

Digital breach across European Union territories and economic development: an analysis based on a novel digital index

Rómulo Quirós-Sánchez

Department of Economics and Economic History, University of Salamanca, Salamanca, Spain, and

Javier Perote

Department of Economics, University of Salamanca (IME), Salamanca, Spain

Abstract

Purpose – This study examines the progress of digitalization across EU NUTS-2 regions from 2017 to 2021 and introduces the NUTS-2 Digital Index (N2DI), a composite indicator that measures regional digital capacity and its correlation with economic performance.

Design/methodology/approach – The N2DI is constructed from four key dimensions: human capital, connectivity, digital technology integration and digital public services. Using principal component analysis, clustering techniques and panel data models, the study assesses regional disparities, digitalization trends and the relationship among N2DI, GDP per capita and digital budget allocations.

Findings – The findings reveal ongoing digital divides between North-Western and South-Eastern regions, with medium-performing regions demonstrating the most significant improvements. The study indicates a positive association between digitalization and GDP per capita; however, patterns of budget absorption expose some structural inefficiencies. While digitalization contributes to regional development, its effects vary across different clusters.

Originality/value – This study presents the first multidimensional digitalization index at the NUTS-2 level and offers a robust analytical framework for understanding regional digital transformation within the context of EU policy.

Keywords Digitalization indices, Economic growth, Clustering, European Union, NUTS-2 territories, Regional development, PCA

Paper type Research article

1. Introduction

Digitalization is widely viewed as having emerged in the 1990s, when organizations began adopting digital technologies and the Internet to enhance processes, productivity and communication. Schallmo and Williams (2018) describe this period as a decisive shift from analog to digital practices, characterized by the computerization of procedures and the introduction of digital goods, services and media. Building on this perspective, Verhoef *et al.* (2021) propose a three-phase conceptual model—digitization, digitalization and digital transformation—identifying digitalization as the stage in which information technologies systematically reconfigure existing business processes, enabling new forms of value creation and operational efficiency.

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Digitalization integrates emerging digital technologies with economy and sociocultural frameworks, transforming them into essential infrastructure. [Teubner and Stockhinger \(2020\)](#) emphasize its impact on societal norms and economic structures. This process enhances communication, mobility and transactions, creating an interconnected marketplace and increasing market transparency. Consumers and businesses can access information more easily, fostering competition. Furthermore, digitalization reshapes interactions among regions, individuals and governments, urging organizations to rethink their technological strategies, [Thorseng and Grisot \(2017\)](#). Key technologies such as artificial intelligence, machine learning, cloud computing and the Internet are pivotal in driving the rise of the digital economy, [Afonasova, Panfilova, Galichkina, and Lusarczyk \(2019\)](#).

In today's rapidly evolving business environment, local leaders must adopt technology to boost regional development and improve living standards, [Kraus et al. \(2021\)](#). Digital transformation is not a single, universally defined concept; instead, it is framed metaphorically across policy, management and technology debates. [Owoseni \(2023\)](#) demonstrates that the term functions as a boundary concept, shaping expectations of economic and institutional change while remaining conceptually ambiguous.

In this way, digitalization is a global priority, emphasized by the European Commission and reflected in government plans, [European Commission \(2021\)](#). Key areas include enhancing digital connectivity, building skills and integrating technology into business and public services. Regions stand to benefit significantly from digitalization through job growth, increased productivity and better environmental outcomes, [van Ark \(2016\)](#). However, establishing a comprehensive framework for adopting digital technologies remains challenging, [Hanelt, Bohnsack, Marz, and Antunes Marante \(2021\)](#). The diffusion of digital technologies is partly determined by institutional actors, particularly trade associations that mediate knowledge, standards and incentives across firms. [Van Veldhoven and Vanthienen \(2023\)](#) highlight that digital transformation is embedded in sectoral governance, not solely within firm-level technological decisions.

The EU aims to bridge the digitalization gap with the U.S. and China, with many companies investing in digital technologies post-pandemic, [European Investment Bank \(2021\)](#). Yet, Europe still faces hurdles in digital innovation and technology reliance, [Afonasova et al. \(2019\)](#). Digital firms showed greater resilience and productivity during economic disruptions like the COVID-19 crisis, [Kraus et al. \(2021\)](#), and the importance of digitalization continues to attract scholarly attention. Digital transformation strengthens organizational resilience by enabling firms to convert intangible assets—such as knowledge, data and digital capability—into strategic agility, [Apostol and Hernández-Rodríguez \(2024\)](#). [Bounfour, Housel, Silkey, and Nonnis \(2023\)](#) argue that the COVID-19 shock accelerated this conversion process, revealing how digital investment influences economic adaptation and competitiveness.

Since 2015, the European Commission has monitored digital transformation across member states through the Digital Economy and Society Index (DESI), which has become increasingly important amid the COVID-19 pandemic, [European Commission \(2021\)](#). However, there is no existing digitalization index for NUTS2 regions. This paper addresses this gap by developing a *tailored NUTS2 Compound Digitalization Index (N2DI)* to promote regional growth and resilience. Previous studies, including those by [Apostol and Hernández-Rodríguez \(2024\)](#) and [Brodny and Tutak \(2022\)](#), have examined digitalization's impact across various EU levels, but a focused NUTS2 index remains lacking.

Our research analyzes N2DI's progression from 2017 to 2021 across 241 regions, assessing its impact on GDP per capita. Using machine learning, principal components analysis and econometric methods, we categorize contributions into three areas: creating a digital index for each region, identifying performance clusters and demonstrating that digitalization fosters economic growth. Our findings confirm advancements in digitalization across NUTS2 regions and highlight areas requiring additional support.

This research examines the complexities of digitalization within the European Union, focusing on key NUTS2 regions and their impact on regional economies. It explores

macroeconomic factors such as GDP per capita, population statistics, digital metrics, income levels and EU budget allocations. The N2DI—a digital, social and economic index—is introduced to clarify these relationships. NUTS2 regions were chosen for their crucial role in EU regional policy, offering a balanced view of data availability and regional specificity, Eurostat (2025). This classification allows meaningful comparisons while avoiding the broad or overly detailed analyses typical of NUTS1 and NUTS3 regions, Charron, Dijkstra, and Lapuente (2015). The study spans from 2017 to 2021 due to data availability for digital sub-indices. Key research questions include.

- RQ1. What are the levels and spatial disparities of digitalization across NUTS-2 regions in the European Union?
- RQ2. How does regional digitalization influence economic performance across NUTS-2 regions?
- RQ3. To what extent do EU digital and cohesion policy interventions generate heterogeneous effects across NUTS-2 regions?

This study aims to illuminate the transformative effects of digitalization across the diverse regions of the EU, establishing a foundation for informed policy recommendations and strategic initiatives. The structure of the paper is as follows: The section 2 provides a clear overview of the NUTS 2 framework, delves into the dynamic digital economy, and identifies key digital indicators that define each region. Sections 3 and 4 detail the rigorous methodology employed and present compelling findings from both clustering and panel data analyses. Finally, Section 5 succinctly summarizes the main conclusions from the research and offers a thoughtful discussion while proposing intriguing avenues for future research in this domain.

2. Literature review/Background

2.1 Digitalization in the EU and NUTS

The Nomenclature of Territorial Units for Statistics (NUTS) is a geocode standard created by the EU in 2003 to define administrative divisions for statistical uses. It facilitates the allocation of Structural Funds and the Cohesion Fund to promote economic development. NUTS classifies EU countries into three levels: NUTS1 (92 major regions), NUTS2 (244 regions for regional policies) and NUTS3 (1,165 smaller regions for detailed analysis). This framework helps in understanding regional dynamics and supports decision-making. Figure 1 illustrates the population density across NUTS2 regions of the EU, while Table A.1, Appendix A, shows the NUTS 2 regions and codes, Table A.5, Appendix A, exhibits abbreviations and Data Sources.

The COVID-19 pandemic accelerated digital transformation in the EU, with a rise in remote services and virtual meetings expected to continue, European Commission (2021). A survey from April to July 2021 found that 46% of EU firms attempted to enhance digital capabilities, compared to 58% in the US, European Investment Bank (2021). While 61% of EU firms used advanced digital technologies, this was 66% in the US. Among previously digitally adopted EU firms, 53% increased their digital investments during the pandemic, whereas only 34% of non-digital firms began their digital transformation. In the US, 64% of tech adopters boosted investments, and 48% of non-digital firms explored digital options.

2.2 NUTS 2 and digitalization

NUTS2 regions are vital for implementing EU regional policies and for channeling resources from the €8.1 billion Digital Europe Programme, which drives digital transformation in line with the 2030 Digital Compass, European Commission (2021). This program supports the EU’s cohesion policy to reduce regional disparities by developing advanced infrastructures such as broadband networks. The Digital Decade Policy Programme sets ambitious targets for

European Union NUTS2

Population 2021

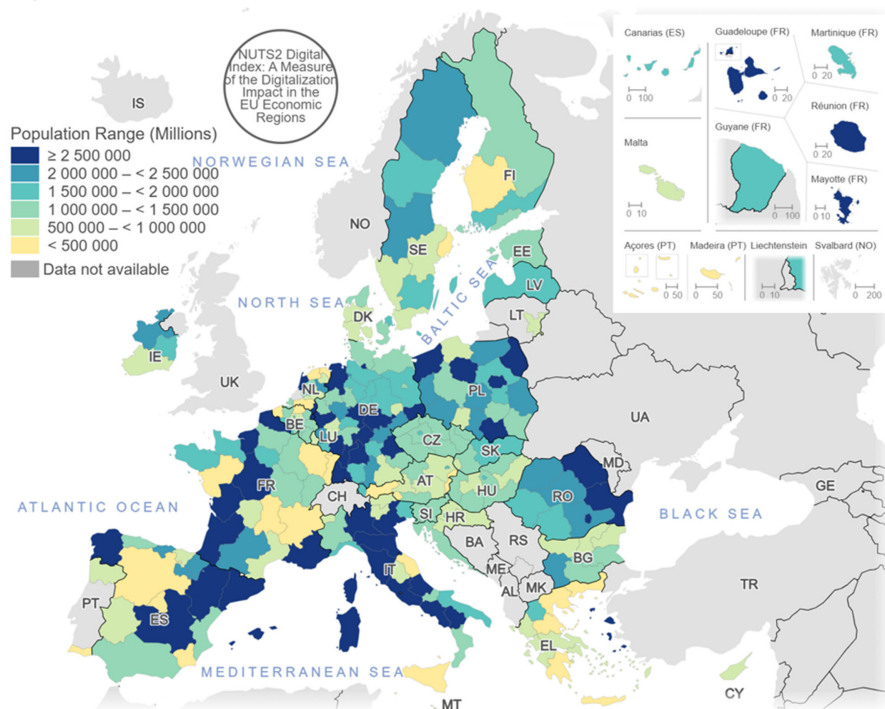


Figure 1. Population by NUTS 2. Source: Eurostat

expanding digital access, improving service quality and enhancing digital skills, thereby fostering a more inclusive digital ecosystem, [European Commission \(2023b\)](#).

At the regional level, NUTS2 entities allocate funds for digitalization initiatives, financing projects that expand infrastructure, improve skills and streamline e-government services, [European Court of Auditors \(2023\)](#). In addition, the *NextGenerationEU* (NGEU) recovery instrument provides significant financial support for digital transition projects aimed at economic recovery after the COVID-19 crisis, [European Commission \(2021\)](#). Progress in these areas is systematically tracked by the European Commission to identify regional disparities and guide future investment, [Eurostat \(2025\)](#).

2.3 EU budget and digitalization

In 2010, the European Union introduced the *Europe 2020* strategy to stimulate post-financial crisis growth, highlighting digitalization as a key driver of recovery, with a budgetary framework of €1.21 trillion, [European Commission \(2010\)](#). The NGEU recovery instrument further promotes digitalization by supporting investments in data processing, artificial intelligence and the connection of research to market applications, [European Commission \(2021\)](#). The EU's broader digital strategy aims to enhance competition, strengthen infrastructure and foster economic growth, while ensuring accountability and transparency in budgetary processes, [European Commission \(2020\)](#). Digitalization has been shown to foster information sharing among member states, thereby driving growth through transparency and improved fund management, [European Court of Auditors \(2023\)](#). Although the 2014–2020

Multiannual Financial Framework improved economic efficiency, it has been noted that it lacked gender-focused digital goals, [Rubery and Figueiredo \(2018\)](#). Future budgets allocate €9.2 billion for digital transformation in supercomputing, AI and cybersecurity, with an additional €4.5 billion for broader digital initiatives under the *Digital Europe Programme*, [European Commission \(2021\)](#). Moreover, the Horizon Europe framework is designed to assist researchers in the post-COVID-19 recovery and support SMEs in adopting AI technologies while strengthening transatlantic cooperation with the United States in digital transformation, [European Commission \(2021\)](#).

2.4 Digital indicators in the NUTS 2

The European Union has established key performance indicators to assess digital progress in NUTS2 regions, with country-level growth data for 2020–2021 outlined in [Table A.2 in appendix A](#). In 2013, indicators for Internet Usage with Public Authorities (IIPA), Remote Internet Access (RIA), Human Resources in Science and Technology (HRST) and Employment in High- and Medium-High-Technology sectors (EHTS) were introduced, [Eurostat \(2025\)](#). The highest rates were noted in DE Hovedstaden (88.35%), HU Budapest (82.30%) and PL Warszawski Stołeczny (62.30%), while the lowest were in RO Vest (2.61%) and EL Ionia Nisia (0.10%) ([Eurostat, 2025](#)). Additional indicators, such as Households with Internet Access (HAI) and Individuals with Basic or Above Basic Digital Skills (IDS), were added later, see [Table A.4 in Appendix A](#). From 2019 to 2021, more metrics were incorporated, contributing to the Digital Economy and Society Index (DESI), [Quirós and Perote \(2025\)](#). Digital skills are vital for technological sovereignty, bridging the digital divide and fostering a human-centered digital environment, [European Commission \(2023a\)](#) and basic digital skills are increasingly recognized as essential for labor market participation, [Brodny and Tutak \(2022\)](#). Additionally, [Schmitter \(2024\)](#) considers basic skills essential for everyday life, while advanced skills are increasingly crucial for employment in a digital economy.

A strong digital economy, supported by skilled individuals, is linked to greater innovation, productivity, job creation and competitiveness in Europe, [European Commission \(2024\)](#). The demand for advanced skills in AI, robotics, quantum technology and 6G has increased as digital technologies reshape labor markets, [European Commission \(2021\)](#). In response, the Digital Decade Policy Programme aims to promote both basic and advanced digital competencies, emphasizing vocational training and lifelong learning. The EU has set ambitious 2030 targets, including ensuring that 80% of adults achieve basic digital skills and creating 20 million ICT specialists, with a commitment to gender balance, [European Commission \(2023b\)](#). However, many Europeans still lack basic digital skills. The Digital Economy and Society Index (DESI) has tracked the digital progress of Member States since 2015, identifying key areas for policy action in human capital, connectivity, the integration of digital technology and digital public services, [Olczyk and Czarnecka \(2022\)](#). Overall, this chapter outlines the framework for digital transformation in the EU and highlights the NUTS2 classification for assessing regional development. The analysis shows improvements and persistent disparities, indicating that EU investments have positively influenced connectivity, skills and digital public services. These components will form the basis for a regional digitalization index to be presented in the next chapter.

The reviewed literature highlights persistent regional digital divides, heterogeneous economic effects of digitalization and uneven budget absorption across EU regions. Building on these insights, the following hypotheses are formulated.

- H1. There are significant disparities in digitalization levels across NUTS-2 regions in the European Union.
- H2. EU digital and cohesion budget allocations exhibit heterogeneous absorption and effectiveness across NUTS-2 regions.
- H3. The economic effects of digitalization differ structurally across NUTS-2 regions.

3. Data and methodology

3.1 The NUTS 2 digital index (N2DI)

Since 2015, the European Commission has monitored digitalization at the country level through the Digital Economy and Society Index (DESI) [Quirós and Perote \(2025\)](#). However, no comparable composite indicator exists for NUTS-2 regions, despite this being the principal territorial unit for EU cohesion policy. To address this gap, this study develops the NUTS-2 Digital Index (N2DI), designed to measure regional digital readiness and adoption across the 241 NUTS-2 regions of the EU-27. (see [Table A.3 in Appendix A](#) for a description of the DESI structure).

The choice of the NUTS-2 level reflects a balance between analytical granularity and data availability, enabling the identification of intra-national digital disparities while ensuring cross-country comparability, [Charron et al. \(2015\)](#). Numerous Eurostat and DESI-related indicators are consistently harmonized at this level, whereas NUTS-1 data are overly aggregated and NUTS-3 data often lack completeness and comparability, [Eurostat \(2025\)](#).

The construction of the N2DI follows a transparent, multi-step procedure aligned with established guidelines for composite indicators.

First, four dimensions are selected to capture the main channels of regional digitalization: human capital, connectivity, integration of digital technology and digital public services, consistent with the DESI framework. For each dimension, regionally available proxies are selected based on data availability, temporal consistency and cross-country comparability, [Table 1](#) summarizes the N2DI methodology and weights. This direct mapping preserves the

Table 1. N2DI methodology calculation and weights

European Union						
The NUTS2 digital index						
Methodology of calculation and weights						
Dimension	Weight	Sub-dimension	Weight	Proxy	Indicator	Weight
1 Human capital	25%	1a Internet user skills	50%	IDS	1a1 Individuals with basic or above basic overall digital skills	50%
		1b Advanced skills and development	50%	IUIF	1a3 At least basic digital content creation skills	50%
2 Connectivity	25%	2a Fixed broadband take-up	25%	HAI	2a1 Overall fixed broadband take-up	50%
		2b Fixed broadband coverage	25%			
		2c Mobile broadband	25%	HBBA	2b1 Fast broadband (NGA) coverage	50%
		2d Broadband prices	25%			
3 Integration of digital technology	25%	3a Digital intensity	33%	EC	3a1 SMEs with at least a basic level of digital intensity	25%
		3b Digital technologies for businesses	33%	EHTS	3b1 Electronic information sharing	25%
		3c e-Commerce	34%	RIA HRST	3b7 e-Invoices 3c3 Selling online cross-border	25% 25%
4 Digital public services	25%	4a e-Government	100%	IIPA	4a1 e-Government users	100%
Source(s): Own construction Eurostat data						

conceptual integrity of DESI while using proxies consistently observed at the NUTS-2 level, ensuring temporal comparability and straightforward interpretation for each pillar in the composite N2DI.

Second, all indicators are normalized using the min–max transformation, yielding values between 0 (lowest observed digitalization) and 100 (highest observed digitalization). Dimension scores are computed as the arithmetic mean of their constituent indicators, and the overall N2DI is obtained as the equally weighted average of the four dimensions (25% each), ensuring transparency and avoiding subjective prioritization.

The N2DI is constructed as a composite indicator (CI), reported in [Table 1. SM \(supplementary material\)](#) is calculated as follows:

$$y_j = \sum_{i=1}^d w_i x_{ij} \tag{1}$$

where y_j denotes the *N2DI* value for the *j*-th *NUTS-2 region*, x_{ij} represents the normalized value of indicator *i*-th in *region j*-th and $w_i = 0.25$ is the weight assigned to each of the four dimensions.

Third, robustness is assessed through alternative index specifications based on Z-score standardization and PCA-derived weights. PCA is applied to standardized component scores with varimax rotation to enhance interpretability and identify latent structures in regional digitalization patterns, [Jolliffe and Cadima \(2016\)](#). Resulting scores are rescaled to the 0–100 interval to ensure comparability with the baseline N2DI. High correlations across specifications confirm that results are not driven by normalization or weighting choices, [Abdi and Williams \(2010\)](#).

Finally, prior to index construction, missing values are treated using linear interpolation or local mean substitution, and extreme observations and (outliers) are winsorized at the 1st and 99th percentiles. These preprocessing steps follow best practices in composite indicator construction and ensure the robustness of the N2DI.

[Table 2. SM. \(supplementary material\)](#) presents N2DI, standardized scores, principal component loadings and DESI for the 241 EU NUTS2 regions.

3.2 Clustering

To identify structural heterogeneity in regional digitalization, NUTS-2 regions are grouped using K-means clustering based on their N2DI scores. Clustering is a multivariate exploratory technique that partitions observations into internally homogeneous and externally heterogeneous groups, [Řezanková \(2014\)](#).

The K-means algorithm assigns regions to clusters by minimizing within-cluster variance and maximizing between-cluster separation, using Euclidean distance as the similarity metric, [Rebala, Ravi, and Churiwala \(2019\)](#). This unsupervised approach is well suited for identifying groups of regions with comparable digitalization profiles without imposing ex ante classification rules.

Formally, Given a dataset represented by $X^1, X^2, \dots, X^m$, observations, where each observation X^j has n elements $x_1^j, x_2^j, \dots, x_n^j$, K-means clustering aims to classify these m observations into K clusters, each one identified by a particular point.

The algorithm proceeds as follows. Firstly, the algorithm randomly identifies K points that represent the *centers* of the K clusters. Next, it takes each data point and assigns it to its closest K center or cluster. Subsequently, for each cluster, the geometric center is recomputed, being the new representative point for this cluster, and the process iterates till no point changes its cluster — i.e. the cumulative distance for each point concerning the assigned cluster's center is minimal. Distance computation is given by [Eq. \(2\)](#),

$$Distance = \left\| (X^i - \mu_k) \right\|^2, \quad (2)$$

and the optimization function is given by Eq. (3),

$$J(C_1, C_2, \dots, C_m, \mu_1, \mu_2, \dots, \mu_K) = \frac{1}{m} \sum_{i=1}^m \left\| x^i - \mu_{c_i} \right\|^2, \quad (3)$$

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where $C_1, C_2, \dots, C_m$ represent the cluster index of each data point x^i , $\mu_1, \mu_2, \dots, \mu_K$ represent the centers for the clusters and μ_{c_i} represents the center for the cluster to which x^i is assigned. This function is minimized by iteratively updating $C_1, C_2, \dots, C_m$ and $\mu_1, \mu_2, \dots, \mu_K$. The first for-loop updates $C_1, C_2, \dots, C_m$ and the second for loop updates $\mu_1, \mu_2, \dots, \mu_K$, thus reducing the cost function in each iteration until it stabilizes.

3.3 Panel data analysis

This section examines the impact of N2DI and selected economic variables on economic growth through panel data analysis. Various authors have used panel data analysis to measure the influence of economic variables on economic growth. [Olczyk and Czarnecka \(2022\)](#) discovered through panel data analysis that both the original and a modified version of DESI positively influence economic growth. [Mura and Donath \(2023\)](#) examined digitalization within the EU using economic variables and digital indices through panel data analysis. The panel data regression model is represented in Eq. (4):

$$y_{it} = X'_{it}\beta + v_{it} \quad \forall i = 1, 2, \dots, N \text{ and } \forall t = 1, 2, \dots, T, \quad (4)$$

where y_{it} represents the dependent variable – in our case GDP per capita (GDPPC) – and $X'_{it} \in \mathbb{R}^k$ is a vector containing the explanatory variables (which may include dummy variables), both varying across N individuals and T periods; $\beta \in \mathbb{R}^k$ is the vector of parameter of interests; and v_{it} is a random error which can be decomposed into two components, as shown in Eq. (5), one associated with the individual (u_i) and one associated with both the individual and time (e_{it}).

$$v_{it} = u_i + e_{it} \quad (5)$$

The model assumes that explanatory variables are uncorrelated to the unobservable individual characteristics (i.e. $E[x_{jit}u_i] = 0, \forall j = 1, 2, \dots, k$, thus procedures must be employed to eliminate the unobserved heterogeneity from the estimation Eq. (6) and solve potential endogeneity problems. Panel diagnostic Breusch-Pagan and Hausman tests were applied to choose between random and fixed effects models due to the limitations of the OLS model. Our model consists of $N = 241$ NUTS2 regions, $T = 4$ (2018–2021 period), time period limited by the recent creation of the N2DI.

The economic theory established that several factors influence or act as determinants of GDP. See [Figures B.1 and B.2 in Appendix B](#) for a geographic illustration of the distribution of GDP per capita by NUTS2 in 2017 and 2021 and [Table 4.SM. \(supplementary material\)](#) for the relation between GDPPCN and N2DI. [Parui \(2021\)](#) indicates that investment and expenditures are important factors. While [Solow \(1956\)](#) identified technology as a core determinant of long-run growth, contemporary research argues that innovation and knowledge accumulation are the principal mechanisms sustaining productivity over time, [Aghion, Akcigit, and Howitt \(2015\)](#). Additionally, [Milbourne, Otto, and Voss \(2003\)](#) refer to public investment as an important determinant of economic growth. The NGEU programs are also considered determinants in GDP growth as well as population growth and

employment, [Sibe, Chiatchoua, and Megne \(2018\)](#). Our model aims to explain the variation rate of EU's GDPPC, namely *Growth* in [Eq. \(6\)](#), in terms of digital variables and control variables, including: (1) N2DI as a technological factor; (2) BUD as determinant of the investment; (3) DIGBUD expenditure as a determinant of the technological investments; (4) POP, INC and UNP as social indicators.

All in all, the model is represented by the following equation:

$$Growth_{it} = \beta_1 + \beta_2 N2DI_{it} + \beta_3 BUD_{it} + \beta_4 DIGBUD_{it} + \beta_5 INC_{it} + \beta_6 POP_{it} + \beta_7 UNP_{it} + v_{it}, \tag{6}$$

Where *Growth* represents the difference of logarithms of gross domestic product per capita; BUD, refers to the European Union budget per capita per NUTS2, DIGBUD refers to the European Union digital budget per capita per NUTS2, POP refers to the Population; UNP is the unemployment rate; INC refers to the net income per capita; N2DI represents the digital economic and social index for NUTS2 which is own construction in this research. All explanatory variables are transformed into logarithms and sub-indexed by country *i* and period *t*.

4. Empirical analysis

4.1 N2DI

4.1.1 Digitalization dynamics in the EU. The evolution of the NUTS-2 Digital Index (N2DI) from 2017 to 2021 highlights significant digital growth across European regions, although persistent structural disparities remain evident, as shown in [Table 1.SM. \(supplementary material\)](#) and [Figure 1. SM.\(supplementary material\)](#). In 2017, the average N2DI for the EU was 37.29, with DK Hovedstaden at the top of the range at 53.19 and PL Świętokrzyskie at the bottom with a score of 16.75. By 2021, leading regions such as NL Utrecht achieved a score of 71.98, while lagging areas like RO Sud-Muntenia saw only modest gains, reaching 26.10. Notably, regions in the Netherlands, Finland and Denmark demonstrated the most substantial improvements during this period, in contrast to Romania, Bulgaria and Italy, which made relatively limited progress. These spatial dynamics are illustrated geographically in [Figures B.3 and B.4 in Appendix B](#).

Despite the accelerated growth in several lower-capacity regions, the findings do not suggest an overall convergence in regional digital development. Instead, the digital trajectories across regions remain uneven, with only select areas—particularly in Ireland, Hungary, Poland and Lithuania—exhibiting signs of partial convergence. The distribution of N2DI growth rates among NUTS-2 regions, as presented in [Table 1, SM. \(supplementary material\)](#) and [Figure B.5 in Appendix B](#), underscores these distinct and divergent regional paths.

To effectively capture this ongoing heterogeneity in digital development, we implement in [Table 1, SM. \(supplementary material\)](#), a quartile-based classification derived from the annual N2DI distribution. Each year, regions are ranked according to their standardized N2DI score (on a 0–100 scale) and categorized into four equally sized groups: Q1 represents the most digitally advanced regions, Q2 includes upper-medium adopters, Q3 consists of emerging or transitional regions, and Q4 encompasses structurally lagging areas, see also [Figures B.6 and B.7 in Appendix B](#). This distributional approach enables us to differentiate varying levels of digital maturity and assess how the economic returns to digitalization vary across advanced, transitional and low-capacity regional profiles. By integrating this quartile framework into our econometric analysis, we explicitly account for the structural asymmetries inherent in Europe's digital transformation.

4.1.2 N2DI, PCA, DESI and Z-scores analysis. To assess the robustness of the New Digital Index (N2DI), two additional measures were created: an equal-weighted Z-score composite and a PCA-based index with data-driven weights. Both closely aligned with the N2DI,

indicating that individual indicators and arbitrary weighting had little effect on rankings, [Greco, Ishizaka, Tasić, and Torrisi \(2019\)](#). When compared to the Digital Economy and Society Index (DESI), similar spatial patterns were observed, though correlations with PCA and N2DI were slightly weaker (0.70 to 0.85).

DESI sometimes ranked certain Southern European regions higher due to their policy inclusion, while PCA effectively distinguished digital leaders from laggards. From 2017 to 2021, rank stability was high, with NL Utrecht, FI Helsinki-Uusimaa and DK Hovedstaden consistently at the top. Dutch regions, alongside Stockholm and Västsverige, remained in the top tier, while Southern Italy, Romania, Bulgaria and parts of Eastern Poland occupied the lowest tier with minimal change. This highlighted a persistent North-West versus South-East divide in the EU and regional mobility, primarily among mid-ranked regions. The consistency across N2DI, PCA and DESI confirmed their robustness, with differences showcasing DESI's policy-driven focus versus PCA's structural emphasis, underscoring the need for multiple methodologies to capture the complexities of digitalization, see Index Analysis: N2DI, Z-Scores, PCA and DESI in [Table 2.SM. \(supplementary material\)](#).

4.1.3 N2DI vs DESI. N2DI highlights within-country digital disparities that the national DESI obscures, showing persistent gaps from 2017 to 2021, see [Table 2.SM. \(supplementary material\)](#).

Germany: Despite mid-high DESI ranks, N2DI reveals a two-speed pattern, with top performers like Berlin and Hamburg contrasting sharply with Sachsen-Anhalt and Thüringen.

Italy: A north-south divide persists, with strong performers like Lombardia and Lazio against laggards like Calabria and Puglia.

Poland: The capital and western regions consistently outperform the eastern and central areas, despite a lower national DESI.

Spain: Madrid and Cataluña exceed national averages, while several interior regions fall short, indicating center-periphery disparities.

France: Île-de-France stands out despite a moderate DESI, with provincial regions often below the national average.

Romania: Low national DESI scores hide sharp disparities, particularly distinguishing București-Ilfov.

Nordics & Netherlands: High DESI scores align with uniformly high N2DI, though capital regions still lead, with less internal variation compared to other countries.

Correlation and ANOVA analyses highlight the distinct yet complementary nature of the digital indices. N2DI aligns strongly with Z-scores ($\rho \approx 0.85$) and DESI ($\rho \approx 0.82$), showing consistency across measures. PCA is moderately correlated with N2DI ($\rho \approx 0.72$) but weakly with DESI ($\rho \approx 0.58$) and Z-scores ($\rho \approx 0.27$), indicating it captures structural disparities not reflected in policy-related indices. Boxplots reveal that PCA and DESI show sharper contrasts, while N2DI is intermediate and Z-scores overlook structural nuances. ANOVA results (F-statistic, $p < 0.01$) confirm that these indices are not interchangeable but rather measure different aspects of digitalization. Quartile analysis indicates that top-performing regions sustain their advantages, whereas lagging regions remain stagnant, underscoring persistent North–South and East–West divides. These insights stress the systemic nature of digital inequalities within the EU, necessitating targeted policy responses for cohesion, see [Table 2](#) and [Figure 2](#).

4.2 European Union budget

The evolution of the EU budget, particularly for digital initiatives, has shifted with policy priorities over time. In the 2014–2020 Multiannual Financial Framework (MFF), digital allocations were mainly included under “Competitiveness for Growth and Jobs” and “Research and Innovation,” funding programs like Horizon 2020 and the Connecting Europe Facility (CEF) to support technological research and digital infrastructure, [European Commission \(2018\)](#). In the 2021–2027 MFF, digital funding became more prominent under

Table 2. Statistical analysis: N2DI, Z-scores, PCA, DESI

Statistical analysis EU-NUTS2 N2DI, Zscores, PCA, DESI 2017–2021		
Result/Finding	Statistical meaning	Economic meaning
PCA variance > DESI variance	PCA shows slightly higher dispersion than DESI, capturing more variability across regions	Digital inequalities appear more pronounced when measured via PCA, exposing gaps not visible in DESI
Correlation PCA–N2DI ≈ 0.72	Strong correlation (≈ 0.72) between PCA and N2DI indices	PCA and N2DI largely reflect the same underlying digital capacity
Correlation PCA–DESI ≈ 0.58	Moderate correlation (≈ 0.58) between PCA and DESI	DESI partially reflects digitalization but is influenced by policy measures
Correlation PCA–Zscores ≈ 0.27	Weak correlation (≈ 0.27) between PCA and standardized Z-scores	Z-scores are not reliable to capture structural digital differences across regions
Rank stability (2017–2021) $\approx$ moderate	Rankings show persistence, but less than the previously assumed 85%	Regional digital divide is entrenched but not perfectly fixed
Quartile mobility (2017–2021) $\approx$ moderate	Inter-quartile movement is higher than 15%, indicating moderate mobility	Some mobility exists, meaning policy can help lagging regions catch up
Top regions remain relatively stable	Leaders (Northern & Western Europe) show relative consistency across years	Advanced regions consolidate their leadership, reinforcing inequalities
Bottom regions persistent	Lagging regions (Southern & Eastern Europe) show persistent low positions	Lagging regions continue to struggle despite EU support mechanisms
DESI sometimes diverges from PCA	DESI includes policy-driven elements, sometimes diverging from statistical PCA	Policy indicators in DESI may overstate progress in some regions compared to PCA
PCA more discriminative than DESI	PCA provides finer separation of middle vs lower performers than DESI	Useful for identifying priority regions needing EU digital policy focus
Z-scores standardize differences	Z-scores normalize indicators but lose structural information compared to PCA	Helps comparability across countries but less informative for structural analysis
Source(s): Own construction		

the heading “Single Market, Innovation and Digital,” reflecting the strategic importance of digital transformation. Additional funds were also allocated under “Cohesion, Resilience and Values” for regional digital initiatives, [European Commission \(2021\)](#). This budgetary transformation highlights the EU’s commitment to digital progress, as shown in [Table 3.SM. \(supplementary material\)](#) and [Figures B.8, B.9, B.10 and B.11 in Appendix B](#).

4.3 Clustering results

4.3.1 *N2DI-GDPPC clustering.* The optimal number of clusters was identified using the Elbow Method and the Silhouette Score, both of which indicated that three clusters—Advanced N2DI, Medium N2DI and Low N2DI—were optimal based on data from 2017 and 2021, see [Figure B.14 in Appendix B](#) and [Table 4.SM. \(supplementary material\)](#). Cluster one included high N2DI and GDP per capita regions like LU Luxembourg and DE Hamburg. Cluster two featured areas such as NL Noord-Brabant and ES Comunidad de Madrid, while cluster three included regions like PL Warszawski stoleczny and IT Valle d’Aosta, as shown in [Figures B.12 and B.13 in Appendix B](#).

Despite growth in N2DI and GDP per capita, the cluster structure remained stable, influenced by national economic characteristics. Wealth disparities were evident, with richer

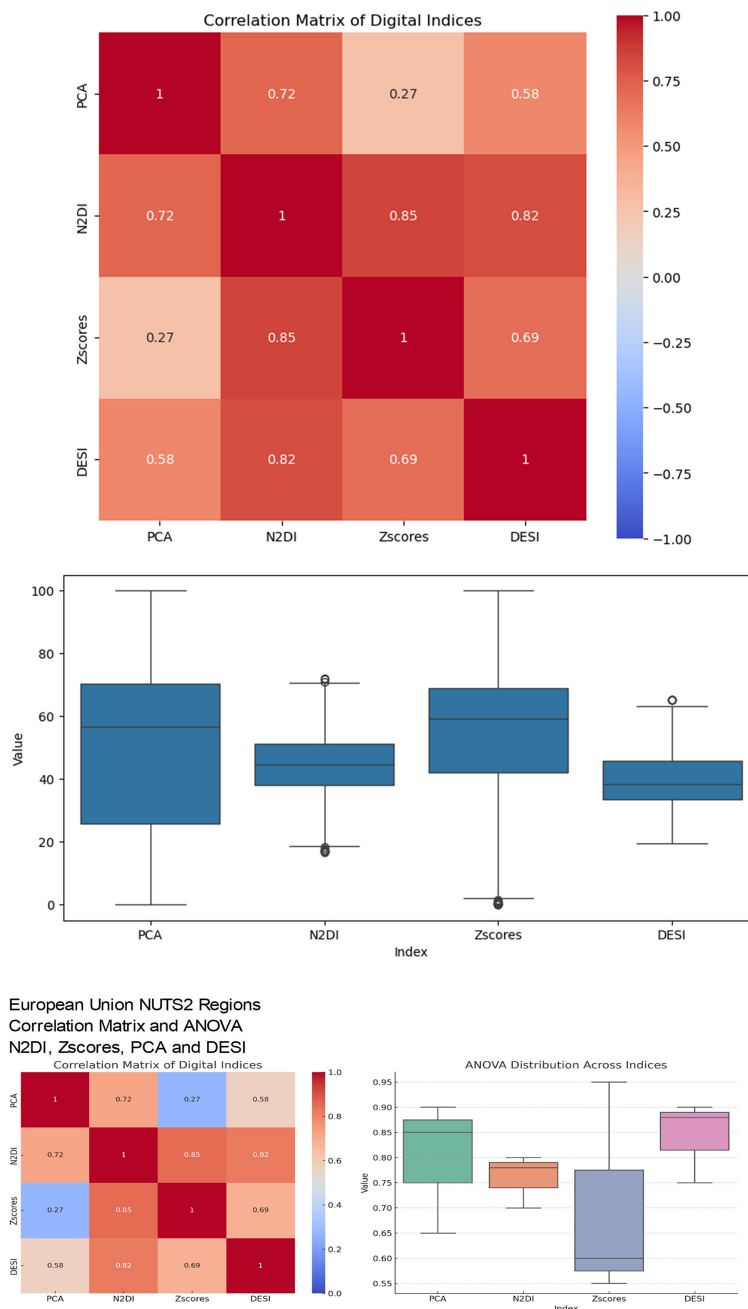


Figure 2. Correlation analysis y Anova distribution: N2DI, PCA, Z-Scores

regions in the EU's core and poorer ones in the periphery. Recent crises, including the 2008 financial crisis and the COVID-19 pandemic, affected less developed regions and highlighted the EU's focus on macroeconomic stability and digitalization.

N2DI improvements were noted across all NUTS 2 regions, though areas in Poland, Italy, Portugal and Romania remained in Quartile 4 by 2021. To address disparities, the EU established a digital budget, leading to significant per capita funding in countries like Luxembourg (€1025.71) and Belgium (€166.03), while Czechia (€19.37) and Romania (€5.23) received much less. Funding distribution patterns were also observed in 2017, with Luxembourg and Estonia among the top recipients.

4.3.2 Clustering ANOVA analysis. Pooled OLS ANOVA models with year controls and one-way ANOVA tests from 2017 to 2021 revealed significant differences in N2DI and GDP per capita across three clusters (F-test, $p < 0.01$).

In low- and medium-performing clusters, higher digital diffusion is associated with significant increases in GDP per capita. However, in advanced regions, the marginal returns to digitalization diminished, leading growth to focus on innovation and specialization. For instance, the, i.e. Eastern and Midland region showed a high GDP per capita with modest N2DI scores, largely due to multinational corporations, while FR Guyane had a high N2DI but low GDP per capita, largely due to EU funding. These deviations stress the influence of structural factors and policies on regional differences.

The findings support a three-cluster framework and suggest tailored policy strategies: diffusion-oriented initiatives in lagging regions, capacity-building in medium performers, and innovation-driven strategies in advanced regions. Table 3 and Figure 3 present results from tests validating the clustering structure.

A K-means clustering analysis categorized regions based on Budget (BUD), Digital Budget (DIGBUDPC) and Digital Index (N2DI) into Low, Normal and Advanced clusters from 2017 to 2021, is reported in Table 3.SM.(supplementary material).

Low regions displayed the weakest digital performance with an average N2DI of 35 and GDP per capita (GDPPC) around 24,000 euros, coupled with modest public spending, BUD of about 59 euros and DIGBUD of 28 euros.

Normal regions showed better digitalization, average N2DI of 49, higher income 31,000 euros, and slightly larger budgets, BUD of 61 euros, DIGBUD of 25 euros.

Advanced regions, while having a high income of 50,000 euros and large budgets, BUD of 5,184 euros, DIGBUD of 1,544 euros, had an average N2DI of 46, raising questions about the effectiveness of spending.

Correlations between spending and digital outcomes were weak across regions. For Low and Normal regions, the relationship between BUD per capita and N2DI was close to zero, while Advanced regions showed negative correlations, necessitating caution in interpretation due to small samples.

This highlights the importance of spending quality over volume and the need for long-term strategies, as digital investments take time to yield results.

Policy recommendations differ by cluster: Low regions should focus on foundational investments like connectivity and digital skills training; Normal regions should enhance productivity through advanced skills and SME incentives; while Advanced regions should optimize investment quality and foster spillovers through knowledge-sharing. Monitoring strategies should employ tier-appropriate KPIs, focusing on broadband coverage for Low, SME adoption in Normal, and innovation indicators for Advanced regions, while accounting for timing effects in assessments.

A refinement of allocation strategies is therefore warranted, with a focus on prioritizing regions and projects that demonstrate the greatest potential for positive effects on N2DI. Such reallocation could optimize the utilization of BUDPC and reduce its unintended negative effects on digital outcomes. In addition, alternative strategies should be considered, including a stronger emphasis on absorptive capacity, institutional quality and the alignment of expenditures with regional digital readiness. The potential benefits of these measures include improved N2DI performance, more efficient resource allocation and enhanced effectiveness in meeting policy objectives. Optimizing BUDPC in this way would not only mitigate its

Table 3. N2DI and GDPPC clustering results

EU NUTS2
Clustering N2DI GDPPC
Descriptive statistics

CL	N	N2DI_mean	GDPPC_ mean	N2DI_sd	GDPPC_sd
1	14	45.95214286	49578.57143	10.76757538	24570.28157
2	818	49.01330073	30901.22249	8.117524079	10744.71654
3	373	35.18884718	24082.30563	8.071888795	10119.14283

EU NUTS2
Clustering N2DI GDPPC
ANOVA N2DI

	sum_ sq	df	F	PR(>F)
C(CL)	48,983	2	369.9227623	6.3909E–126
Residual	79,581	1202		

EU NUTS2
Clustering N2DI GDPPC
ANOVA GDPPC

	sum_ sq	df	F	PR(>F)
C(CL)	2E+10	2	76.72424168	4.37212E–32
Residual	1E+11	1202		

EU NUTS2
Clustering N2DI GDPPC
Tukey N2DI

group1	group2	Meandiff	p-adj	Lower	Upper	Reject
1	2	3.0612	0.3434	–2.0854	8.2077	NO
1	3	–10.7633	0	–15.9612	–5.5654	YES
2	3	–13.8245	0	–15.0174	–12.6315	YES

EU NUTS2
Clustering N2DI GDPPC
Tukey N2DI

group1	group2	Meandiff	p-adj	Lower	Upper	Reject
1	2	–18677.3489	0	–25509.8478	–11844.8501	YES
1	3	–25496.2658	0	–32397.0051	–18595.5265	YES
2	3	–6818.9169	0	–8402.655	–5235.1787	YES

Source(s): Own construction

negative impact but also strengthen the overall efficiency of the EU's digital investment framework [Veugelen \(2017\)](#).

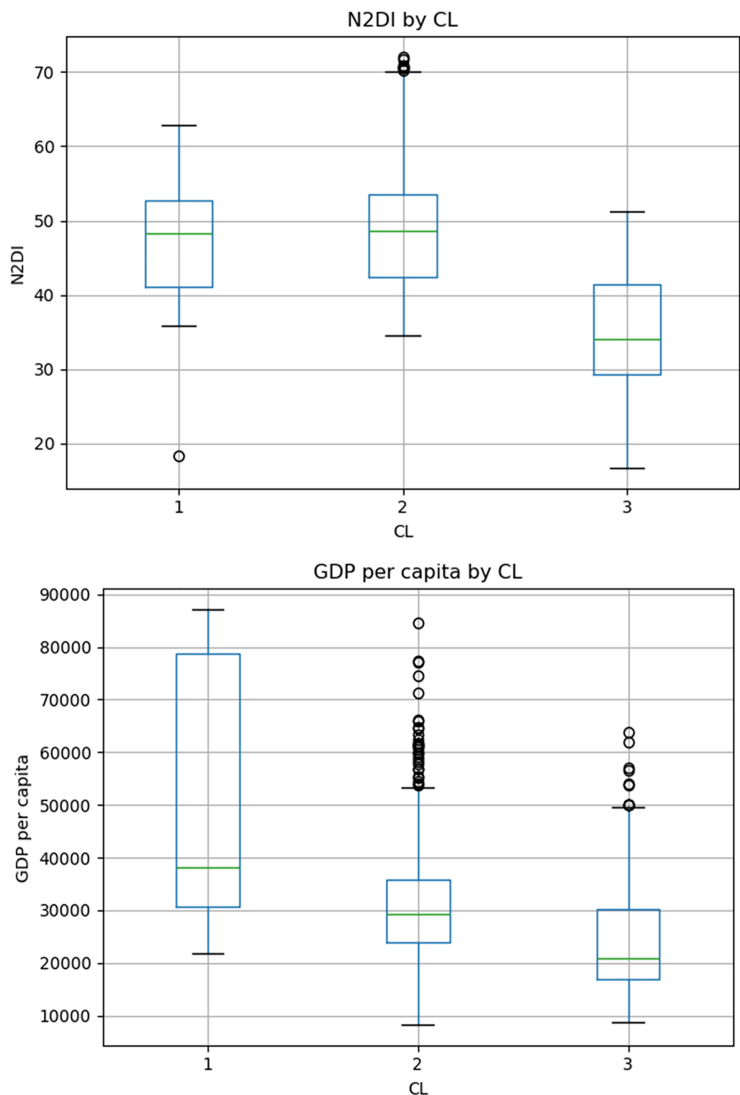


Figure 3. NSDI and GDPPC:box and whisker plots. Source: Own construction

4.4 Panel data analysis

The panel data analysis assessed the impact of digitalization (N2DI) on economic growth in the EU’s NUTS2 regions from 2017 to 2021, using a balanced dataset of 241 regions over five years.

The dependent variable was GDP per capita growth ($\Delta \ln(\text{GDPPC})$), while N2DI served as the main explanatory variable. Control variables included population (POP), unemployment rate (UNP), personal income (INC), employment in high- and medium-high-tech sectors (EHTS), and human resources in science and technology (HRST). EU budget allocations (BUD) and digital budget allocations (DIGBUD) were included to capture the impact of public investment.

All variables were logarithmically transformed, with annual dummies added to account for time-specific effects. Three estimators—pooled OLS, RE and FE—were used, selected based on Breusch-Pagan and Hausman tests, with robust standard errors clustered by region.

A dynamic specification was also estimated using the System-GMM estimator to address endogeneity. EHTS and HRST were included both in N2DI and as separate variables to differentiate between the overall digitalization effect and the specific impact of human capital on economic performance, [Niebel \(2018\)](#).

[Table 4](#) summarizes the determinants of GDP per capita growth in European NUTS-2 regions from 2017 to 2021. The analysis uses the logarithmic change in GDP per capita as the dependent variable, with strong explanatory power (within- R^2 between 0.65 and 0.82) and significant overall F-tests ($\text{Prob} > F = 0.0000$). Fixed-effects estimation is employed based on Breusch-Pagan and Hausman tests ($\text{Prob} > F = 0.0000$). The digitalization index ($\ln N2DI$) has a coefficient of 0.0307, indicating that a 10% increase in digital readiness leads to a 0.3% rise in GDP per capita growth, though effects vary by region: advanced regions show a high coefficient (0.143), medium regions exhibit a negative impact (-0.1238), and low regions see negligible effects.

The EU budget per capita ($\ln BUD$) has weak overall effects, while the digital budget ($\ln DIGBUD$) shows negative or insignificant coefficients, particularly in medium regions (-0.0294). Population ($\ln POP$) and unemployment ($\ln UNP$) have neutral to weak negative impacts, while income per capita ($\ln INC$) is the strongest determinant of growth (0.4908 overall; 0.7333 in low regions). Employment in high- and medium-high-technology ($\ln EHTS$) and Human Resources in Science and Technology ($\ln HRST$) positively influences growth, particularly in advanced regions (0.0323 and 0.0341, respectively). Year dummies capture common shocks, with 2018 and 2019 showing positive growth, 2020 as insignificant, and 2021 reflecting recovery.

Overall, the results indicate that digitalization fosters regional growth in a heterogeneous manner, with significant roles for income and human capital, while unemployment constrains growth. This aligns with the EU macroeconomic cycle of expansion, pandemic shock and recovery. Skills and scientific capacity enhance the benefits of digitalization [Caravella, Cirillo, Crespi, Guarascio, and Menghini \(2022\)](#). Weaker effects in medium and low clusters indicate limited technology absorption, [European Investment Bank \(2023\)](#). Year dummies show that 2018 and 2019 had positive returns (pre-pandemic), 2020 was insignificant (pandemic), and 2021 showed recovery, [European Commission \(2021\)](#).

This pattern holds across clusters, with stronger rebounds in medium and low regions, [European Investment Bank \(2022\)](#). Overall, digitalization fosters regional growth in a nonlinear way: saturation in advanced areas, transitional costs in medium, and latent potential in low regions. Income and human capital support growth, while unemployment and demographic pressures hinder it. This aligns with the EU's macroeconomic cycle, underscoring the robustness of the fixed-effects estimates, [Wooldridge \(2010\)](#).

4.4.1 Robustness and model diagnostics. To ensure the reliability and internal consistency of the econometric results, several robustness and diagnostic procedures were implemented in [Table 5](#).

Dynamic specifications were estimated through a two-step System-GMM estimator with Windmeijer-robust standard errors and collapsed instruments, [Wooldridge \(2010\)](#).

The autoregressive term ($L1.\ln GDP_{PC}$, 1.0100) indicates strong income persistence across European NUTS-2 regions, confirming the dynamic nature of regional growth and justifying the inclusion of a lagged dependent variable.

The Arellano–Bond tests support model validity, with $AR(1)$ p-values < 0.05 and $AR(2)$ p-values > 0.10 , implying that serial correlation is appropriately addressed.

Hansen test statistics ($p = 0.05$ – 0.23) and non-rejection of the Sargan over-identification test ($p > 0.10$, except for the low-cluster model = 0.011) confirm that the instruments are both relevant and exogenous. Difference-in-Hansen values remain within acceptable limits (0.016–0.387), reinforcing the absence of specification bias or instrument proliferation.

Table 4. Panel data models on economic growth by NUTS2 regions

EU NUTS2 Panel data analysis N2DI 2017–2021												
Detail Variables dif_lnGDPPC	No clustered analysis Analysis of EU NUTS 2			Clustered NUTS2 regions Advanced			Medium			Low		
	PO	RE	FE	PO	RE	FE	PO	RE	FE	PO	RE	FE
lnN2DI	0.00762	0.06445 ***	0.03070 ***	−0.55078 ***	0.13499 ***	0.14303 ***	0.26690 ***	−0.0609279	−0.12377 **	0.05776	0.01409	0.02857
lnBUD	0.03584	0.00537	0.01301	0.05346	0.02168 ***	0.01551	−0.12027 ***	0.04402 ***	−0.05585 ***	−0.00850	0.00574	0.04133 **
lnDIGBUD	−0.03686	−0.01259 ***	−0.01252	−0.02336	−0.01945 **	−0.01702	0.11621 ***	−0.06047 ***	−0.02944 ***	−0.05435	−0.00421	−0.03109
lnPOP	−0.40072 ***	−0.10771 ***	0.00365	−0.39202 ***	−0.0194493	0.00926	−0.35581 ***	−0.15514 **	0.37304	−0.29059 ***	−0.45194	−0.17637
lnUNP	−0.08367 ***	−0.03140 ***	−0.00846	−0.05031 ***	−0.03383 **	−0.01474	−0.03982 ***	−0.05654 ***	−0.02745	−0.09714 ***	0.01219	0.03007
lnINC	0.39566 ***	0.28203 ***	0.49077 ***	0.34823 ***	0.07437 **	0.19286 ***	0.39663 ***	0.27863 ***	0.37304	0.29202 ***	0.50998	0.73328 ***
lnEHTS	0.12532 ***	0.01405 ***	0.00854 ***	0.18742 ***	0.04470 ***	0.03225 ***	0.04320 ***	0.00932	0.00533	0.11717 ***	0.00940	0.00904
lnHRST	0.13045 ***	0.01534 ***	0.00899	0.18839 ***	0.04517 ***	0.03412 ***	0.05951 ***	0.01259 **	0.00729	0.10697 ***	0.00841	0.00784
<i>Year</i>												
2018	0.02372	0.01895 ***	0.01623 ***	0.05099	0.02528 ***	0.02071 ***	−0.06405 ***	0.04641 ***	0.04509 ***	0.01453	0.02101 **	0.03465 ***
2019	0.02739	0.02674 ***	0.02366 ***	0.13963 ***	0.01502	0.00676	−0.10422 ***	0.07239 ***	0.08281 ***	0.02377	0.04079 ***	0.04628 ***
2020	0.03034	−0.00092	−0.00212	0.12522 ***	−0.0094062	−0.01912 ***	−0.14800 ***	0.03846 ***	0.04847 ***	0.05113	0.02615 ***	0.04022 ***
2021	0.01801	0.05868 ***	0.05569 ***	0.18126	0.03203	0.02757	−0.12668 ***	0.12993 ***	0.14084 ***	0.00585	0.08827 ***	0.10105 ***
Cons	11.328	8.625	5.063	13.460	9.439	7.685	10.139	9.787	7.230	10.883	11.309	5.060
Sigma u	—	0.19272	0.44630	—	0.14853	0.02757	—	0.10778	0.25334	—	0.22886	0.55623
sigma e	—	0.03186	0.03186	—	0.02541	0.02541	—	0.02926	0.02926	—	0.02935	0.02935
rho	—	0.97340	0.99493	—	0.97156	0.99028	—	0.93135	0.98683	—	0.98382	0.99722
<i>Adj R-squared</i>												
Within	0.7174	0.6123	0.6516	0.6009	0.6521	0.6521	0.774	0.6179	0.6557	0.6096	0.8042	0.8196
Between	0.7146	0.5005	0.3264	0.0732	0.188	0.188	0.7685	0.7167	0.5186	0.594	0.463	0.3085
Overall	—	0.5021	0.328	—	0.1934	0.1934	—	0.6779	0.4955	—	0.4559	0.284
Number of obs	1205	1205	1205	382	382	382	510	510	510	313	313	313
Number of groups	241	241	241	89	89	89	25	25	25	78	78	78
corr(u i, Xb)	—	—	−0.7109	—	—	−0.5164	—	—	−0.7285	—	—	−0.8622
Hausman test	—	—	269.56	—	—	82.91	—	—	118.42	—	—	62.68
Prob > χ^2	—	—	0.0000	—	—	0.0000	—	—	0.0000	—	—	0.0000
Breusch-Pagan Test	—	—	1933.88	—	—	53.43	—	—	612.97	—	—	365.34
Prov > F = 0.0000	—	—	0.0000	—	—	0.0000	—	—	0.0000	—	—	0.0000

Note(s): *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

No clustered analysis: panel data analysis for 241 NUTS2 regions of EU, for 5 years and strongly balanced data

Clustered NUTS2: panel data analysis for clustered NUTS2 regions (Adv. 89 Reg., 5 Ye., Med. 25 Reg., 5 Ye, Low 78 Reg., 5 Ye.)

Catalyst and dependent variable: Δ GDPPC (variation in logarithm of gross domestic product per capita), N2DI, (NUTS2 Digital Index), Control variables: EUBUD (Budget of European Union per Capita per NUTS2), DIGBUD (Digital Budget per capita per NUTS2), POP (Population), UNP (Unemployment), INC, (Income per Capita per NUTS2), EHTS, (Employment in High and Medium-High Technology Manufacturing Sectors), HRST (Human Resource in Science and Technology)

Calculations are executed in logarithm form

Source(s): Own building, Eurostat Data

Table 5. Dynamic panel data estimations System-GMM (EU NUTS2, 2017–2021)

European Union-NUTS2 econometrics								
Heteroskedasticity-robust SE and clusters								
Detail	Heteroskedasticity-robust SE				Heteroskedasticity-robust SE clusters			
Variables	EU NUTS 2				Advanced clusters			
				System- GMM, two- step, robust small, instruments collapsed: Inst. 14				System- GMM, two- step, robust small, instruments collapsed
Model	FE (within)	FE (within)	FE (within)		FE (within)	FE (within)	FE (within)	
Dependent variable	baseline	lagged N2DI 1	lagged	lnGDPPC	baseline	lagged N2DI 1	lagged N2DI 2	lnGDPPC
	lnGDPPC	lnGDPPC	N2DI 2		lnGDPPC	lnGDPPC	lnGDPPC	
L1.lnGDPPC	–	–	–	1.01000 ***	–	–	–	1.02105***
lnN2DI (contemp.)	0.03070 ***	–	0.0299057	–	0.14303 ***	–	–	–
L1.lnN2DI	–	0.02991 ***	–	–0.01254	–	0.04497	–	0.0195
L2.lnN2DI	–	–	0.05267 ***	–	–	–	0.05427 ***	–
L1.lnBUD	–	–0.00340	–	0.00582	–	0.02270 ***	–	–
L2.lnBUD	–	–	–0.01394	–	–	–	0.00116	–
lnBUD (contemp.)	0.01301	–	–	–	0.01551	–	–	–
L1.lnDIGBUD	–	0.00710	–	–0.00462	–	–0.02532 ***	–	0.01410
L2.lnDIGBUD	–	–	0.00761	–	–	–	–0.01496	–
lnDIGBUD (contemp.)	–0.03686	–	–	–	–0.01702	–0.13651 ***	–	–
lnPOP	–0.40072	0.0093	–0.0110	0.02306	0.00926 ***	0.22415 ***	–0.04487	0.02855
lnUNP	–0.00846	–	–	–	–0.01474	–	–	–
lnINC	0.39566 ***	0.46076 ***	0.42367 ***	–0.02600	0.19286 ***	0.17619 ***	0.21749 ***	–0.02669
lnEHTS	0.12532 ***	0.00764 ***	0.00844 ***	0.01188 ***	0.03225 ***	0.04059 ***	0.03831 ***	0.00647
lnHRST	0.13045	0.00766	0.00702	–0.00169	0.03412 ***	0.03463 ***	0.03294 ***	–0.01547
Year								
2018	0.01623 ***	–	–	–0.00330 ***	0.02071 ***	–	–	0.00870 ***
2019	0.02366 ***	0.00907 ***	–	–	0.00676	0.01593 ***	–	–
2020	–0.0021152	–0.02300 ***	–0.0362497	–0.0710619	–0.01912 ***	–0.0167931	–0.02886 ***	–0.04924 ***
(continued)								

Table 5. Continued

European Union-NUTS2 econometrics Heteroskedasticity-robust SE and clusters					Heteroskedasticity-robust SE clusters Advanced clusters			
Detail Variables	Heteroskedasticity-robust SE EU NUTS 2				Heteroskedasticity-robust SE clusters Advanced clusters			
Model Dependent variable	FE (within) baseline lnGDPPC	FE (within) lagged N2DI 1 lnGDPPC	FE (within) lagged N2DI 2 lnGDPPC	System- GMM, two- step, robust small, instruments collapsed: Inst. 14 lnGDPPC	FE (within) baseline lnGDPPC	FE (within) lagged N2DI 1 lnGDPPC	FE (within) lagged N2DI 2 lnGDPPC	System- GMM, two- step, robust small, instruments collapsed lnGDPPC
2021	0.05569 ***	0.03320 ***	0.00944 ***	0.00355 ***	0.02757	0.023869	−0.0080867	−0.00226
AR(1) <i>p</i> -value	—	—	—	0.00000	—	—	—	0.00001
AR(2) <i>p</i> -value	—	—	—	0.08600	—	—	—	0.2840
Hansen test <i>p</i> -value	—	—	—	0.05600	—	—	—	0.6260
Sargan test <i>p</i> -value	—	—	—	0.00700	—	—	—	0.4890
Difference-in-Hansen	—	—	—	0.01600	—	—	—	0.3870
Instruments	—	—	—	14	—	—	—	14
Observations/Groups	—	—	—	964/241	—	—	—	286/83
<i>Adj R-squared</i>								
Within	0.65160	0.61790	0.68450	—	0.6521	0.6102	0.6958	—
Between	0.32640	0.31830	0.33890	—	0.188	0.0619	0.051	—
Overall	0.32800	0.31950	0.34030	—	0.1934	0.0594	0.0655	—
Number of obs	1205	964	723	—	382	286	208	—
Number of groups	241	241	241	—	89	83	81	—
corr(u i, Xb)	−0.71090	−0.67810	−0.59830	—	−0.5164	−0.8551	−0.4739	—
(continued)								

Table 5. Continued

European Union-NUTS2 econometrics								
Heteroskedasticity-robust SE and clusters								
Detail	Heteroskedasticity-robust SE clusters							
Variables	Medium clusters				Low clusters			
				System- GMM, two- step, robust small, instruments				System- GMM, two- step, robust small, instruments
Model	FE (within)	FE (within)	FE (within)	collapsed	FE (within)	FE (within)	FE (within)	collapsed
Dependent variable	baseline lnGDPPC	lagged N2DI 1 lnGDPPC	lagged N2DI 2 lnGDPPC	lnGDPPC	baseline lnGDPPC	lagged N2DI 1 lnGDPPC	lagged N2DI 2 lnGDPPC	lnGDPPC
L1.lnGDPPC	–	–	–	0.72377 ***	–	–	–	0.89021 ***
lnN2DI (contemp.)	–0.12377 ***	–	–	–	0.0285732	–	–	–
L1.lnN2DI	–	–0.25521 ***	–	0.11666 ***	–	0.0042758	0.05117 ***	0.04801
L2.lnN2DI	–	–	–0.14717 ***	–	–	–	–	–
L1.lnBUD	–	0.02075 ***	–	–0.04838	–	–0.0271564	–0.0530321	–0.00648
L2.lnBUD	–	–	0.01172 ***	–	–	–	–	–
lnBUD (contemp.)	–0.05585 ***	–	–	–	0.04133 **	–	–	–
L1.lnDIGBUD	–	–0.0172903	–	0.05017 **	–	0.03557 ***	–	0.00099
L2.lnDIGBUD	–	–	–0.00998 ***	–	–	–	0.0406311	–
lnDIGBUD (contemp.)	–0.02944 ***	–	–	–	–0.03109	–	–	–
lnPOP	0.37304	–0.4008188	–0.3024929	–0.1170713	–0.17637	–0.5717441	1.78943***	–0.00844
lnUNP	–0.02745	–	–	–	–	–	–	–
lnINC	0.37304	0.4724205	0.6615331	0.1223448	0.73328 ***	0.63208 ***	0.31279 ***	0.01331
lnEHTS	0.00533	0.006093	0.0001583	0.02153 **	0.00904	0.00828 ***	0.0070565	0.01432
lnHRST	0.00729	0.006175	0.0007976	0.0140609	0.00784	0.0072722	0.0095403	0.00975 ***
Year								
2018	0.04509 ***	–	–	0.11737 ***	0.03465 ***	–	–	0.07549 ***
2019	0.08281 ***	0.03468 ***	–	0.09477 ***	0.04628 ***	–0.01445	–	0.07182 ***
2020	0.04847 ***	0.03900 ***	–0.02414 ***	–	0.04022 ***	–0.02621 ***	–0.06233 ***	–
2021	0.14084 ***	0.10034 ***	0.05002 ***	0.06996 ***	0.10105 ***	0.03057	0.00527	0.09638 ***

(continued)

Table 5. Continued

European Union-NUTS2 econometrics								
Heteroskedasticity-robust SE and clusters								
Detail	Heteroskedasticity-robust SE clusters							
Variables	Medium clusters				Low clusters			
				System- GMM, two- step, robust small, instruments collapsed lnGDPPC				System- GMM, two- step, robust small, instruments collapsed lnGDPPC
Model	FE (within) baseline lnGDPPC	FE (within) lagged N2DI 1 lnGDPPC	FE (within) lagged N2DI 2 lnGDPPC		FE (within) baseline lnGDPPC	FE (within) lagged N2DI 1 lnGDPPC	FE (within) lagged N2DI 2 lnGDPPC	
Dependent variable								
AR(1) <i>p</i> -value	–	–	–	0.03600	–	–	–	0.00100
AR(2) <i>p</i> -value	–	–	–	0.158	–	–	–	0.906
Hansen test <i>p</i> -value	–	–	–	0.236	–	–	–	0.007
Sargan test <i>p</i> -value	–	–	–	0.147	–	–	–	0.011
Difference-in-Hansen	–	–	–	0.317	–	–	–	0.002
Instruments	–	–	–	14	–	–	–	14
Observations/Groups	–	–	–	374/104	–	–	–	234/64
<i>Adj R-squared</i>								
Within	0.6557	0.6527	0.7641	–	0.8196	0.7491	0.7419	–
Between	0.5186	0.7068	0.582	–	0.3085	0.3853	0.0073	–
Overall	0.4955	0.6902	0.5736	–	0.284	0.4373	0.0017	–
Number of obs	510	374	276	–	313	234	171	–
Number of groups	25	104	100	–	78	64	60	–
corr(u i, Xb)	–0.7285	–0.0206	–0.8471	–	–0.8622	–0.5898	–0.9697	–

Note(s): Significance: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Panel of EU NUTS-2 regions, 2017–2021 (balanced). Logs of all variables. FE columns are within estimators with region FE and year dummies; SE clustered by region. “Lk.” means k -year lag (L1 = 1-year, L2 = 2-year)

System-GMM (two-step) uses Windmeijer-robust SE, collapsed instruments; L1.lnGDPPC is instrumented with lags (L2–L4). We report AR(1)/AR(2) (want AR(1) $p < 0.05$, AR(2) $p > 0.10$), Hansen J (prefer $p = 0.1$ – 0.9) Sargan (non-robust), and Diff-in-Hansen

Samples. “Total sample” = all 241 regions. “Advanced/Medium/Low” = cluster subsamples; same specs and clustering applied

Calculations are executed in logarithm form

Source(s): Own building, Eurostat Data

The adjusted R^2 values between 0.65 and 0.82 across fixed-effects models demonstrate substantial within-region explanatory power, indicating that time-invariant heterogeneity—such as geographic, institutional, or structural characteristics—is properly controlled for, [Hair, Black, Babin, and Anderson \(2019\)](#).

The stability of the coefficients across contemporaneous, one-year and two-year lagged specifications further corroborates the robustness of the digitalization–growth relationship. In the dynamic framework, the sign and relative magnitude of the N2DI coefficients remain consistent with the fixed-effects results: positive and economically meaningful in the full sample, small or insignificant in advanced regions, negative during transitional phases in medium clusters, and weakly positive yet imprecise in low-capacity regions. These stable patterns confirm that the observed heterogeneity is structural rather than model driven.

All in all, the diagnostic evidence from both static and dynamic estimates demonstrates that the models are well-specified, statistically robust and econometrically sound. The results withstand alternative lag structures, instrumentation strategies and subsample estimations, confirming that the identified relationships between digitalization, budgets and regional contexts are consistent. Consequently, the empirical framework provides a credible foundation for examining the dynamic interactions between growth and digitalization presented in the following section.

5. Discussion and conclusions

The Nomenclature of Territorial Units for Statistics (NUTS) provides a harmonized framework for regional analysis within the European Union. At the NUTS-2 level, 241 regions with populations between 800,000 and 3 million constitute the core territorial units for cohesion policy design and evaluation. In the context of accelerating digital transformation, measuring regional disparities through multidimensional indicators such as the NUTS-2 Digital Index (N2DI)—encompassing human capital, connectivity, integration of digital technology, and digital public services—has become essential for understanding the uneven diffusion of digitalization across Europe, [Quirós and Perote \(2025\)](#).

The descriptive analysis based on the N2DI reveals pronounced and persistent regional disparities, thereby confirming [Hypothesis 1 \(H1\)](#): *there is a significant gap in digitalization between NUTS-2 regions of the European Union*. The highest N2DI values are observed in highly urbanized and innovation-intensive regions such as DK Hovedstaden and NL Utrecht, while the lowest scores are concentrated in structurally weaker regions, including PL Świętokrzyskie and RO Sud-Muntenia. Despite convergence efforts and sustained EU digital investment, a clear North–West versus South–East divide remains visible. Nevertheless, the period 2017–2021 shows gradual overall improvement, suggesting that EU digital strategies have contributed to upward movement, albeit at an uneven pace.

Cluster analysis further supports this finding by revealing differentiated trajectories of digital development. K-means clustering indicates an expansion of medium-digitalization regions (Cluster NOR 2), a contraction of low-digitalization regions (Cluster LOW 3), and a moderate increase in advanced regions (Cluster ADV 1), pointing to gradual upward mobility in regional digital readiness. However, persistent anomalies—such as wealthy regions with relatively low N2DI scores and less affluent regions performing above expectations—underscore the structural heterogeneity of the European regional landscape. These patterns provide additional support for [Hypothesis 3 \(H3\)](#), which posits *structural differences among NUTS-2 regions as a consequence of digitalization*.

The econometric analysis strengthens these conclusions. Fixed-effects estimations for the period 2017–2021, controlling for unobserved heterogeneity and heteroskedasticity, indicate that digitalization has a statistically significant and positive impact on regional economic performance. For the full sample of 241 regions, a 10% increase in the N2DI is associated with an approximate 0.3% increase in GDP per capita. However, the magnitude and significance of

this effect vary markedly across clusters, confirming the heterogeneous nature of digital returns.

Advanced regions benefit from digitalization primarily through innovation, productivity gains and efficiency improvements, but they also exhibit diminishing marginal returns as digital ecosystems mature. Medium regions show the strongest growth response, suggesting that digital adoption and skill upgrading generate particularly high marginal returns at intermediate stages of digital development. In contrast, low-digitalization regions display largely insignificant effects, indicating that digitalization alone is insufficient to overcome deep-rooted structural constraints. This differentiated impact pattern reinforces [Hypothesis 3 \(H3\)](#) and highlights the importance of absorptive capacity and complementary factors.

Fiscal variables display more nuanced effects. EU budget allocations and digital-specific funding are generally insignificant in the short run, consistent with delayed impacts and absorption lags. However, in low-digitalization regions, EU budget variables exert a positive and significant effect on growth, emphasizing their redistributive role and providing empirical support for [Hypothesis 2 \(H2\)](#): *there are disparities in EU digital budget allocation and regional absorption capacity*. These findings suggest that while EU funds are essential for lagging regions, their growth impact depends critically on institutional capacity and implementation efficiency. Human capital and income variables—particularly employment in high-technology sectors—emerge as the strongest growth drivers, whereas unemployment and population size play a limited role. Time dummies accurately capture macroeconomic dynamics, reflecting expansion in 2018–2019, contraction in 2020 and a strong rebound in 2021 driven by the Recovery and Resilience Facility and NextGenerationEU.

A key contribution of the N2DI lies in its ability to uncover within-country digital divides that remain hidden in country-level indicators such as DESI. While DESI often portrays countries like the Netherlands, Denmark, Finland and Sweden as uniformly high performers, the N2DI reveals substantial internal dispersion in many Member States. In Germany, Italy and Poland, clear “two-speed” patterns emerge: capital and metropolitan regions (e.g. Berlin, Lazio/Rome, Warszawski stołeczny) dominate national rankings, while peripheral or structurally weaker regions (e.g. Sachsen-Anhalt, Calabria, Sicilia and several eastern Polish regions) fall well below national averages. These gaps can reach double-digit N2DI points even when national DESI scores are relatively high, underscoring the limitations of country-level assessments and reinforcing [H1](#) and [H3](#).

5.1 Policy implications

The results imply that EU digital policy must adopt a place-sensitive and tier-specific approach. Advanced regions should prioritize frontier innovation, interoperability, artificial intelligence and cross-regional R&D collaboration to sustain productivity at the technological frontier. Medium regions—where marginal returns to digitalization are highest—should focus on SME digital adoption, process modernization and workforce upskilling. Lagging regions require foundational investments in connectivity, digital inclusion and institutional capacity, supported by targeted cohesion funding and enhanced administrative support.

Institutionalizing the N2DI at the NUTS-2 level would allow the European Commission to align digital and cohesion budgets more closely with regional needs and performance. Such an approach would improve budget absorption, reduce persistent regional digital divides and strengthen the contribution of digitalization to inclusive and sustainable growth across the Union.

5.2 Limitations

Despite the robustness of heteroskedasticity-robust and cluster-adjusted estimations, several limitations must be acknowledged. First, the 2017–2021 timeframe constrains long-term inference. Second, data availability limits the inclusion of qualitative dimensions such as governance quality and innovation culture. Third, the equal weighting of N2DI dimensions

may not fully reflect their relative importance across regions. Finally, the analysis is confined to EU NUTS-2 regions and may not generalize to other territorial contexts.

5.3 Further research

Future research should extend the analysis beyond 2021 to capture medium- and long-term effects of the COVID-19 shock and the implementation of the EU Digital Compass 2030. This extended horizon would allow for a systematic evaluation of whether EU digital strategies effectively reduce regional disparities or risk reinforcing them. Incorporating indicators of governance quality and institutional capacity is also crucial, as digital transformation depends not only on infrastructure and skills but on effective policy implementation and absorptive capacity.

From a methodological perspective, dynamic panel models could better capture lagged effects of digital investments and budget allocations, while spatial econometric techniques would help identify interregional spillovers arising from trade, labor mobility and policy diffusion. Together, these extensions would provide a more comprehensive understanding of Europe's digital evolution and offer actionable insights for policymakers designing resilient, inclusive and future-oriented digital strategies.

Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Rómulo Quirós. The first draft of the manuscript was written by Rómulo Quirós and revised by Javier Perote.

Supplementary material

The supplementary material for this article can be found online.

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Corresponding author

Rómulo Quirós-Sánchez can be contacted at: romulo.quirós@usal.es, rquiros CPA@gmail.com

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