“Uncovering patterns of digital transformation of European economies using self-organizing maps”

AUTHORS	Olena Pakhnenko Hanna Yarovenko Andrii Semenog Yevgeniya Mordan Oleksii Tarasenko

ARTICLE INFO	Olena Pakhnenko, Hanna Yarovenko, Andrii Semenog, Yevgeniya Mordan and Oleksii Tarasenko (2025). Uncovering patterns of digital transformation of European economies using self-organizing maps. *Problems and Perspectives in Management*, *23*(3), 581-596. doi:10.21511/ppm.23(3).2025.42
DOI	http://dx.doi.org/10.21511/ppm.23(3).2025.42
RELEASED ON	Wednesday, 17 September 2025
RECEIVED ON	Thursday, 10 July 2025
ACCEPTED ON	Friday, 08 August 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
50	5	4

BUSINESS PERSPECTIVES

LLC "CPC "Business Perspectives"
Hryhorii Skovoroda lane, 10,
Sumy, 40022, Ukraine

www.businessperspectives.org

Olena Pakhnenko (Ukraine), **Hanna Yarovenko** (Ukraine), **Andrii Semenog** (Ukraine), **Yevgeniya Mordan** (Ukraine), **Oleksii Tarasenko** (Ukraine)

UNCOVERING PATTERNS OF DIGITAL TRANSFORMATION OF EUROPEAN ECONOMIES USING SELF-ORGANIZING MAPS

Type of the article: Research Article

Received on: 10th of July, 2025
Accepted on: 8th of August, 2025
Published on: 17th of September, 2025

Olena Pakhnenko, Ph.D. in Economics, Associate Professor, Department of Financial Technologies and Entrepreneurship, Education and Research Institute of Business, Economics and Management, Sumy State University, Ukraine. (Corresponding author)

Hanna Yarovenko, Dr., Associate Professor, Economics Cybernetics Department, Education and Research Institute of Business, Economics and Management, Sumy State University, Ukraine.

Andrii Semenog, Dr., Associate Professor, Department of Financial Technologies and Entrepreneurship, Education and Research Institute of Business, Economics and Management, Sumy State University, Ukraine.

Yevgeniya Mordan, Ph.D. in Economics, Associate Professor, Department of Financial Technologies and Entrepreneurship, Education and Research Institute of Business, Economics and Management, Sumy State University, Ukraine.

Oleksii Tarasenko, Ph.D. in Economics, Department of Management and Smart Innovation, Kyiv National University of Technologies and Design, Ukraine.

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

Abstract

Digital technologies have become a key driver of economic growth, competitiveness, and social inclusion, while significant disparities in digital development persist across national economies. The aim of this study is to map and interpret the trajectories of digital transformation in 30 selected European countries (EU member states, associated economies, and Ukraine) during 2011–2022. The study employs the self-organizing map (SOM) with Ward hierarchical clustering to uncover latent structures of digital development, using a balanced panel of 20 indicators across three domains: ICT sector development, digital infrastructure, and digital technology adoption and skills. Cluster validity was assessed via the Elbow Method, Silhouette Coefficient, Calinski-Harabasz, and Davies-Bouldin indices. Results indicate that the two-cluster solution is statistically robust, while the three-cluster solution provides additional insight into transitional patterns of digital transformation. The two-cluster solution revealed a clear distinction between digital leaders and less advanced economies, with the greatest disparities observed in online banking (71% vs. 29%), online purchases (68% vs. 32%), and e-government use (68% vs. 34%). The three-cluster solution provided further nuance, showing that in 2011 most European economies were concentrated in the weakest cluster, while only Northern Europe achieved high levels of digitalization. By 2020, all European countries had reached at least the middle cluster, reflecting a shift from strong polarization toward a more balanced distribution of digital development. Despite progress, structural gaps remain, emphasizing the need for policies that advance digital skills, encourage inclusive adoption, and build trust in online services to sustain digital transformation.

Keywords digitalization, digital economy, ICT sector, digital infrastructure, e-government, online banking, e-commerce, digital services, cybersecurity, self-organizing maps

JEL Classification F63, O33, C38

INTRODUCTION

The rapid advancement of digital technologies has transformed the foundations of economic and social development, reshaping the way countries compete, innovate, and interact on the global stage. In European countries, this process has become particularly significant, as digital transformation is closely tied to broader objectives such as sustainable development, economic resilience, and social inclusion. Digitalization is not limited to the expansion of information and communication technologies (ICT); it represents a multidimensional phenomenon encompassing infrastructure, institutional frameworks, business models, and human capital.

Despite the EU's policy efforts to promote cohesion and reduce disparities, the pace of digital transformation across European countries remains uneven. Northern and Western Europe have consistently demonstrated higher levels of digital adoption, while Southern and Eastern regions face persistent challenges in infrastructure, skills, and institutional readiness (Hunady et al., 2022). For example, in 2023 only 58% of SMEs across the EU achieved a basic level of digital intensity (using at least four of 12 key digital technologies), while large firms reached 91%. The disparity is stark: SMEs in Romania and Bulgaria lag at just 27–28%, compared to 80% in Sweden and 86% in Finland (European Commission, 2024). This divergence risks reinforcing socio-economic inequalities, hindering competitiveness, and slowing the integration of lagging economies into the digital single market.

The scientific problem lies in the complexity of capturing and interpreting multidimensional differences in digital development. Traditional composite indices and benchmarking approaches, while useful, often fail to reflect non-linear relationships and hidden structures across diverse indicators. Addressing this limitation requires advanced methodological tools capable of revealing latent patterns, trajectories, and convergence processes.

Therefore, the present study is situated within the broader scientific discussion on measuring and interpreting digital transformation, focusing on the European context where both opportunities and structural divides remain highly pronounced.

1. LITERATURE REVIEW

The study of digital transformation has expanded significantly over the last decade, reflecting its growing impact on economic development, institutional frameworks, and social systems. In scientific research, this multidimensional process has been examined from various perspectives, including socio-economic and governance effects, security challenges, and methodological approaches to capture its complexity. This review follows the same logic, gradually moving from the general theoretical background to specific challenges and gaps that motivated the present analysis.

Digital transformation is increasingly recognized not merely as the adoption of digital tools, but as a structural reconfiguration of economic and social systems, institutional frameworks, and value creation processes (Zhang et al., 2024; Suntsova, 2024; Unerbayeva et al., 2025). It encompasses the integration of advanced ICT into production, governance, and services, alongside organizational and cultural changes, regulatory adaptation, and citizen engagement (Karimov et al., 2021; Kreiterling, 2023). Within the EU, this transformation is shaped by policy frameworks promoting innovation, sustainability, and competitiveness, often linked to the Digital Decade targets and the European Green Deal (Burinskienė & Seržantė, 2022; Bocean & Vărzaru, 2023). However, research highlights uneven progress. Hunady et al. (2022) point to a pronounced North-South divide, with Northern Europe showing stronger infrastructure and literacy, while Southern and Eastern countries struggle with investment gaps and skills. Pinto et al. (2023) extend this observation to adoption rates across sectors and demographic groups, while Małkowska et al. (2021) attribute disparities to institutional quality and regulatory efficiency.

The impacts of digitalization are studied across economic, social, and governance dimensions. Economically, digital advancement drives productivity gains, industrial upgrading, and GDP growth (Cuong et al., 2025; Török, 2024; Zhang et al., 2024; Suntsova, 2024; Massaoudi et al., 2025). Bocean and Vărzaru (2023) find that countries with high digital performance also achieve better sustainability outcomes, suggesting coordination between economic and environmental goals. Tutak and Brodny (2022) highlight the contribution of digital maturity to fostering open innovation and cross-sector collaboration, while Fura et al. (2025) confirm that robust ICT infrastructure enhances industrial competitiveness.

The financial sector provides clear examples of transformation-induced value creation. Alrawashedh and Shubita (2024) show that in Jordanian banks, the adoption of digital technologies improves financial performance and operational efficiency. Mustafa (2024a) links digital payment systems and financial stability, while Alhanatleh et al. (2024) demonstrate that public value from mobile fintech depends on parallel

http://dx.doi.org/10.21511/ppm.23(3).2025.42

improvements in cybersecurity awareness. In the insurance sector, Alzubi (2025) identifies digital channels as a key driver of adoption and customer engagement.

Social impacts of digitalization include changes in consumption behavior, labor market dynamics, and inclusion. Yuan et al. (2023) find that mobile payment adoption influences sustainable consumption patterns, indicating broader shifts in consumer preferences. Digital marketing strategies, as discussed by Hadiyati et al. (2024), enhance small business competitiveness, but also demand adaptive skills.

From a governance perspective, digital transformation can enhance transparency, improve service delivery, and increase accountability. Darusalam et al. (2024) report that in Indonesia, digitalization in public administration reduced corruption opportunities by streamlining processes and reducing human intervention. Similar effects are observed in Brazil (Saldanha et al., 2022) and in a range of developing countries (Marjerison & Gatto, 2024). Munshi and Manni (2025) provide a meta-analysis confirming that digital tools can reduce corruption, though Yamen et al. (2022) warn that in high-corruption environments, benefits are limited without institutional reform. The interaction between digitalization and the shadow economy is another critical dimension. Bozhenko et al. (2024) suggest that digital finance increases transaction traceability, thereby limiting informal economic activity. Zhang et al. (2024) note that while industrial digitalization can enhance efficiency, it requires regulatory adaptation to prevent unintended economic distortions.

Alongside benefits, digitalization creates new risks. Cybersecurity emerges as both an enabler and a potential bottleneck for digital transformation. Effective cybersecurity strategies safeguard infrastructure, maintain public trust, and support innovation (Kuzior et al., 2024; Saeed et al., 2023). Comparative studies show that countries with stronger cybersecurity capacity achieve greater resilience to cyber threats (Chen et al., 2023; Sendjaja et al., 2024; Valackiene & Odejayi, 2024). The perception of security among citizens and businesses also significantly influences the adoption of digital services (Korjonen-Kuusipuro & Wojciechowski, 2025). At the same time, the rapid evolution of cyberattacks increases systemic risks in sectors such as finance, requiring adaptive policy and regulatory responses (Lesmana et al., 2023; Juneja et al., 2024; Hasan et al., 2025; Mustafa, 2024b). Broader concerns link digital transformation to economic and national security, where transparency and accountability mechanisms are seen as safeguards against both external and internal threats (Karimov et al., 2021; Reischauer et al., 2024).

Despite substantial research, notable gaps remain in the literature. First, most studies analyze single aspects of digital transformation – such as infrastructure development (Burinskienė & Seržantė, 2022), sectoral adoption (Alzubi, 2025; Straková et al., 2022), or governance impacts (Munshi & Manni, 2025; Darusalam et al., 2024) – without offering integrated, multidimensional assessments. Second, while comparative studies (Hunady et al., 2022; Małkowska et al., 2021; Pinto et al., 2023) provide valuable benchmarking, few apply advanced machine learning techniques to capture the complexity of interrelated indicators.

Current measurement frameworks – composite indices (Fura et al., 2025; Török, 2024) and bibliometric mappings (Zherlitsyn et al., 2025) – have analytical merit but may overlook non-linear interactions between economic, social, governance, and security factors. Zinchenko et al. (2025) demonstrate, through cluster analysis of sustainability indicators, how unsupervised learning techniques can uncover latent groupings among countries – an approach well suited for mapping the multifaceted nature of digital transformation. The potential of unsupervised learning methods remains underexplored in the context of mapping Europe's digital transformation.

Against this backdrop, self-organizing maps (SOM) offer methodological advantages. They can process high-dimensional datasets while preserving the topology of relationships and revealing latent patterns. This enables the identification of clusters and outliers, offering insights for targeted policy interventions. By applying this method to European countries, this paper addresses the need for integrated, multidimensional, and policy-relevant mapping of digital transformation. Thus, the aim of the study is to map and interpret the trajectories of digital transformation in European countries during 2011–2022.

2. METHODS

This study applies a quantitative methodological approach to identify and analyze structural patterns of digital transformation across 30 countries of the European region over the period 2011–2022 using the self-organizing map (SOM) algorithm. The methodological design aimed not only to classify countries according to their digital profiles but also to track the movement of countries between clusters over time, thereby identifying digital convergence, divergence, or structural shifts in national trajectories.

The analysis is based on a panel dataset of 20 cross-country comparable and relative indicators reflecting different aspects of digital development. The indicators include three thematic categories (Table 1).

Table 1. Indicators (SOM method)

Indicator Code	Indicator Description
ICT Sector Development	
GVA_ICT	ICT sector contribution to Gross Value Added (%)
EMP_ICT	ICT sector personnel (% of total employment)
EXP_ICTg	ICT goods exports (% of total goods exports)
IMP_ICTg	ICT goods imports (% of total goods imports)
EXP_ICTs	ICT service exports (% of service exports, BoP)
Digital Infrastructure	
INV_TEL	Annual investment in telecommunication services (% of revenues)
SUB_MB	Active mobile-broadband subscriptions per 100 inhabitants
SUB_FB	Fixed broadband subscriptions per 100 inhabitants
HH_INT	Households with Internet access at home (%)
SUB_MC	Mobile-cellular subscriptions per 100 inhabitants
COV_MC	Population covered by a mobile-cellular network (%)
COV_3G	Population covered by at least a 3G mobile network (%)
COV_4G	Population covered by at least a 4G mobile network (%)
Digital Technology Adoption and Skills	
E_COMM_ENT	Enterprises with e-commerce sales (%)
E_COMM_VAL	Value of e-commerce sales (% of turnover)
INT_USE	Individuals using the Internet (%)
E_GOV	Internet use for interaction with public authorities (past 12 months) (%)
E_BANK	Internet use for Internet banking (%)
E_PURCH	Internet purchases by individuals (past 12 months) (%)
DIG_SKILL	Individuals with basic or above basic digital skills (%)

The data sources used in the study include the databases of Eurostat, the World Bank, the International Telecommunication Union (ITU), and the State Statistics Service of Ukraine (for Ukraine-specific indicators). Table 2 summarizes the sources by indicator.

Table 2. Data sources for the indicators

Indicator Code	Data Source
GVA_ICT, EMP_ICT, E_COMM_ENT, E_COMM_VAL, E_GOV, E_BANK, E_PURCH	Eurostat (2025a, 2025b, 2025c, 2025d, 2025d, 2025e, 2025f, 2025g, 2024); for Ukraine, the State Statistics Service of Ukraine database
EXP_ICTg, IMP_ICTg, EXP_ICTs, INT_USE	DataBank Database of the International Telecommunication Union, World Development Indicators
INV_TEL, SUB_MB, SUB_FB, HH_INT, SUB_MC, COV_MC, COV_3G, COV_4G, DIG_SKILL	DataHub Database of the International Telecommunication Union

The study covers 30 European countries: Austria, Belgium, Bulgaria, Croatia, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Italy, Latvia, Lithuania, Malta, the Netherlands, North Macedonia, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Ukraine, and the United Kingdom. Countries with significant data gaps were excluded.

The research period spans from 2011 to 2022. This timeframe was selected due to the onset of accelerated digitalization across European countries around 2011, including the expansion of broadband infrastructure and increased Internet adoption. More recent data were excluded due to incomplete availability across countries.

Given the panel nature of the dataset, some country-year observations were partially missing. To maintain completeness while preserving analytical consistency, missing values (affecting less than 10% of all observations) were imputed using linear interpolation by country across adjacent years. This approach is commonly used for time series with gradual evolution, such as digital development indicators.

All indicators are expressed in relative and normalized units (such as percentages or per-capi-

http://dx.doi.org/10.21511/ppm.23(3).2025.42

ta values), making them inherently comparable across countries and over time. As the variables exhibit similar numerical scales and no single indicator dominates the overall variance structure, no additional standardization was deemed necessary prior to clustering.

To uncover latent structures in the digital profiles of countries, the self-organizing map (SOM) algorithm was applied. SOM is a type of unsupervised neural network that projects high-dimensional data onto a lower-dimensional (typically two-dimensional) grid, preserving the topological relationships between data points. This makes it a powerful tool for visualizing complex structures and identifying clusters in multidimensional socio-economic data.

The SOM algorithm was applied to the entire panel dataset, rather than to individual years separately. This approach offers several analytical advantages. First, it allows for the construction of a unified map onto which all observations (country × year) are projected, thereby enabling the analysis of temporal dynamics – specifically, how countries transition between zones or clusters over time. Second, it facilitates the visualization of longitudinal development trajectories for each country within a consistent topological space. Third, training the SOM on the full dataset increases the volume and variability of input data, which contributes to more stable and reliable map formation, as the algorithm typically performs better with larger and more diverse datasets.

The Kohonen self-organizing map (SOM) algorithm was implemented using the MiniSom library and the Python programming language. It combined SOM and Ward hierarchical clustering to detect structured groups in multidimensional data and adapt to panel data. A regular two-dimensional neural network topology of dimension 20×20 was created, where each neuron is represented by a weight vector, the dimension of which coincides with the number of features in the input space. The initial adjustment of the weight coefficients was carried out using the principal component analysis (PCA) method, which allowed us to arrange the initial code vectors in the data space, taking into account the main directions of dispersion, providing a better initial approximation. The SOM training process was performed in a random sample selection mode for 2000 iterations using a Gaussian neighborhood function and an initial learning rate of 0.5, which allowed us to preserve the topological correspondence between the original multidimensional data structure and the two-dimensional map projection.

After completing the SOM training, a winning neuron (Best Matching Unit, BMU) was determined for each sample object, i.e., the map node whose weight vector has the smallest Euclidean distance to the feature vector of this object. Based on the set of such BMUs, a subset of unique nodes was formed, namely a compact representative set of prototypes without duplication, which reflects the key structural elements of the data space. Further grouping of code vectors was carried out using the Ward hierarchical clustering method, aimed at minimizing intra-cluster variance and obtaining clearly separated groups. In the implemented approach, the code vector space was divided into three clusters, after which each input data object was assigned a cluster according to its BMU membership, which ensured a consistent transfer of the cluster structure detected by SOM to the entire study sample.

The optimal number of clusters was justified using several established validation techniques: Elbow Method, Silhouette Coefficient, Calinski-Harabasz Index, and Davies-Bouldin Index. Given the potential inconsistency in the outcomes produced by individual validation metrics, the simultaneous application of multiple evaluation methods enhances the robustness of cluster selection. By comparing results across techniques, the most frequently suggested number of clusters can be identified, thus ensuring a more reliable and evidence-based determination of the optimal solution.

3. RESULTS

The analysis proceeds in several stages. First, we determined the optimal number of clusters using established validation indices. Second, we assessed the robustness of clustering through silhouette analysis. Third, we interpreted the characteristics of the clusters based on the three thematic groups of indicators: ICT sector development, digital infrastructure, and digital technology adoption and skills. Finally, we examined the spatial and temporal dynamics of cluster membership across European countries.

3.1. Validation of cluster solutions

The optimal number of clusters was evaluated using the Elbow Method, Silhouette Coefficient, Calinski-Harabasz Index, and Davies-Bouldin Index. The results of these validation procedures are presented in Figure 1.

All four indices consistently indicate that the most robust solution is a two-cluster partition. Specifically, the two-cluster solution achieved the highest silhouette and Calinski-Harabasz scores, the lowest Davies-Bouldin index, and the sharpest decline in the Elbow Method. The three-cluster solution also received relatively strong support, with moderately high silhouette and Calinski-Harabasz scores and a comparatively low Davies-Bouldin index. Thus, while two clusters provide the most parsimonious representation, a three-cluster solution also appears feasible and offers additional analytical insights.

The silhouette plots for the two- and three-cluster solutions are shown in Figures 2 and 3.

For the two-cluster solution, most observations achieved silhouette values above 0.4, with very few negative values, indicating well-separated and internally coherent clusters. The homogeneity within each cluster suggests a stable and interpretable structure.

The three-cluster solution exhibited somewhat lower homogeneity. Several observations recorded silhouette values near zero or negative, indicating partial misclassification. Nevertheless, this solution captures an additional group of countries with distinct characteristics, thereby enabling a more nuanced interpretation of digital development trajectories.

3.2. Two-cluster solution: Characteristics and dynamics

Table 3 presents the summary statistics for the two-cluster solution.

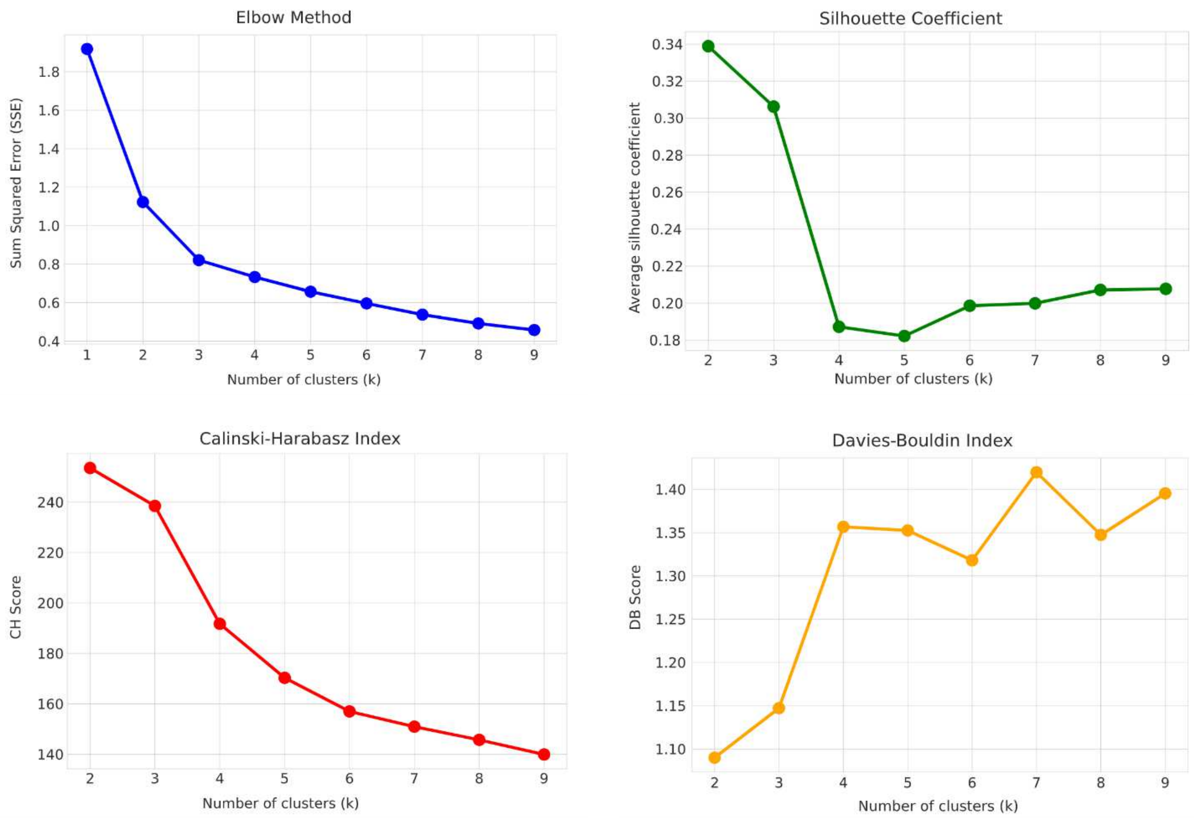

Figure 1. Cluster validation results (Elbow, Silhouette, Calinski-Harabasz, Davies-Bouldin)

http://dx.doi.org/10.21511/ppm.23(3).2025.42

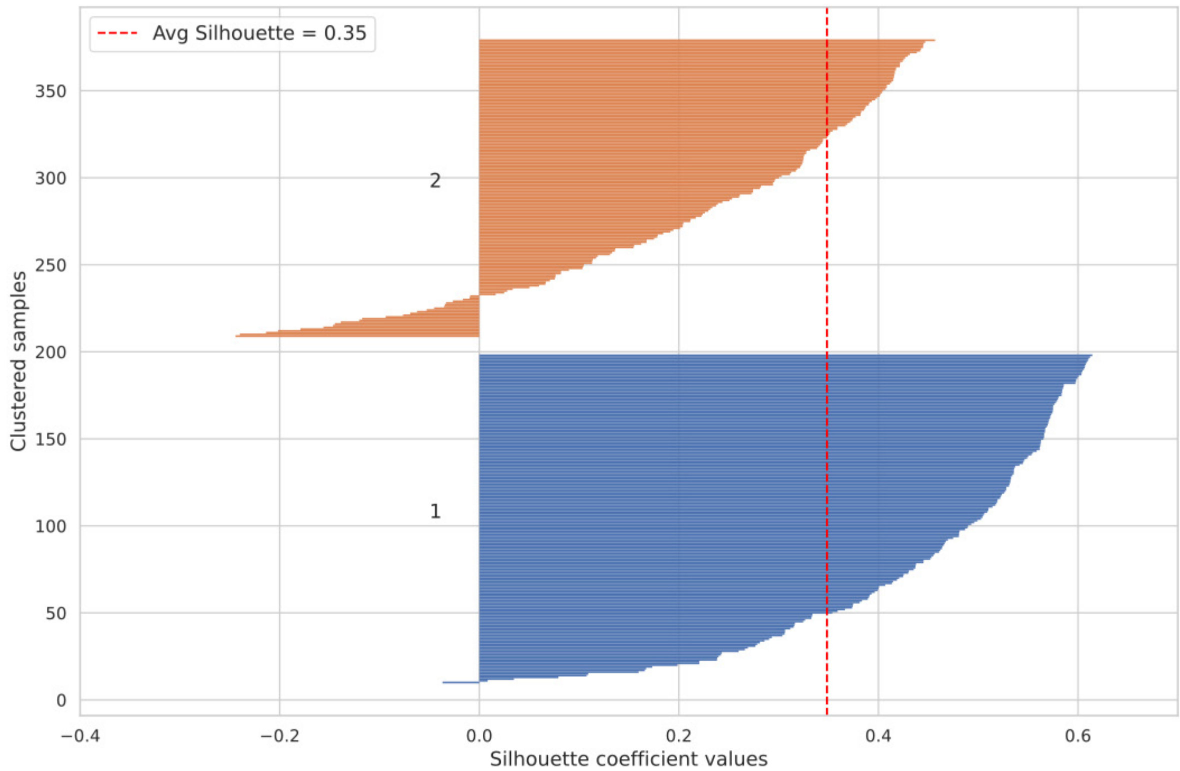

Figure 2. Silhouette plot for a two-cluster solution

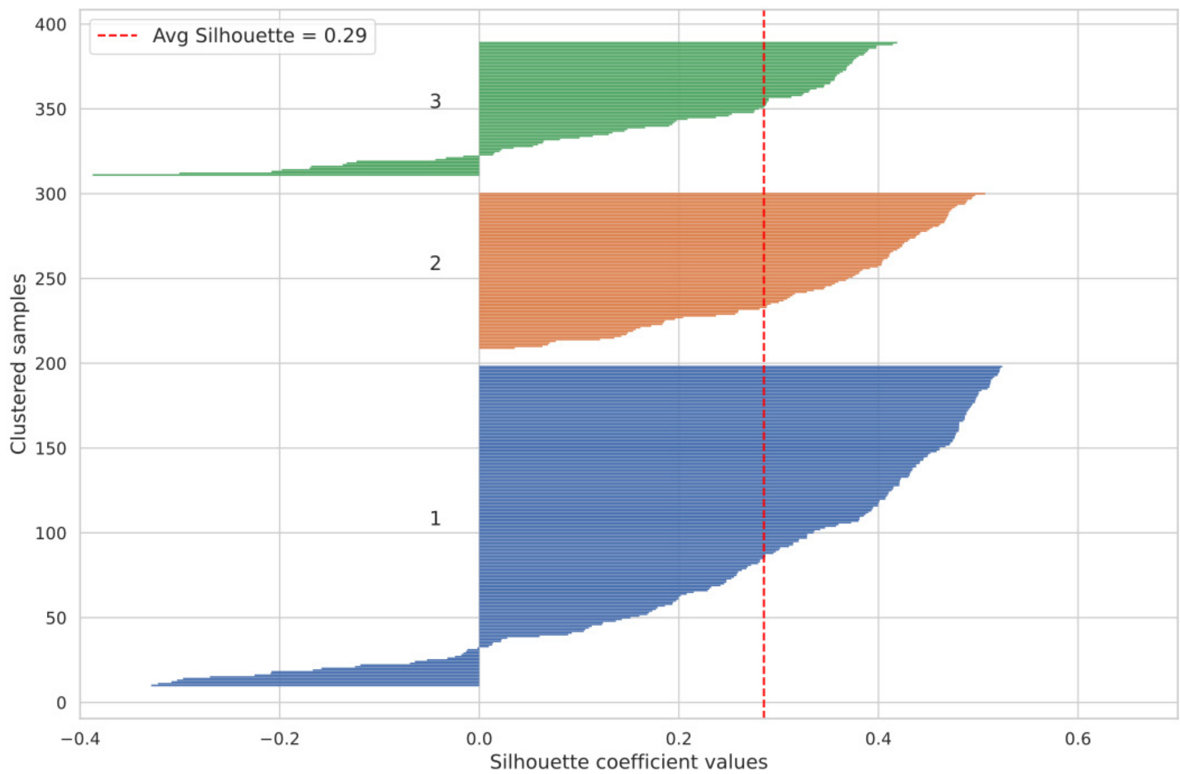

Figure 3. Silhouette plot for a three-cluster solution

Table 3. Cluster characteristics: Two-cluster solution (SOM results)

Indicator Code	Cluster 1			Cluster 2		
	Mean	Min	Max	Mean	Min	Max
GVA_ICT	4.7	2.7	10.1	4.1	2.0	8.8
EMP_ICT	3.4	1.6	6.0	2.4	1.2	4.2
EXP_ICTg	5.8	0.1	25.7	4.6	0.1	22.9
IMP_ICTg	8.0	3.2	20.1	6.4	2.6	17.5
EXP_ICTs	11.7	0.7	43.5	10.3	0.7	45.3
INV_TEL	23.9	12.3	47.2	19.5	2.3	42.5
SUB_MB	**106.8**	57.4	210.5	60.6	4.4	122.5
SUB_FB	**35.9**	20.0	48.3	25.3	7.0	40.1
HH_INT	**89.2**	72.1	99.4	71.3	29.3	93.6
SUB_MC	122.1	99.8	172.1	**123.1**	93.9	167.2
COV_MC	99.7	99.0	100.0	99.7	97.4	100.0
COV_3G	**98.8**	67.0	100.0	91.9	1.7	100.0
COV_4G	**95.8**	39.0	100.0	58.7	0.0	100.0
E_COMM_ENT	**24.9**	10.2	41.1	14.3	3.1	36.4
E_COMM_VAL	**18.2**	4.3	32.6	10.0	0.8	25.8
INT_USE	**88.9**	74.2	99.8	69.5	28.7	94.8
E_GOV	**67.6**	30.8	95.1	33.6	0.8	84.1
E_BANK	**70.9**	36.6	96.1	29.3	3.2	80.4
E_PURCH	**68.1**	42.5	93.1	31.6	4.8	72.6
DIG_SKILL	**63.7**	41.2	89.3	49.8	14.5	80.6

Note: Items in bold denote mean values that are significantly higher in Clusters 1 or 2.

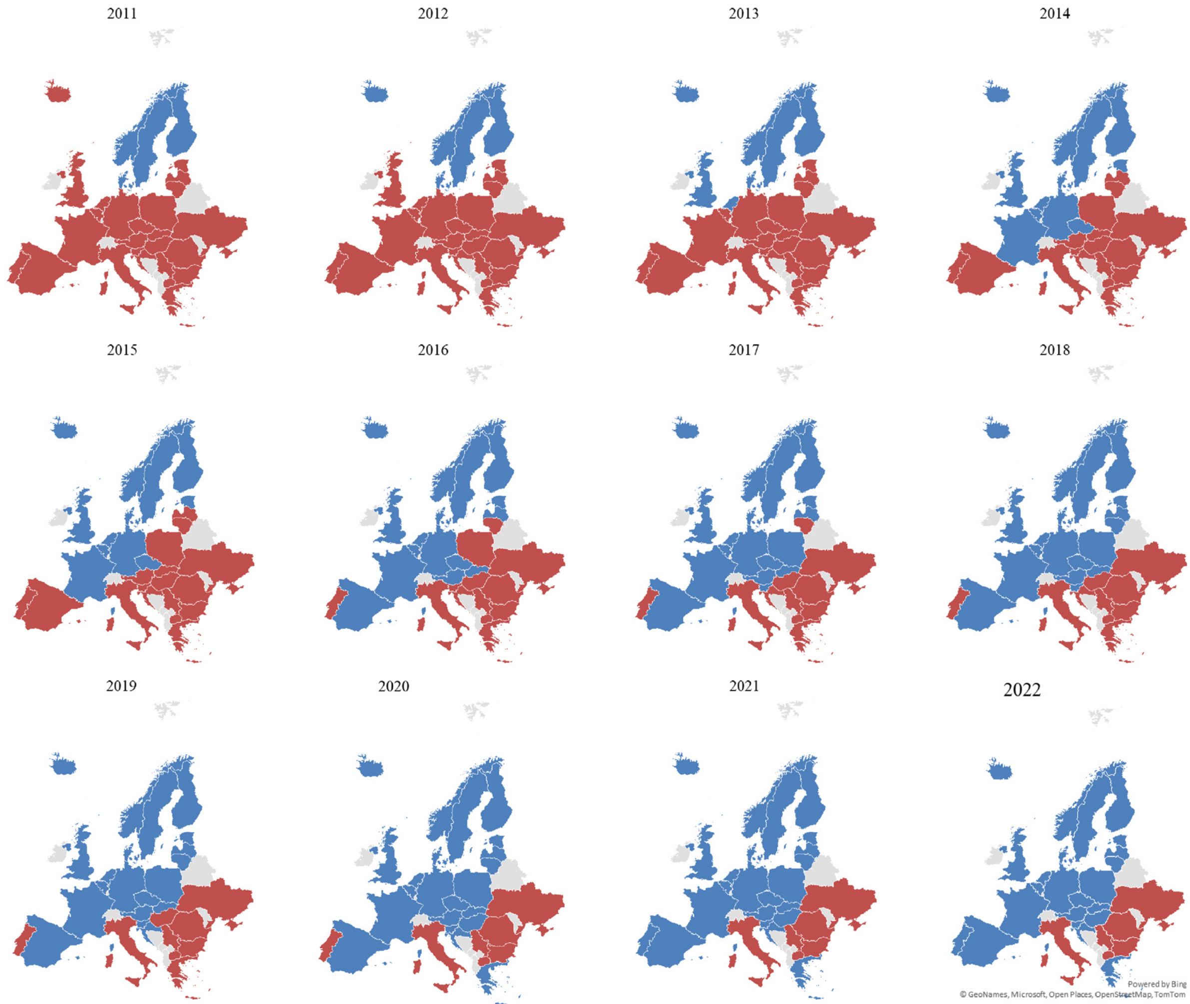

Figure 4. Geographical distribution of European countries by clusters (Two-cluster solution, 2011–2022)

http://dx.doi.org/10.21511/ppm.23(3).2025.42

Cluster membership was balanced, with 52.5% of observations assigned to the first cluster and 47.5% to the second. The first cluster represents countries with consistently higher levels of digital transformation across most indicators, whereas the second cluster reflects relatively lower performance.

The ICT sector development indicators (contribution to GVA, ICT sector personnel, ICT goods and services exports, ICT goods imports) did not constitute the primary basis of cluster separation, as both clusters exhibited overlapping ranges and some outliers. More pronounced differences emerged in digital infrastructure indicators, particularly active mobile broadband subscriptions, 4G coverage, fixed broadband penetration, and household internet access. The greatest disparities, however, were observed in digital technology adoption and skills. The mean values of the first cluster in online government services, internet banking, and e-commerce were more than double those of the second cluster. Thus, the clustering process was primarily driven by the adoption of digital technologies and the quality of digital infrastructure, rather than by ICT sector size alone.

The spatial distribution of the two clusters is shown in Figure 4.

In 2011, Northern European countries (Denmark, Finland, Norway, and Sweden) were grouped in the high-digitalization cluster, while all other countries were classified into the lower-digitalization cluster. Over time, the frontier of digitalization moved progressively southeastward, with many countries transitioning from the second to the first cluster. This dynamic highlights a gradual convergence across European countries, albeit with persistent differences in digital adoption levels.

3.3. Three-cluster solution: Characteristics and dynamics

To capture more fine-grained differences, a three-cluster solution was also examined. Table 4 summarizes the corresponding cluster statistics.

With respect to the first group of indicators – ICT sector development – the distinction between the second and third clusters is not clear-cut. The second cluster exhibits higher mean values in the ICT sector's contribution to gross value added (GVA_ICT) and employment (EMP_ICT), suggesting a relatively stronger integration of ICT activities into their domestic economies. However, maximum values for these same indicators are found

Table 4. Cluster characteristics: Three-cluster solution (SOM results)

Indicator Code	Cluster 1			Cluster 2			Cluster 3		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
GVA_ICT	4.7	2.7	10.1	**4.2**	2.0	7.4	3.9	2.0	8.8
EMP_ICT	3.4	1.6	6.0	**2.5**	1.4	4.0	2.2	1.2	4.2
EXP_ICTg	5.8	0.1	25.7	4.1	0.6	17.7	**5.1**	0.1	22.9
IMP_ICTg	8.0	3.2	20.1	6.2	3.1	15.0	**6.7**	2.6	17.5
EXP_ICTs	11.7	0.7	43.5	**11.6**	0.8	45.3	8.9	0.7	21.9
INV_TEL	23.9	12.3	47.2	20.7	10.6	40.6	18.2	2.3	42.5
SUB_MB	106.8	57.4	210.5	**74.5**	27.7	122.5	44.4	4.4	80.6
SUB_FB	35.9	20.0	48.3	27.8	16.2	40.1	22.3	7.0	39.3
HH_INT	89.2	72.1	99.4	**76.7**	58.0	89.4	65.0	29.3	93.6
SUB_MC	122.1	99.8	172.1	121.4	98.3	156.5	**125.1**	93.9	167.2
COV_MC	99.7	99.0	100.0	99.7	98.9	100.0	99.7	97.4	100.0
COV_3G	98.8	67.0	100.0	**98.2**	85.0	100.0	84.6	1.7	100.0
COV_4G	95.8	39.0	100.0	**90.7**	43.0	100.0	21.5	0.0	78.2
E_COMM_ENT	24.9	10.2	41.1	**14.9**	4.8	29.4	13.6	3.1	36.4
E_COMM_VAL	18.2	4.3	32.6	10.8	1.7	23.6	9.0	0.8	25.8
INT_USE	88.9	74.2	99.8	**74.1**	55.3	87.5	64.2	28.7	94.8
E_GOV	67.6	30.8	95.1	36.6	2.3	60.2	30.2	0.8	84.1
E_BANK	70.9	36.6	96.1	**32.2**	4.4	72.2	26.0	3.2	80.4
E_PURCH	68.1	42.5	93.1	**36.2**	14.8	72.6	26.3	4.8	71.1
DIG_SKILL	63.7	41.2	89.3	50.7	23.9	71.9	48.8	14.5	80.6

Note: Items in bold denote mean values that are significantly higher in Clusters 2 or 3.

within the third cluster, indicating that individual countries with generally lower levels of digitalization may nevertheless host relatively large ICT-intensive activities. Moreover, the third cluster surpasses the second cluster in average ICT goods exports and imports. This pattern can be explained by structural features of some Eastern and Southern European economies, where ICT goods production or assembly is concentrated due to lower labor costs, favorable fiscal conditions, or outsourcing arrangements. In such cases, the external trade dimension of ICT may not directly translate into broad-based digital adoption within the domestic economy.

The second group of indicators – digital infrastructure – shows more distinct disparities. The most pronounced differences are observed in active mobile broadband subscriptions (SUB_MB), 4G population coverage (COV_4G), fixed broadband subscriptions (SUB_FB), and household internet access (HH_INT). Cluster 1 consistently outperforms both clusters 2 and 3, reflecting the advanced state of infrastructure in Northern and Western European countries. While cluster 2 demonstrates moderate development, cluster 3 lags significantly behind in terms of broadband infrastructure and 4G penetration. At the same time, an interesting counter-pattern emerges with mobile-cellular subscriptions (SUB_MC), where cluster 3 records relatively high values compared to cluster 2. This phenomenon is consistent with substitution effects in countries with weaker broadband infrastructure: when fixed broadband and next-generation mobile networks are underdeveloped, reliance on traditional mobile connectivity tends to increase.

The third group of indicators – digital technology adoption and skills – reveals the starkest differences. Although clusters 2 and 3 display overlapping ranges for some indicators, the average performance of cluster 2 is consistently higher. Countries in cluster 2 report significantly greater internet usage, higher rates of internet banking, and more frequent online purchases compared to cluster 3. For example, average values of internet banking (E_BANK) and online purchasing (E_PURCH) in cluster 2 are more than 20 percentage points higher than in cluster 3. Nevertheless, cluster 3 also includes certain outliers: individual observations occasionally demonstrate relatively high values of e-government interaction or digital skills despite being situated in the weakest cluster overall. These exceptions suggest that progress in particular policy domains may not always align with the broader trajectory of digital transformation.

Taken together, the three-cluster solution highlights important structural nuances that are masked in the two-cluster analysis. While cluster 1 clearly represents the digital leaders, the differentiation between clusters 2 and 3 captures the transitional stage of digital development. Cluster 2 reflects economies that, despite not reaching the level of the frontrunners, have achieved substantial improvements in infrastructure and digital technology adoption. Cluster 3, by contrast, represents the countries that, especially in the early 2010s, faced the greatest challenges in adopting digital technologies, building adequate infrastructure, and fostering digital skills.

The geographical and temporal distribution of European countries under the three-cluster solution is shown in Figure 5.

At the beginning of the observation period in 2011, the European digital landscape was highly polarized. Cluster 1, composed of a small group of Northern European countries (Denmark, Finland, Norway, and Sweden), represented the digital leaders. By contrast, the vast majority of European countries belonged to cluster 3, reflecting low levels of digital transformation. Only one country (Portugal) was positioned in cluster 2, occupying an intermediate position. This initial configuration illustrates the substantial digital divide that characterized the European region at the start of the 2010s.

Over the subsequent years, a clear process of upward mobility can be observed. Countries gradually moved from cluster 3 into cluster 2, signaling progress from a low to a medium level of digitalization. The first wave of transitions occurred as early as 2012, when Estonia, Germany, and the United Kingdom joined cluster 2. In 2013, Austria, Belgium, France, and Slovenia followed. The trend accelerated in 2014 with Hungary, Italy, Latvia, Lithuania, Malta, Poland, Slovakia, and Spain making the transition. Further shifts included

http://dx.doi.org/10.21511/ppm.23(3).2025.42

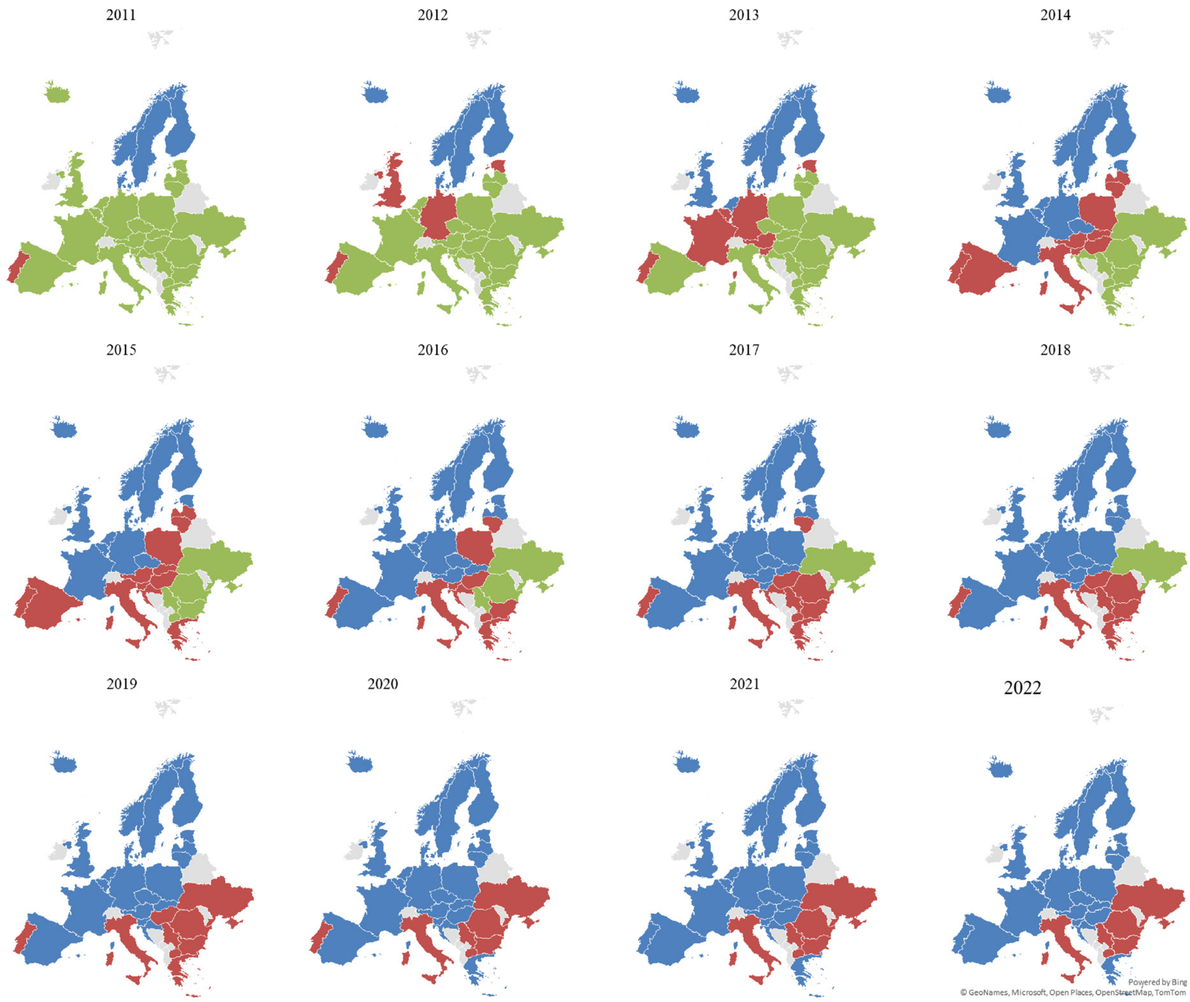

Figure 5. Geographical distribution of European countries by clusters (Three-cluster solution, 2011–2022)

Croatia and Greece (2015), Bulgaria and North Macedonia (2016), Romania and Serbia (2017), and finally Ukraine (2019), which was the last country to exit the lowest cluster.

In parallel, several countries advanced directly from cluster 2 into cluster 1, reflecting rapid digital upgrading. Notably, the United Kingdom joined the leading cluster in 2013, followed by Belgium, Estonia, France, and Germany in 2014. Malta reached cluster 1 in 2015, Latvia, Spain, Austria, and Slovakia in 2016, and Poland and Slovenia in 2017. Lithuania advanced in 2018, Croatia in 2019, Greece and Hungary in 2020, and Portugal in 2021. Some countries even experienced accelerated digital convergence, bypassing the intermediate stage altogether: Iceland moved directly from cluster 3 to cluster 1 in 2012, the Netherlands in 2013, and Czechia in 2014.

By 2020, the European digital landscape had undergone a profound transformation. No countries remained in cluster 3, and the map of Europe was effectively divided into two groups: medium-digitalization economies (cluster 2) and high-digitalization economies (cluster 1). This structure persisted through 2022, with no further reclassification of countries. In other words, by the early 2020s, the initial polarization of Europe into highly advanced and lagging countries had given way to a more balanced distribution, where all countries had achieved at least medium levels of digital transformation.

The three-cluster solution is therefore particularly insightful for understanding the trajectory of convergence. While the two-cluster solution captures the final stage of Europe's digital evolution, the three-cluster framework reveals

http://dx.doi.org/10.21511/ppm.23(3).2025.42

the earlier stage when disparities were far more pronounced. It highlights that during the first half of the 2010s, many countries were situated in the lowest tier of digital development, but subsequently made gradual progress, eventually joining the intermediate group and, in some cases, advancing to the digital leaders.

This temporal perspective underscores two important dynamics. First, it reveals a northwest-to-southeast gradient of digital transformation, with early adopters concentrated in Northern and Western Europe and later adopters located in Southern and Eastern Europe. Second, it demonstrates the narrowing of the digital divide: although differences between the leaders and followers remain, the absence of a low-digitalization cluster in the 2020s signals substantial convergence across the region.

Overall, the SOM analysis highlights several key findings:

- The two-cluster solution provides the most robust statistical fit, but the three-cluster solution yields additional insights into the early stages of divergence and subsequent convergence.
- The most substantial differences between clusters concern digital technology adoption and skills, rather than ICT sector development.
- Geographical patterns reveal a northwest-to-southeast trajectory of digital transformation, with gradual diffusion of advanced digital practices.
- Over time, the digital divide within European countries has narrowed considerably, with all countries reaching at least medium levels of digitalization by 2020.

These findings underscore that while infrastructure and ICT sector development have become relatively widespread across European countries, disparities remain in the uptake of digital services such as online banking, e-government, and e-commerce, as well as in the distribution of digital skills.

4. DISCUSSION

The results of this study confirm both the persistence and gradual reduction of digital divides across European countries. The application of self-organizing maps enabled the identification of structural clusters of digital transformation, showing that while Northern and Western European countries have consistently led in digital adoption, Southern and Eastern European countries have steadily converged over time. This finding is consistent with the conclusions of Hunady et al. (2022), who emphasized the leading role of Northern Europe and the lagging position of Southern regions, as well as with Pinto et al. (2023), who highlighted significant intra-European disparities in the digitalization landscape.

A central insight of this research is that the most significant differences between clusters were not found in the size of the ICT sector or even in the availability of basic infrastructure, but rather in the adoption of digital technologies and the distribution of digital skills. Countries in the lower-performing clusters demonstrated relatively adequate progress in building ICT infrastructure but continued to lag in online service adoption, e-government use, e-commerce penetration, and digital literacy. Similar conclusions were reached by Małkowska et al. (2021), who showed that while the technological base is expanding across European countries, actual usage and integration into socio-economic life remain uneven. Likewise, Burinskienė and Seržantė (2022) argued that digitalization serves as an important indicator of sustainability, but its transformative potential depends critically on how digital technologies are embedded in everyday practices.

From a temporal perspective, this study provides empirical evidence of a narrowing digital gap. The three-cluster solution revealed that at the beginning of the study period (2011), most European countries were located in the lowest tier of digital transformation. Over the next decade, however, almost all countries progressed to at least medium levels, and by 2020, the weakest cluster disappeared altogether. This trajectory corresponds with the findings of Fura et al. (2025), who statistically demonstrated that EU countries have gradually aligned their digital transformation performance under the frame-

http://dx.doi.org/10.21511/ppm.23(3).2025.42

work of Sustainable Development Goal 9 (industry, innovation, and infrastructure). Similarly, Török (2024) confirmed the positive association between digital development and economic growth, which may partly explain why lagging countries have prioritized catching up with the frontrunners.

Nevertheless, the persistence of a medium-level cluster suggests that important structural barriers remain. As of 2022, six countries (Bulgaria, Italy, North Macedonia, Romania, Serbia, and Ukraine) continue to belong to the intermediate group and require intensified measures to accelerate digital transformation. This finding echoes Pinto et al. (2023), who emphasized the uneven readiness of European economies to transition into the digital age. It also aligns with Fura et al. (2025), who noted that progress remains highly differentiated depending on institutional capacity, investment levels, and human capital.

The policy implications of these results point toward key areas for improvement. First, the widespread adoption of online financial services, including internet banking and fintech solutions, remains uneven, with substantial gaps between leaders and followers. Second, cybersecurity systems must be reinforced, as increasing digital service penetration inevitably raises exposure to cyber risks. Third, the enhancement of financial literacy and digital skills is critical, particularly in countries where infrastructure is present but usage lags behind. These directions are consistent with the findings of Małkowska et al. (2021) and Burinskienė and Seržantė (2022), who underscored the role of human capital and institutional readiness in leveraging the benefits of digitalization.

Future research should expand on these findings in several directions. First, a more granular analysis of sectoral adoption (e.g., digital finance, e-health, or smart manufacturing) would help identify areas where lagging countries can leapfrog by adopting specific technologies. Second, further work should examine the interplay between digitalization and socio-economic resilience. Third, more attention should be paid to the role of policy design and governance frameworks, as institutional factors often determine the speed and depth of digital transformation.

In summary, while the evidence indicates significant convergence across European countries, persistent disparities remain, particularly in the domain of digital service adoption and skills. Addressing these gaps requires not only investment in infrastructure but also targeted measures to promote digital literacy, trust in online services, and the development of secure and inclusive digital ecosystems.

CONCLUSION

The study set out to map and interpret the digital transformation trajectories of European countries, focusing on the structural differences and convergence patterns that have emerged over the past decade. By applying the self-organizing map methodology, it was possible to uncover multidimensional clusters that reveal the underlying logic of digital development across the region.

The results demonstrate that while Northern and Western European countries have consistently maintained their leadership in digitalization, many Southern and Eastern countries have gradually narrowed the gap, progressing from low to medium levels of digitalization. The most striking differences between clusters were not found in the size of the ICT sector but in the adoption of digital services and the distribution of digital skills, highlighting the decisive role of human capital and behavioral readiness in digital transformation.

From these findings, several important conclusions can be drawn. First, countries of the European region have experienced significant digital convergence, with all countries reaching at least medium levels of transformation by 2020. Second, persistent disparities remain in online service adoption, financial digitalization, and digital literacy, which continue to separate digital leaders from followers. Third, the sustainability of Europe's digital progress depends on policies that simultaneously strengthen infrastructure, trust, skills, and cybersecurity.

The practical value of this study lies in its ability to provide policymakers with a multidimensional mapping tool for identifying both convergence trends and persistent weaknesses. Future research should further explore sector-specific dynamics and the interplay between digital transformation, economic resilience, and inclusive growth.

AUTHOR CONTRIBUTIONS

Conceptualization: Olena Pakhnenko, Hanna Yarovenko, Andrii Semenog.
Data curation: Andrii Semenog, Oleksii Tarasenko.
Formal analysis: Yevgeniya Mordan.
Funding acquisition: Olena Pakhnenko, Hanna Yarovenko, Yevgeniya Mordan.
Investigation: Olena Pakhnenko, Hanna Yarovenko, Andrii Semenog.
Methodology: Olena Pakhnenko, Hanna Yarovenko.
Project administration: Olena Pakhnenko, Hanna Yarovenko.
Resources: Olena Pakhnenko, Andrii Semenog, Oleksii Tarasenko.
Supervision: Hanna Yarovenko.
Validation: Andrii Semenog, Yevgeniya Mordan, Oleksii Tarasenko.
Visualization: Hanna Yarovenko, Andrii Semenog.
Writing – original draft: Olena Pakhnenko, Andrii Semenog, Yevgeniya Mordan, Oleksii Tarasenko.
Writing – review & editing: Olena Pakhnenko, Hanna Yarovenko.

ACKNOWLEDGMENT

The authors acknowledge with gratitude the financial support provided by the Ministry of Education and Science of Ukraine for the research project "Cybersecurity and digital transformations of the country's wartime economy: the fight against cybercrime, corruption and the shadow sector", state registration number 0124U000544).

REFERENCES

1. Alhanatleh, H., Khaddam, A., Abudabaseh, F., Alghizzawi, M., & Alzghoul, A. (2024). Enhancing the public value of mobile fintech services through cybersecurity awareness antecedents: A novel framework in Jordan. *Investment Management and Financial Innovations, 21*(1), 417-430. https://doi.org/10.21511/imfi.21(1).2024.32
2. Alrawashedh, N. H., & Shubita, M. F. (2024). Impact of digital transformation on the organization's financial performance: A case of Jordanian commercial banks listed on the Amman Stock Exchange. *Banks and Bank Systems, 19*(1), 126-134. https://doi.org/10.21511/bbs.19(1).2024.11
3. Alzubi, M. M. S. (2025). Factors influencing e-commerce adoption in Jordanian online insurance sector. *Insurance Markets and Companies, 16*(2), 1-10. https://doi.org/10.21511/ins.16(2).2025.01
4. Bocean, C. G., & Vărzaru, A. A. (2023). EU countries' digital transformation, economic performance, and sustainability analysis. *Humanities and Social Sciences Communications, 10,* Article 875. https://doi.org/10.1057/s41599-023-02415-1
5. Bozhenko, V., Boyko, A., Vondráček, M., & Karácsony, P. (2024). Shadow economy and financial stability from the perspective of finance digitalization. *Journal of International Studies, 17*(2), 191-205. https://doi.org/10.14254/2071-8330.2024/17-2/10
6. Burinskienė, A., & Seržantė, M. (2022). Digitalisation as the indicator of the evidence of sustainability in the European Union. *Sustainability, 14*(14), Article 8371. https://doi.org/10.3390/su14148371
7. Chen, X., Wang, T., Lin, X., Hinde, D., Yan, Q., & Zmire, Z. (2023). The potential of the digital economy: A comparative assessment of key countries' cybersecurity. *International Journal of Education and Humanities, 11*(1), 1-7. https://doi.org/10.54097/ijeh.v11i1.12740
8. Cuong, N. K., Ngoc-Long, N., Dung, H. T., & Hai, T. V. (2025). Digital transformation, organizational agility, and firm performance in emerging markets: Evidence from Vietnam's machinery sector. *Problems and Perspectives in Management, 23*(3), 342-357. https://doi.org/10.21511/ppm.23(3).2025.25
9. Darusalam, D., Janssen, M., Jayanti, S., Sitompul, R., Said, J., &

Sanusi, Z. (2024). Public administration digitalization effects on corruption: Lesson learned from Indonesia. *Digital Government: Research and Practice, 5*(4), 1-13. https://doi.org/10.1145/3691351

10. European Commission. (2024). *Interactive publication: Digitalisation in Europe – 2024 edition.* Eurostat. Retrieved from https://ec.europa.eu/eurostat/en/web/interactive-publications/digitalisation-2024
11. Eurostat. (2024). *Internet purchases by individuals (2002-2019)* [Dataset]. https://doi.org/10.2908/ISOC_EC_IBUY
12. Eurostat. (2025a). *Percentage of the ICT sector in Gross value added* [Dataset]. https://doi.org/10.2908/ISOC_BDE15AG
13. Eurostat. (2025b). *Percentage of the ICT sector personnel in total employment* [Dataset]. https://doi.org/10.2908/ISOC_BDE15AP
14. Eurostat. (2025c). *E-commerce sales of enterprises by NACE Rev. 2 activity* [Dataset]. https://doi.org/10.2908/ISOC_EC_ESELN2
15. Eurostat. (2025d). *Value of e-commerce sales by NACE Rev. 2 activity* [Dataset]. https://doi.org/10.2908/ISOC_EC_EVALN2
16. Eurostat. (2025e). *E-government activities of individuals via websites* [Dataset]. https://doi.org/10.2908/ISOC_CIEGI_AC
17. Eurostat. (2025f). *Individuals – internet activities* [Dataset]. https://doi.org/10.2908/ISOC_CI_AC_I
18. Eurostat. (2025g). *Internet purchases by individuals (2020 onwards)* [Dataset]. https://doi.org/10.2908/ISOC_EC_IB20
19. Fura, B., Karasek, A., & Hysa, B. (2025). Statistical assessment of digital transformation in European Union countries under sustainable development goal 9. *Quality & Quantity, 59,* 937-972. https://doi.org/10.1007/s11135-024-01972-0
20. Hadiyati, E., Mulyono, S., & Gunadi (2024). Digital marketing as a determinant variable for improving the business performance. *Innovative Marketing, 20*(3), 28-41. https://doi.org/10.21511/im.20(3).2024.03
21. Hasan, S. M., Islam, K. M. A., Tawfiq, T. T., & Saha, P. (2025). Triple pillars of sustainable finance: The role of green finance, CSR, and digitalization on bank performance in Bangladesh. *Banks and Bank Systems, 20*(1), 38-50. https://doi.org/10.21511/bbs.20(1).2025.04
22. Hunady, J., Pisár, P., Vugec, D. S., & Bach, M. P. (2022). Digital transformation in European Union: North is leading, and South is lagging behind. *International Journal of Information Systems and Project Management, 10*(4), 39-56. https://doi.org/10.12821/ijispm100403
23. Juneja, A., Goswami, S.S., & Mondal, S. (2024). Cyber security and digital economy: Opportunities, growth and challenges. *Journal of Technology Innovations and Energy, 3*(2), 1-22. https://doi.org/10.56556/jtie.v3i2.907
24. Karimov, N. G., Khamidova, F. A., Saydullaev, S. S., & Parpieva, R. A. (2021). Digital transformation of the economy as a new challenge to economic security. *ICFNDS 21: Proceedings of the 5th International Conference on Future Networks and Distributed Systems* (pp. 348-355). Dubai, the United Arab Emirates. https://doi.org/10.1145/3508072.3508129
25. Korjonen-Kuusipuro, K., & Wojciechowski, A. (2025). Sense of security in the digital age. *Human Technology, 21*(1), 1-5. https://doi.org/10.14254/1795-6889.2025.21-1.0
26. Kreiterling, C. (2023). Digital innovation and entrepreneurship: A review of challenges in competitive markets. *Journal of Innovation and Entrepreneurship, 12,* Article 49. https://doi.org/10.1186/s13731-023-00320-0
27. Kuzior, A., Tiutiunyk, I., Zielińska, A., & Kelemen, R. (2024). Cybersecurity and cybercrime: Current trends and threats. *Journal of International Studies, 17*(2), 220-239. https://doi.org/10.14254/2071-8330.2024/17-2/12
28. Lesmana, D., Afifuddin, M., & Adriyanto, A. (2023). Challenges and cybersecurity threats in digital economic transformation. *International Journal of Humanities Education and Social Sciences (IJHESS), 2*(6). https://doi.org/10.55227/ijhess.v2i6.515
29. Małkowska, A., Urbaniec, M., & Kosała, M. (2021). The impact of digital transformation on European countries: Insights from a comparative analysis. *Equilibrium, 16*(2), 325-355. https://doi.org/10.24136/eq.2021.012
30. Marjerison, R. K., & Gatto, A. (2024). Public sector digitalization, corruption, and sustainability in the developing world: A scoping review. *Sustainable Development, 32*(5), 5627-5638. https://doi.org/10.1002/sd.2900
31. Massaoudi, E. M. E., Rachid, M., Bennacer, M. K., Hammoumi, A. E., Seghyar, N., & Lahmouchi, M. (2025). Digital transformation and new management and organizational modes: Impacts on companies' financial performance. *Problems and Perspectives in Management, 23*(3), 385-393. https://doi.org/10.21511/ppm.23(3).2025.28
32. Munshi, M., & Manni, U. H. (2025). Can digital transformation reduce government corruption? A meta-analysis. *Quantitative Economics and Management Studies, 6*(1), 1-8. https://doi.org/10.35877/454RI.qems3020
33. Mustafa, J. A. (2024a). From innovation to stability: Evaluating the ripple influence of digital payment systems and capital adequacy ratio on a bank's Z-score. *Banks and Bank Systems, 19*(3), 67-79. https://doi.org/10.21511/bbs.19(3).2024.07
34. Mustafa, J. A. (2024b). Integrating financial literacy, regulatory technology, and decentralized finance: A new paradigm in Fintech evolution. *Investment Management and Financial Innovations, 21*(2), 213-226. https://doi.org/10.21511/imfi.21(2).2024.17
35. Pinto, H., Nogueira, C., & Vieira, G. (2023). Digitalisation landscape in the European Union: Statistical insights for a digital transformation. *European Public & Social Innovation Review, 8*(1), 20-38. https://doi.org/10.31637/epsir.23-1.2

36. Reischauer, G., Hess, T., Sellhorn, T., & Theissen, E. (2024). Transparency in an age of digitalization and responsibility. *Schmalenbach Journal of Business Research, 76,* 483-494. https://doi.org/10.1007/s41471-024-00203-4
37. Saeed, S., Altamimi, S. A., Alkayyal, N. A., Alshehri, E., & Alabbad, D. A. (2023). Digital transformation and cybersecurity challenges for businesses resilience: Issues and recommendations. *Sensors, 23*(15), Article 6666. https://doi.org/10.3390/s23156666
38. Saldanha, D. M. F., Dias, C. N., & Guillaumon, S. (2022). Transparency and accountability in digital public services: Learning from the Brazilian cases. *Government Information Quarterly, 39*(2), Article 101680. https://doi.org/10.1016/j.giq.2022.101680
39. Sendjaja, T., Irwandi, Prastiawan, E., Suryani, Y., & Fatmawati, E. (2024). Cybersecurity in the digital age: developing robust strategies to protect against evolving global digital threats and cyber attacks. *International Journal of Science and Society, 6*(1), 1008-1019. https://doi.org/10.54783/ijsoc.v6i1.1098
40. Straková, J., Talíř, M., & Váchal, J. (2022). Opportunities and threats of digital transformation of business models in SMEs. *Economics and Sociology, 15*(3), 159-171. https://doi.org/10.14254/2071-789X.2022/15-3/9
41. Suntsova, O. (2024). Digital transformation of the global economy: Challenges and opportunities. *Financial and Credit Systems: Prospects for Development, 3*(14), 87-10. https://doi.org/10.26565/2786-4995-2024-3-08
42. Török, L. (2024). The relationship between digital development and economic growth in the European Union. *International Review of Applied Sciences and Engineering, 15*(3), 375-389. https://doi.org/10.1556/1848.2024.00797
43. Tutak, M., & Brodny, J. (2022). Business digital maturity in Europe and its implication for open innovation. *Journal of Open Innovation: Technology, Market, and Complexity, 8*(1), Article 27. https://doi.org/10.3390/joitmc8010027
44. Unerbayeva, R., Kozhirova, S., Kenzhegulova, G., Mukatay, A., & Abdykadyr, T. (2025). The role of education, human capital, and quality of life in regional development: Evidence from Kazakhstan. *Problems and Perspectives in Management, 23*(3), 256-273. https://doi.org/10.21511/ppm.23(3).2025.19
45. Valackiene, A., & Odejayi, R. O. (2024). The impact of cyber security management on the digital economy: Multiple case study analysis. *Intellectual Economics, 18*(2), 261-283. https://doi.org/10.13165/IE-24-18-2-02
46. Yamen, A., Coskun, A., & Mersni, H. (2022). Digitalization and tax evasion: The moderation effect of corruption. *Economic Research-Ekonomska Istraživanja, 36*(2). https://doi.org/10.1080/1331677X.2022.2142634
47. Yuan, J., Jiang, S., & Dela Cruz, B. M. J. (2023). Toward the digital economy: Mobile payment affecting sustainable consumption behavior. *Innovative Marketing, 19*(1), 220-232. https://doi.org/10.21511/im.19(1).2023.19
48. Zhang, Q., Wu, P., Li, R., & Chen, A. (2024). Digital transformation and economic growth. Efficiency improvement in the digital media era: Digitalization of industry or digital industrialization? *International Review of Economics & Finance, 92,* 667-677. https://doi.org/10.1016/j.iref.2024.02.010
49. Zherlitsyn, D., Kolarov, K., Rekova, N. (2025). Digital transformation in the EU: Bibliometric analysis and digital economy trends highlights. *Digital, 5*(1). https://doi.org/10.3390/digital5010001
50. Zinchenko, O., Redko, V., Iakovenko, V., & Privarnikova, I. (2025). Cluster analysis of the capitals of European countries by the "green" image indicators in the context of sustainable development. *Environmental Economics, 16*(2), 104-118. https://doi.org/10.21511/ee.16(2).2025.08