RECENT J. (2025), 77:212-221
https://doi.org/10.31926/RECENT.2025.77.212

Regional Patterns of Digitalization in South-East Europe: Evidence from Principal Component Analysis and Clustering

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Abstract
This study investigates the evolution of digital disparities and convergence trends among six South-East European countries, Bulgaria, Greece, Croatia, Romania, Slovenia, and Türkiye, between 2015 and 2024. Drawing on fifteen indicators related to digital employment, technological education, and internet usage behaviours, the analysis employs Principal Component Analysis (PCA), K-means clustering, and hierarchical dendrogram techniques to uncover latent patterns and structural similarities. The findings reveal consistent clustering of Bulgaria and Romania, as well as Croatia and Slovenia, suggesting regionally coherent trajectories. Türkiye exhibits an irregular digital profile, frequently detaching from the other countries, particularly in pandemic years, while Slovenia's position shifts toward digital leadership in later periods. The hierarchical clustering of indicators highlights how COVID-19 disrupted traditional correlations, with structural coherence recovering after 2022. These results demonstrate a mix of stability and disruption in digital development across the region and underscore the need for territorially differentiated digital policies. The study participates to the literature on digital transformation by offering a multi-method analysis of convergence and fragmentation and provides a replicable framework for assessing digital readiness and policy alignment at the regional level.

Keywords
digitalization, South-East Europe, PCA, clustering, regional convergence

1. Introduction

Assessing the progress of digital transformation in European public administrations has become increasingly important, given the accelerating pace of technological change and the growing demand for efficient and inclusive digital public services. Among the key instruments used to monitor this evolution, the Digital Economy and Society Index (DESI) serves as a central benchmark for evaluating digital performance and exposing structural disparities across EU member states. Recent research has emphasized the relevance of this index, particularly in revealing persistent challenges related to interoperability, cybersecurity, and administrative transparency [1]. Moreover, the fragmentation of national digitalization strategies exacerbates existing divides between urban and rural regions, underscoring the need for a more integrated and comparative framework to reduce territorial digital inequalities [2].

Recent research has emphasized additional dimensions of digital inequalities across Europe. The COVID-19 pandemic significantly amplified regional disparities in the use of information and communication technologies (ICT), shifting the analytical focus from purely technological gaps to broader socio-economic imbalances aligned with the sustainable development goals [3]. Furthermore, the availability and quality of e-services are not solely determined by the implementation of EU-level digital policies, but also by national institutional factors such as administrative capacity, innovation orientation, and strategic coordination [4]. In this context, the level of digitalization has been shown to directly support progress toward a circular economy, particularly through the mobilization of digital human capital and effective technological integration [5].

The region of Southeastern Europe remains relatively underexplored in academic research, despite its structural vulnerabilities and asynchronous digital development trajectories [6]. Spatial clustering models, such as the "high–high" configurations in Northern Europe and "low–low" patterns in the South, underscore persistent territorial asymmetries that require refined multivariate analyses [7]. Cluster based approaches, employed in recent studies [8, 9], offer valuable methodological tools for capturing such structural divergences. Although Southeast European countries differ in their pace of digital transformation, they share a strategic commitment to align with EU energy and digital agendas, navigating both structural barriers and integration opportunities [10].

Building on these premises, the present study aims to explore digital convergences and fragmentations in six Southeastern European countries, Bulgaria, Greece, Croatia, Romania, Slovenia, and Turkey, during the period 2015–2024. By combining principal component analysis (PCA), the K-means algorithm, and hierarchical clustering methods, the research investigates the digital behaviors and structural profiles of these countries, based on 15 indicators derived from the socio-economic component of the DESI index. The results highlight latent patterns and temporal discontinuities, particularly during crisis years, offering a valuable contribution both to the comprehension of regional digital disparities and to the evolution of differentiated and inclusive public policies.

The structure of the article is organized as follows: Section 2 provides a synthesis of the literature on digital convergence and regional disparities within the EU; Section 3 describes the methodology used, including PCA and clustering techniques; Section 4 details the dataset and the variables analyzed; Section 5 presents the results and related discussions; whereas the latter part offers conclusions and implications for digital public policies.

2. Literature Review

The DESI is widely recognized in academic literature as a key instrument for assessing the level of digitalization across EU member states. Its relevance in capturing persistent disparities between Southeastern European countries and the broader Union has been underlined by recent studies [11]. These disparities justify the need for deeper comparative investigations into regional digital trajectories. Moreover, the evolution of DESI between 2015 and 2021 has been shown to correlate strongly with socio-economic conditions, suggesting that structural determinants play a critical role in shaping national digitalization dynamics [12].

From a structural perspective, recent analyses highlight the formation of distinct clusters across EU member states regarding access to digital healthcare services. Only a few countries, such as the Nordic states, Spain, and Cyprus, achieve high levels of digital readiness, while most continue to face significant infrastructure gaps in this sector [6]. Moreover, the trend toward digital convergence within the EU appears to be underway, with economic development emerging as a more influential factor than education in narrowing these disparities [13].

From a methodological perspective, recent studies have used indicators such as DESI and Eurostat databases in combination with multivariate analysis methods, PCA, clustering, or hierarchical techniques, to identify structural patterns and divergent digital trajectories between countries [12, 14]. Wu et al., [15], identify distinct clusters of digital transformation maturity based on readiness and data capability, offering relevant insights for understanding heterogeneous digital development across organizations.

Convergence and clustering based approaches are increasingly used to understand digital fragmentation. Borowiecki et al., [16], analyse digital convergence based on the five components of the DESI, observing a general alignment in terms of connectivity and human capital, but a marked polarization regarding the digital technology adoption in the private sector [16]. Complementarily, Jenčová, Vašaničová, and Miškufová [8] assess the digital performance of 28 EU countries and, through cluster analysis, identify internally homogeneous groupings and significant differences across digital dimensions, thereby helping to address a methodological gap in the current literature.

In a similar vein, Kolupaieva and Tiesheva [9] explore digital asymmetry and convergence using fuzzy sets and Granger causality tests, demonstrating the existence of differences between the transactional, informational, and operational dimensions of digitalization, with important implications for the competitiveness of member states. Additionally, Noja et al., [17], employ a complex approach, robust regression, SEM models, and GGM networks, to show that digitalization, improvements in energy and environmental performance contribute synergistically to the EU countries' sustainable development, within a context shaped by globalization and digital convergence.

The COVID-19 pandemic's impacts on these trajectories are well documented. Ruiz-Rodríguez et al., [3], demonstrate that the pandemic amplified regional disparities in ICT use at the household level across Europe, shifting the differentiation criteria from technological factors (2011–2018) to socio-economic factors correlated with the Sustainable Development Goals (SDGs) starting in 2020. This shift was highlighted through the application of composite indices and cluster analyses on 231 European regions.

In a complementary vein, Bilal et al., [18], analyse the relationship among digitalization, globalization, and CO_2 emissions within Belt and Road economies, including European regions. The authors show that in Europe and Central Asia, digitalization is positively correlated with pollution, in contrast to the MENA and Southeast Asia regions. This finding draws attention to the risks associated with the intensive use of polluting infrastructure and underscores the need for differentiated and environmentally responsible digital policies.

Finally, Marienfeldt [4] emphasizes that the availability of e-services depends not only on EU-wide policies but also on national institutional particularities, such as administrative capacity, the degree of centralization, and the governance orientation toward innovation, identifying three distinct trajectories of digital change in the European public sector [4].

Overall, the academic literature highlights a complex dynamic of digitalization within the European Union, characterized by selective convergences, structural asymmetries, and persistent fragmentations, particularly in Southeastern Europe. These findings justify the use of exploratory multivariate methods to map regional digital profiles and to identify patterns relevant for the formulation of contextually adapted public policies.

3. Data and Methodology

3.1. Data

This study's data came from the Eurostat information platform, the official statistical source of the European Union, and cover a ten-year period (2015–2024). The analysis focuses on six European countries: Bulgaria (A1), Greece (A2), Croatia (A3), Romania (A4), Slovenia (A5), and Türkiye (A6). The selection of these countries reflects the objective of conducting a regional comparative analysis centered on Southeastern Europe, a region characterized by unequal levels of digitalization and distinct institutional trajectories.

The selection of indicators was based on their relevance for measuring the level of digitalization of society and the economy, covering both structural dimensions (ICT workforce, technological education) and behavioral dimensions (ways in which the population uses the internet). A total of 15 indicators were included, grouped into three major categories (Table1):

- Digital human capital (Indicators 1–5);
- Access to and digital infrastructure (Indicator 6);
- Actual internet usage by individuals (Indicators 7–15).

These indicators enable a detailed characterization of the digital ecosystem in each country and provide a solid foundation for the application of multivariate analysis methods.

3.2. Methodology

The methodological approach is grounded in recent studies from the academic literature. Alqararah and Alnafrah [14] use cluster analysis to group countries based on innovation performance, providing a useful framework for the development of differentiated policies. Similarly, Košíková and Vašaničová [19] apply a two-level analysis to explore the relationship between digital readiness (Network Readiness Index) and progress in achieving the SDG. In addition, Lnenicka et al., [20], propose a combination of qualitative analysis of e-government reports and quantitative methods such as regression and clustering to capture the key drivers of digital progress.

This research adopts a mixed methodological strategy, integrating quantitative components (PCA, K-means, hierarchical clustering) to provide a comprehensive view of digital convergences and fragmentations among Southeastern European countries.

The comparative analysis of digitalization in the selected countries requires the use of a multidimensional dataset, which includes variables expressed in different units and scales. To ensure comparability between criteria and to avoid distortions caused by scale variations, a normalization step is necessary.

Table 1. Indicators of digitalization in society and the economy

1	Employed ICT specialists - total
2	Employed ICT specialists by sex Male (Percentage)
3	Employed ICT specialists by sex Females (Percentage)
4	Persons with tertiary education (ISCED) and/or employed in science and technology
5	Employment in high- and medium-high technology manufacturing sectors and knowledge-intensive service sectors
6	Level of internet access - households
7	Individuals using the internet for participating in social network
8	Individuals using the internet for internet banking
9	Individuals using the internet for selling goods or services
10	Individuals using the internet for finding information about goods and services
11	Individuals using the internet for sending/receiving e-mails
12	Individuals who have never used the internet
13	Individuals frequently using the internet
14	Individuals regularly using the internet. Frequency of internet access: once a week (including every day)
15	Internet use by individuals

Through this procedure, each variable is changed so that it has a mean of zero and a standard deviation of one:

$$x'_{ij} = \frac{x_{ij} - \mu_i}{\sigma_i} \quad (1)$$

where x_{ij} is the original value of criterion i for country j, μ_i s the mean of criterion i, and σ_i is the corresponding standard deviation. This transformation ensures that all indicators contribute equally to the subsequent multivariate analysis, regardless of their initial scale or units of measurement.

3.2.1. Determining the optimal number of clusters

To avoid the arbitrary selection of the value of k in the clustering method, the silhouette method is used, which evaluates the internal coherence of each observation in relation to the nearest alternative cluster. The silhouette score is determined as follows:

$$s(i) = \frac{b(i) - a(i)}{max\big(a(i), b(i)\big)} \quad (2)$$

where $a(i)$ is the average distance between observation i and all other points within the same cluster, and $b(i)$ is the minimum average distance to the observations in the nearest other cluster. The value of k that maximizes the average silhouette score $\bar{s}$ is selected, indicating a clear separation between groups.

3.2.2. K-means clustering

The K-means algorithm is a partitional clustering method that divides observations into a predefined number of clusters by minimizing within-cluster variation. Every observation has a cluster attached to it whose center is closest, and the centers are iteratively recalculated until convergence. The objective function is as follows:

$$J = \sum_{i=1}^{k} \sum_{x_j \in C_i} \left\| x_j - \mu_i \right\|^2 \quad (3)$$

where C_i is cluster i, μ_i is the mean center of cluster i, and x_j is a data point, representing a country. Each country is assigned to the cluster with the closest center μ_i.

3.2.3. PCA analysis

In order to decrease dimensionality and facilitate data visualization, Principal Component Analysis (PCA) is applied. PCA transforms correlated variables into a set of uncorrelated components, maximizing the explained variance. The transformation is expressed as follows:

$$Z = XW \tag{4}$$

where X is the matrix of normalized data, W contains the eigenvectors of the covariance matrix, and Z represents the projection onto the principal components. The covariance matrix is defined as:

$$\sum = \frac{1}{n-1} X^T X \tag{5}$$

The silhouette score is also used to evaluate the quality of the clustering. Values close to 1 indicate a clear assignment of observations to a cluster, values near 0 suggest ambiguity, and negative values indicate incorrect assignments. The graphical representation of the scores provides a synthetic overview of clustering quality.

3.2.4 Hierarchical clustering

To deepen the understanding of the relationships between observations and variables, an agglomerative hierarchical clustering method is also applied, based on Euclidean distance and Ward's linkage method. The distance between two observations is calculated as follows:

$$d(i,j) = \sqrt{\sum_{k=1}^{n} (x_{ik} - x_{jk})^2} \tag{6}$$

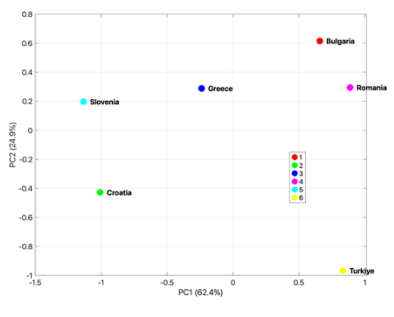
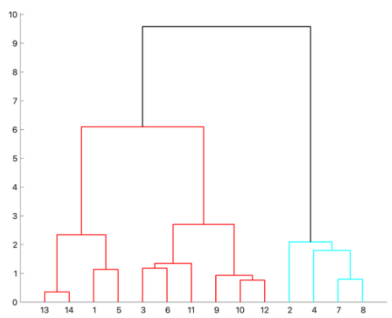
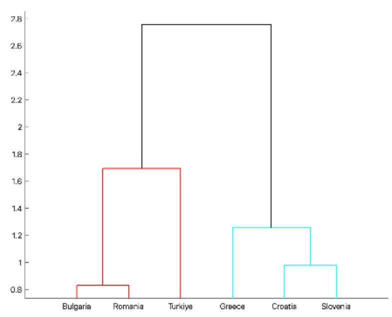
Ward's method minimizes the within-cluster variance:

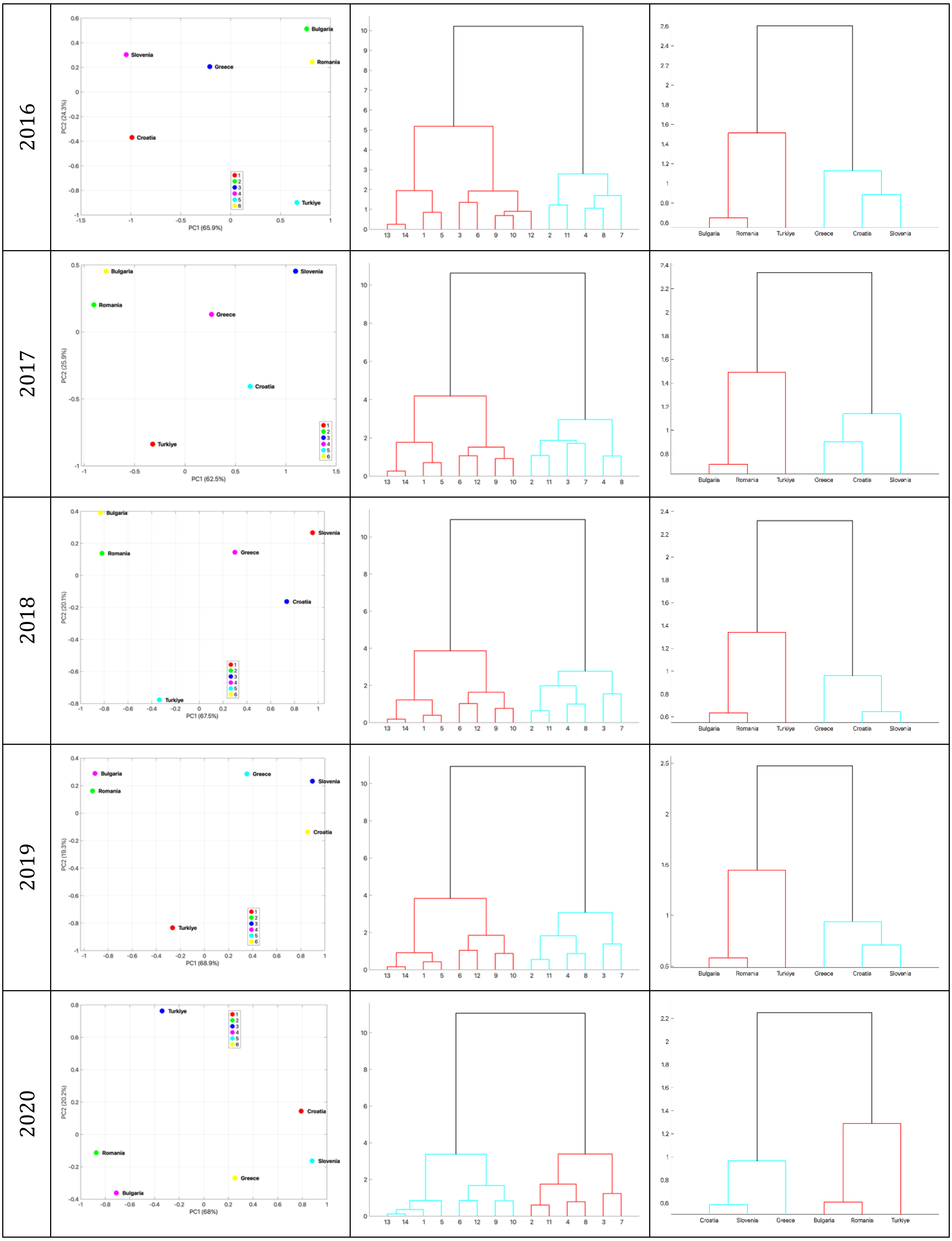
$$\Delta E = \sum_{x \in C_1 \cup C_2} \|x - \mu\|^2 - \sum_{x \in C_1} \|x - \mu_1\|^2 - \sum_{x \in C_2} \|x - \mu_2\|^2 \tag{7}$$

The result is represented in the form of a dendrogram, which progressively reflects the way clusters are formed. When applied to variables, it identifies correlated indicators; when applied to countries, it highlights those with similar digital profiles.

4. Results and Discussions

This section explores the evolving structural relationships among six Southeastern European countries, Bulgaria, Greece, Croatia, Romania, Slovenia, and Türkiye, based on a set of fifteen socio-economic indicators reflecting digitalization trends between 2015 and 2024. To uncover hidden patterns in the data and highlight potential natural groupings among countries, multivariate analysis methods were applied: K-means clustering projected onto the first principal components of a PCA analysis, as well as hierarchical agglomerative methods represented through dendrograms. The results are presented comparatively for each year, using three graphical representations: PCA clustering, dendrogram by indicators, and dendrogram by countries (Figure 1).

	K-Means PCA clustering	Dendrogram criterion	Dendrogram country
2015			


2016
2017
2018
2019
2020
PC1 (65.9%)
PC2 (24.3%)
PC1 (62.5%)
PC2 (25.9%)
PC1 (67.5%)
PC2 (20.1%)
PC1 (68.9%)
PC2 (19.3%)
PC1 (68%)
PC2 (20.2%)
Bulgaria
Romania
Turkiye
Greece
Croatia
Slovenia

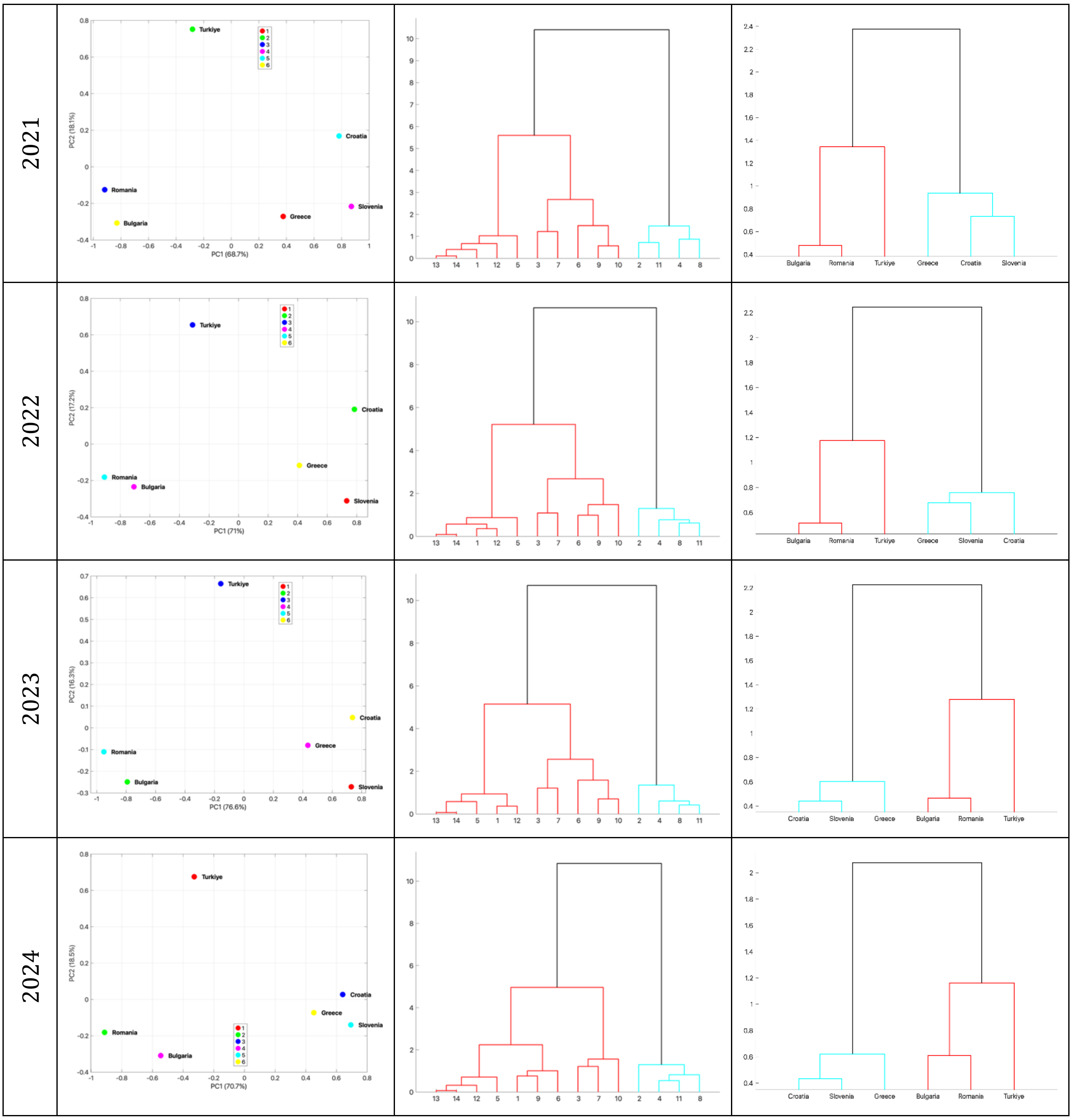


Fig. 1. Clustering and hierarchies among countries and criteria

4.1. Regional Patterns in PCA and K-means Analysis

The PCA representation reduced the dimensionality of the data while retaining between 80% and 90% of the total variability in the first two principal components. This approach enabled the identification of significant structural regularities. Bulgaria and Romania frequently formed a common cluster between 2015 and 2020, indicating a convergent digital development trajectory. Croatia and Slovenia also showed a relatively consistent structural proximity. In contrast, Türkiye stood out with a less synchronized behavior compared to the other countries, tending to form separate clusters in 2020 and 2023, which may suggest specific economic transitions or internal structural imbalances. A noteworthy aspect is Slovenia's dominant position on the first principal component in 2023, indicating significantly higher digital performance in that year.

4.2. Dendrogram by Indicators: Coherence and Systemic Disruptions

The hierarchical clustering of indicators generally reveals stable structural coherence throughout the observed period. However, during 2020–2021, the dendrogram displays an evident disintegration of this structure, marked by increased inter-cluster distances. This fragmentation reflects the multifaceted disruptions brought about by the COVID-19 pandemic, which simultaneously affected digital infrastructure, ICT employment, and online behaviour. A gradual return to systemic equilibrium begins in 2022, culminating in a restored coherence of variables by 2024.

4.3. Dendrogram by Countries: Stability and Temporary Reconfigurations

The country-focused dendrogram indicates a relative stability of regional relationships in the early years of the analysis (2015–2017), with two consistent groups: one composed of Romania and Bulgaria, and the other of Croatia and Slovenia. However, between 2020 and 2021, these configurations are disrupted: Türkiye clearly separates itself, while Croatia temporarily shifts closer to the Eastern Balkan countries. After 2022, the initial groupings tend to reconfigure, but new significant variations emerge, such as Romania in 2024 aligning more closely with Türkiye than with Bulgaria, possibly indicating a subtle shift in relative digital performance.

4.4. Structural Interpretations and Political-Economic Implications

Overall, the results indicate a complex and regime-dependent dynamic of the digitalization process in Southeastern Europe. The years 2020–2021 represent a period of systemic instability, with a visible impact on inter-indicator coherence and country positioning, while Slovenia and Türkiye emerge as distinct cases, with digital trajectories that are relatively decoupled from those of the other analyzed countries.

These findings are supported by recent literature. The study by Feurich et al. (2024) highlights the fragmentation of national digitalization strategies and the challenges of harmonizing digital infrastructures, especially in rural areas, which contributes to persistent regional disparities [2]. In addition, the research conducted by Gil-Lamata et al., (2023) emphasizes the role of digital human capital, technological integration, and digital public services in accelerating the transition to a circular economy. The convergence or divergence of these factors may explain the structural proximities and distances observed among the analyzed countries [2].

These insights support the broader narrative emerging in the post-pandemic digital policy literature, which emphasizes the importance of adaptive, region-specific strategies. The observed realignments, especially Romania's shift towards Türkiye, may suggest the emergence of alternative digitalization pathways in response to national policy adjustments and external economic pressures.

In summary, the multivariate results illustrate a nuanced interplay of digital convergence and divergence across Southeastern Europe. These dynamics highlight the urgent need for coordinated, evidence-based public policies capable of addressing persistent asymmetries while promoting resilience in the face of exogenous shocks.

5. Conclusions

This study investigates the dynamics of digitalization across six Southeastern European countries, Bulgaria, Greece, Croatia, Romania, Slovenia, and Türkiye, over the period 2015–2024. Employing a triangulated multivariate framework, the analysis uncovers patterns of structural convergence and divergence in digital development. The findings reveal a predominantly stable regional architecture, periodically disrupted by exogenous shocks such as the COVID-19 pandemic, and shaped by distinct national pathways.

A key insight emerging from the results is the early formation of a relatively cohesive digital bloc between Romania and Bulgaria, contrasted by the more idiosyncratic trajectories of Slovenia and Türkiye. These divergences are likely driven by heterogeneity in digital public policy, infrastructural investment, and levels of digital human capital. The analysis further supports the notion that digital disparities are dynamic phenomena, continuously reconfigured by conjunctural, structural, and geopolitical forces, rather than fixed gaps.

The main contribution of this research lies in proposing a visually intuitive and exploratory analytical framework that enables the identification of digital convergence trajectories based on socio-economic indicators. The integration of PCA, K-means, and dendrogram techniques provides a multifaceted lens to examine both cross-country digital proximity and inter-variable coherence, offering insights relevant for both academic audiences and public policy practitioners.

Despite its contributions, the study is subject to several limitations. First, the selection of indicators was constrained by cross-country data availability and harmonization, which may omit critical dimensions of the digital transition such as cybersecurity, artificial intelligence integration, or digital governance quality. Second, the approach remains primarily exploratory and descriptive, lacking causal inference or advanced econometric testing. Third, the national-level analysis does not account for within-country disparities, particularly those between urban and rural regions, which are often pronounced in digital contexts.

Future research could expand this analytical framework by incorporating additional variables such as high-level digital competencies, R&D investment in emerging technologies, or metrics on digital institutional quality. Furthermore, the application of causal inference models, panel regressions, spatial econometrics, or machine learning algorithms, could enhance the understanding of structural drivers of digital convergence. Lastly, a comparative extension to include other European macro-regions (Central Europe, Baltic States) could provide a more comprehensive mapping of the continent's evolving digital geography.

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Paper presented at The 17th International Conference
“STANDARDIZATION, PROTYPES and QUALITY: A means of Balkan Countries’ collaboration”