
Slovenia	88.9	92.6	96.0	99.8	99.8	0.4	1.8	97.8	3.8	4.8	66.17	9.48	78.51	78.51	89.16	82.13	68.10	100.00
Spain	94.5	96.1	110.8	99.7	99.7	1.3	1.3	99.2	4.4	5.2	93.54	20.34	96.32	95.21	95.44	92.28	58.29	98.33
Min	84.5	87.3	81.6	99.0	95.0	0.4	0.6	90.0	2.6	2.3	63.64	2.07	71.45	25.00	85.19	32.75	0.00	25.00
Median	89.0	92.0	101.5	100.0	99.9	0.6	1.0	96.5	4.5	4.9	71.53	9.28	82.76	77.56	89.67	87.99	38.35	60.69
Max	94.5	96.1	202.7	100.0	100.0	1.3	1.8	99.2	5.4	6.8	94.04	51.57	100.00	95.21	95.44	100.00	68.10	100.00
CV[1], %	3.5	3.0	27.8	0.4	1.4	42.9	33.1	2.4	16.0	30.8	14.2	96.2	10.6	23.8	3.2	29.3	51.5	36.4
Cluster III																		
Bulgaria	79.1	87.3	115.6	100.0	99.9	0.9	1.5	95.7	4.3	4.8	53.41	1.01	88.61	88.61	79.56	70.88	45.07	96.67
Croatia	82.1	85.5	126.5	99.9	99.7	0.5	0.5	76.8	4.3	5.2	38.62	3.22	67.79	62.09	82.76	83.43	39.97	100.00
The Czech Rep.	84.5	85.4	105.0	99.8	99.8	0.9	1.0	98.8	4.3	5.4	40.38	2.95	50.54	36.05	90.30	94.60	39.30	66.67
Germany	91.6	91.4	95.5	99.9	99.9	0.3	1.0	77.9	4.9	5.5	46.88	5.45	74.74	29.80	89.85	98.14	43.85	100.00
Greece	83.2	85.5	100.1	99.7	99.2	1.4	1.9	93.3	2.4	3.6	29.51	0.00	38.41	38.41	83.48	98.07	58.83	99.17
Italy	85.1	83.1	95.9	100.0	100.0	0.6	1.0	95.6	4.1	1.5	69.47	19.29	59.29	59.29	85.56	99.49	88.29	93.33
Slovakia	87.2	90.3	86.7	99.0	99.0	1.4	0.9	97.7	4.2	4.8	45.15	1.76	69.12	64.19	85.20	79.03	47.51	66.67
Min	79.1	83.1	86.7	99.0	99.0	0.3	0.5	76.8	2.4	1.5	29.51	0.00	38.41	29.80	79.56	70.88	39.30	66.67
Median	84.5	85.5	100.1	99.9	99.8	0.9	1.0	95.6	4.3	4.8	45.15	2.95	67.79	59.29	85.20	94.60	45.07	96.67
Max	91.6	91.4	126.5	100.0	100.0	1.4	1.9	98.8	4.9	5.5	69.47	19.29	88.61	88.61	90.30	99.49	88.29	100.00
CV[1], %	4.3	3.2	12.1	0.3	0.4	46.2	37.6	9.6	17.7	30.0	25.4	127.4	23.7	35.3	4.2	11.7	31.0	16.0
For all countries																		
Min	79.1	83.1	81.6	95.0	90.0	0.2	0.5	76.8	2.4	1.5	29.51	0.00	38.41	25.00	79.56	32.75	0.00	25.00
Median	89.6	92.6	115.6	100.0	99.8	0.5	1.0	96.6	4.7	5.2	67.10	5.44	81.09	76.94	90.29	93.21	47.51	66.67
Max	98.2	97.6	209.6	100.0	100.0	1.4	1.9	99.2	8.7	9.6	94.04	51.57	100.00	95.21	98.73	100.00	89.72	100.00
CV[1], %	5.4	4.3	26.1	1.0	2.1	51.8	34.2	6.0	28.8	35.6	28.5	117.9	18.5	28.0	5.5	20.8	47.1	32.8

Note: [1]CV – Coefficient of variation.

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