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Analysis of European competitiveness based on its innovative capacity and digitalization level

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ABSTRACT

The competitiveness of countries can be measured through their innovative capacity and the level of digitalization they have achieved. Technological advances have proven to be an engine of economic growth, promoting employment and sustainable development. In Europe, policies are being focused on investments to make this the "Digital Decade". Against this backdrop, the aim of the study is to analyse the competitiveness of the 27 countries of the European Union by producing a synthetic indicator that includes factors relating to innovation (measured by the *Global Innovation Index*) and to digitalization (based on the *Digital Economy and Society Index*), which in turn yields an annual ranking of the analysed economies between 2017 and 2021. Furthermore, in a second stage of the analysis, three panel data models are estimated to determine how factors relating to economic, social and environmental development foster advances in technology and innovation. The multicriteria decision-making method Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) is applied to establish a ranking of EU members according to their level of digitalization and innovation, while the Prais-Winsten regression with Panel Corrected Standard Errors is used to obtain robust estimators. The results of the ranking indicate that the countries hold similar positions in the five years analysed, with Sweden leading the way throughout, which reflects its stable development in terms of digitalization and innovation. A digital and innovation gap can be seen between the top and bottom positions of the ranking, that is, between north-central and south-eastern Europe. Finally, the estimated models suggest that governments should promote wealth, employment, research and infrastructure investments in order to improve innovative and technological development in their countries.

1. Introduction

Innovation has become a critical weapon for business and a growth factor for countries seeking a competitive advantage, as well as fostering economic development and increasing wealth [1,2]. In part, digitalization refers to the adaptation of new technologies in companies and society as a whole. Advances in digitalization help ensure better quality of life and life satisfaction for citizens [3]. In turn, digital advances can act as a boost to science, medicine, and economic growth, among others, facilitating progress for all economic agents [4–7].

The difficulties associated with economic or health crises have led governments to invest in innovation and digitalization, with widely varying aims, from improving the quality of life of the population, to promoting good environmental practices, preventing future pandemics and even reducing inequalities [8]. For its part, the European Union (EU) has, since 2014, been promoting policies aimed at boosting innovation and digitalization, thereby fostering the development of infrastructure and increasing access to and use of new technologies; indeed, the European Commission is committed to making this the "Digital Decade". Recently, the Horizon Europe (2021–2027) initiative has been making funding available to researchers in the form of scholarships, awards, and public procurement, with a larger budget than in previous programmes [9].

The creation of an ecosystem that enables progress in innovation and the development of digital technologies is important for countries' international positioning [10]. Against this backdrop, the aim of the study is twofold. The first is to analyse the competitiveness of EU member states in the period 2017–2021 by producing a synthetic indicator representing their digitalization and innovation capacity, called SIDI (*Synthetic Indicator of Digitalization and Innovation*). The second is to determine which economic, social and environmental factors explain Europe's competitiveness. Digitalization is measured using the *Digital*

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Economy and Society Index (DESI), which is a composite index that summarizes relevant indicators of countries' digital performance [11]. Innovation is measured using the *Global Innovation Index* (GII), which covers aspects relating to the political, educational, infrastructure and knowledge-creation environment [12]. The sample for the empirical analysis includes the 27 EU countries and covers a time span of five years (2017–2021). Our analysis will allow us to answer two research questions.

Q1. Has there been progress in EU digitalization and innovation between 2017 and 2021?

To deal with an ever more competitive environment, it is important for both industries and societies to make progress in the field of digitalization and innovation. This in turn requires a focus on the decisions made strategies implemented to achieve that progress. Multicriteria decision-making (MCDM) methods have become established as a useful tool for gaining a better understanding of decision-making processes, facilitating the comparison of alternatives. This study uses the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS), which has proven suitable for solving problems that require the ranking of a set of alternatives. The annual SIDI is constructed, including the pillars of the DESI and the GII, and then used to rank the EU countries based on both their innovation and digitalization capacities. We also analyse whether there has been any variation in countries' positions during the period under study.

Q2. What economic, social and environmental factors are determinants of the modernization of European countries?

The goal here is to make decision-makers aware of how economic, social and environmental development fosters technological progress and advances in innovation. We will answer the question by estimating three models on a sample of panel data for the 27 EU countries during the period 2017–2021. We use the Prais-Winsten regression with Panel Corrected Standard Errors to obtain robust estimators.

The result of the research will be of interest to investors, informing them of the latest trends and advances in European economies, thereby enabling them to engage with the projects that ensure success. Companies from countries at the top of the ranking will be more attractive to investors and will therefore find it easier to secure financing and enjoy the possibility of continuous development.

The proposed research represents a novel contribution to the literature since no previous studies have ranked European countries based on both indices used here. Pençe et al. [13] produced a ranking of countries based on the GII using neural networks, while Zerhouni and Özarı [14] classified economies solely based on the DESI. In the context of the G20, Cahyadi and Magda [15] confirm a positive and significant relationship between digital readiness and innovation; their findings justify the joint consideration of the two concepts at the EU level. Indeed, our results show the level of correlation between digital development and innovation, offering a glimpse of each country's strategic position. In addition, the determinants of digitalization and innovation are identified; this is very useful for decision-makers, allowing them to target their efforts at the elements that have had the greatest impact. Although the analysis focuses on a five-year period, the main limitation of this research lies in the need to expand the information to be able to examine whether the pandemic has caused an exponential or linear increase in digitalization and innovation in Europe.

The rest of the article is structured as follows. Section 2 presents a review of the literature, analysing other works focused on innovation and/or digitalization. Section 3 explains the variables, the sample and the methodology used in the empirical analysis. Section 4 sets out the results of the research. Finally, section 5 summarizes the main conclusions.

2. Literature review

2.1. Digitalization

The degree of digitalization of a nation can be analysed using different indicators [16]: the ICT development index proposed by the International Telecommunication Union [17], the digital intensity index for 36 industries produced by Calvino et al. [18], the digitalization index [19] developed by BBVA. For its part, the European Commission has been producing the DESI since 2014. It has been widely used in the literature for the study of digitalization, applied in research on countries such as Romania [20,21], Greece [22], Denmark [23], Croatia [24], as well as the 27 member states as a group. Using the DESI, Liu [25] identifies the geographical areas that show the most similarities in terms of the components of the index. The results provide valuable information to economic agents on the level of development, guiding investments in infrastructure, human resources and other technological aspects and directing them towards the most pivotal issues. Likewise, Kovacs and Bittner [26], based on the 2016–2021 time series of the DESI, show evidence of convergence in digital public services among all European countries.

The recent literature contains several studies that examine the link between the degree of digitalization of the EU and various different areas. Specifically, the connection with economic growth is analysed, revealing a positive relationship between the two [27–29]. For example, Oğuz and Esin Cumhur [30] conclude that an increase in the DESI leads to a rise in the employment rate and personal income, and a drop in long-term unemployment and labour market insecurity. More recently, in a sustainable economy context, Ha et al. [31] show that the digital transformation process improves environmental outcomes relating to the protection of health and ecosystems. Guaita-Martinez et al. [32] explore the connection between digitalization and sustainable production, highlighting the importance of each of the aspects that define Industry 4.0. Skvarciany and Jurevičienė [33] affirm that the digital economy partially contributes to sustainable development; connectivity and human capital are the only pillars of the DESI positively correlated with the Sustainable Development Goals, whereas the rest have a negative influence. Along similar lines, Magazzino et al. [34] demonstrate a two-way relationship between ICT penetration and electricity consumption, but neither help reduce environmental pollution.

At the business level, Ghazy et al. [35] use panel data to examine the connection between entrepreneurship (taken from the DESI) and productivity for the 27 EU members, showing a positive and significant relationship between them. In a financial context, Ha [36] demonstrates the positive influence of digitalization on markets and financial institutions. Digitalization and its impact on competitiveness is a subject that has been explored in the literature; Martincevic [37] conducts a review, concluding that new modern digital technologies are essential to do business and achieve digital competitiveness in the world market. Digitalization has erupted into all sectors of society; in response, the scientific community is making notable efforts to analyse the impact of this new way of working and interacting, to help decision-makers focus on the aspects that foster its deployment.

2.2. Innovation

Innovation is becoming one of the fundamental pillars for ensuring the more sustainable growth of world economies [38]. Its definition in the GII is based on the Oslo Manual [39]: "An innovation is the implementation of a new or significantly improved product (good or service), a new process, a new marketing method, or a new organizational method in business practices, workplace organization, or external relations". The GII is frequently used in the literature to analyse the innovative development of countries [40–42]. In a study using this index, Jankowska et al. [43] conclude that higher innovation input does not necessarily produce higher output, as is the case in Poland, because the support from innovation fails to meet the expectations of companies or institutions.

Studies on the capacity to innovate usually relate it to other economic and/or social aspects of countries. Some analyses carried out have demonstrated a significant positive relationship between the GII and other indices such as the *Doing Business Index*, *Economic Freedom Index* and *Corruption Perceptions Index* [44], the *Global Competitiveness Index* [45], and university performance [46]. In the field of the public sector, Suzuki and Demircioglu [47] show that innovation levels are significantly higher in countries that have a more professional and impartial administration. For their part, Sener and Delican [48] find unidirectional causality from export to innovation and information-communication technology, in both developed and developing countries. More recently, Minović and Jednak [49] identify a two-way relationship between economic growth and capacity for innovation, and between foreign direct investment and capacity for innovation. In addition, Magazzino et al. [50] demonstrate that improvements in technological innovation and human capital, urbanization, and trade openness all have a positive and significant effect on logistics performance. These studies highlight the need for countries to develop their capacity for innovation, enabling them to adapt to the changes being imposed by globalization and thereby guarantee the survival and competitiveness of all productive sectors.

2.3. Digitalization and innovation

The connection between digitalization and innovation is a line of research that has recently been gaining importance in the literature. Mostaghel et al. [51] carry out a bibliometric analysis of 170 papers, revealing the need to develop digitalization capabilities to foster efficiency and innovation. The scientific community is proposing a new theoretical framework related to the concept of digital innovation, characterized by rising social inequality and changing business models [52]. According to Ciarli et al. [53] digital technologies, innovation and skills evolve alongside one another, requiring a reorganization of production processes.

In turn, the knock-on effects of the COVID-19 pandemic have brought about major changes, where the processes of entrepreneurship and digital transformation have acted as an accelerant of technology, fostering the growth of digital business models [54]. Focusing on family firms, Soluk [55] demonstrates that external shocks such as those stemming from the pandemic accelerate digital innovation (digital process innovation, digital product innovation and digital business model innovation), which serves as a defensive tool. Furthermore, Hung et al. [56] analyse the nexus between digitalization and environmental innovation, concluding that digital public services are less critical than private ones when it comes to driving innovation performance. Digitalization is an effective tool for boosting investment in environmental innovation as well as securing more financial support from the government and raising public awareness about climate change.

3. Materials and methods

3.1. Materials

The DESI and the GII used in the empirical analysis of this paper are composed of a set of pillars, which are explained in Table 1. The publication of the DESI (https://digital-agenda-data.eu/charts/desi-components), produced by the European Commission since 2014, allows the comparison of the 27 EU countries, as well as providing an overall view of the digital ecosystem. The GII, prepared annually since 2012 by the World Intellectual Property Organization (https://www.wipo.int/global_innovation_index/en/), analyses the degree of innovation of 132 economies, enabling the study of recent trends [12]. The pillars of both indices are normalized to values from 0 to 100. The higher the score, the more innovative/digitalized a country is.

Table 1
Pillars of the DESI and GII.

Index	Pillars	Composition
DESI	Connectivity (CON)	Fixed broadband take-up, Fixed broadband coverage, Mobile broadband, Broadband prices
	Human capital (HC)	Internet user skills and Advanced skills and development.
	Integration of digital technology (IDT)	Digital intensity, Digital technologies for businesses and e-Commerce
	Digital public services (DPS)	e-Government
GII	Institutions (INS)	Political environment, Regulatory environment and Business environment.
	Human Capital and Research (HCR)	Education, Tertiary education and Research & development.
	Infrastructure (INF)	ICTs, General infrastructure and Ecological sustainability.
	Market sophistication (MS)	Credit, Investment and Trade, competition, and market scale
	Business sophistication (BS)	Knowledge workers, Innovation linkages, and Knowledge absorption.
	Knowledge and technology outputs (KTO)	Knowledge creation, Knowledge impact and Knowledge diffusion
	Creative outputs (CO)	Intangible assets, Creative goods and services and Online creativity

The economic, social and environmental determinants of the SIDI have been obtained from the Sustainable Governance Indicators (SGI) database.[1] The SGI is especially valuable for users seeking a comprehensive measure of policy performance [57]. These data, which are well regarded in the literature [57–59], encompass a set of variables that a priori could be determinants of the competitiveness of EU countries in the analysed period (Table 2).

The sample is composed of the 27 countries of the EU, for a period of analysis spanning the years from 2017 to 2021. Table 3 presents annual descriptive statistics referring to the pillars of the DESI and the GII.

Analysing the time series of the indices, we see an increase in the mean of all the pillars of the DESI between 2017 and 2021, most notably in *Connectivity* (68%) and *Integration of digital technology* (47.3%). However, in the GII, only *Institutions* and *Knowledge and technology outputs* rise slightly (0.23% and 3.11%, respectively), whereas the rest show a slight decrease, with a significant drop of 15.6% in *Creative outputs*. Therefore, European policies have a positive influence on advances in digitalization, while innovation is stagnating or in decline due to the economic difficulties of recent years.

Bearing in mind that the values for all the pillars lie within the range 0–100, *Institutions* is the closest to the maximum, reaching a value of 93.6 in 2019 for Finland, while the rest of the countries still have room for improvement. Most of the maximum values correspond to nations in northern Europe. Examining which countries maintain their leading positions between 2017 and 2021, in addition to Finland in *Institutions* and *Human Capital*, we find Sweden in *Infrastructure*, Denmark in *Market sophistication* and Luxembourg in *Creative outputs.* From the point of view of the worst ranking countries, Romania registers the lowest value for *Digital public services* between 2017 and 2019 with only 7.4 and 11.8, respectively, as well as other minimum values such as those for *Human Capital and Research* (30.5 and 28.9) and *Creative outputs* (32.9 and 22.2*)*. Greece also stands out for the low scores recorded in *Connectivity, Institutions, Business sophistication* and *Knowledge and technology outputs.* All of this highlights the gap between the north and the southeast of Europe in the levels of digitalization and innovation. Table 4 presents the descriptive statistics for the factors that explain the SIDI.

The descriptive statistics for the explanatory variables of the SIDI (Table 4) have been calculated for the sample as a whole, covering the

[1] https://www.sgi-network.org.

Table 2
Economic, social and environmental factors.

	Variable	Definition
Economics variables	GDP per capita	Gross domestic product per capita, purchasing power parity, constant 2017 international dollar.
	Employment rate	Employment to population ratio, age group 15–64 years.
	Total researchers	Total researchers per 1,000 jobs (fulltime equivalents).
	Quality of overall Infrastructure	1 = extremely poor—among the worst in the world; 7 = extremely good—among the best in the world
Social variables	Gini coefficient	Unit: percent.
	NEET rate	Percentage of population neither in education nor employed, age group 20–24 years
	Gender equality in parliaments	Proportion of seats held by women in national parliaments
	Life satisfaction	Life satisfaction on a scale from 0 to 10
	Gender wage gap	Gender wage gap unadjusted and defined as the difference between median wages of men and women relative to the median wages of men.
Environment variables	Energy productivity	Energy productivity level of primary energy (constant 2017 purchasing power parity GDP per megajoule)
	Greenhouse gas emissions	Greenhouse gas emissions, tonnes in CO2 equivalents per capita, excluding land use, land-use change and forestry
	Particulate matter	Particulate matter, PM2.5, proportion of the population whose exposure is above WHO threshold 15 μg/m3.
	Waste generation	Municipal waste, generation intensities kg/capita
	Material recycling	Proportion of municipal waste recovered by material recycling
	Renewable energy	Renewable energy share in the total final energy consumption (%)
	Material footprint	Material footprint per capita. The material footprint refers to the global allocation of used raw material extracted to meet the final demand of an economy.

five-year period of analysis. The correlation matrix shows low values, confirming the absence of multicollinearity among the variables.

3.2. Methods

To achieve the research objective, we follow the methodological process set out in Fig. 1. These steps allow us to answer the research questions posed above, which require the calculation of the SIDI and the estimation of the determinants of said indicator.

The ranking of EU members according to their level of digitalization and innovation is created by applying the MCDM method TOPSIS, which was initially proposed by Hwang and Yoon [60]. TOPSIS is a technique that has been applied in various different areas to manage decision-making [61]. Due to its sound mathematical basis, it is a widely accepted tool in the literature [62,63] and can be found in studies from different fields: countries' vulnerability [64], tourism [65], digitalization [13,66], and innovation [67–69], among others. In all these studies, TOPSIS has proven to be an optimal technique to establish a ranking based on different alternatives, grouping together variables for their joint analysis. The method is based on the following steps [70] (Fig. 2).

Step 1. The decision matrix $(X_{ij})_{mxn}$ is created, where *m* alternatives and *n* criteria are developed. Every component in the decision matrix represents the real value of the i_{th} alternative according to the j_{th} criteria. In this study, the criteria are each of the pillars that make up the DESI and the GII, while the alternatives are the countries under analysis.

Step 2. The normalized decision matrix $(r_{ij})_{mxn}$ is then created, which represents the relative performance of the generated alternatives. Every value in decision matrix is divided by the sum of the squares of the values in the same column as the divided value.

Step 3. The weighted normalized decision matrix $(V_{ij} = w_j \cdot r_{ij})_{mxn}$ is calculated. The weights (w_j), which indicate the importance of the criteria, are specified by the decision-maker $(\sum_j^n w_j = 1)$. At this stage, the normalized matrix is multiplied by the weights of criteria. In this study, the same weights are used for each criterion, so as not to introduce any subjectivity into the analysis.

Step 4. Positive and negative ideal solutions are identified. Positive

Table 3
Descriptive statistics for the pillars of the DESI and GII.

	DESI				GII						
	CON	HC	IDT	DPS	INS	HCR	INF	MS	BS	KTO	CO
2017											
Mean	26.8	43.4	22.9	47.2	79.0	47.8	58.3	52.5	45.1	37.8	46.9
Max	39.5	64.7	35.3	67.1	92.2	66.4	69.1	70.2	63.7	62.9	65.8
Min	12.7	27.9	10.1	7.4	65.2	30.5	48.1	41.5	28.8	20.4	32.9
SD	6.7	8.9	7.3	14.2	7.4	10.9	5.4	7.7	9.3	11.3	7.8
2018											
Mean	28.6	43.9	25.2	51.3	79.1	46.1	57.2	52.6	45.6	40.0	44.6
Max	41.0	65.9	38.8	72.1	92.8	64.2	67.1	68.3	65.1	63.7	57.9
Min	13.4	27.5	11.4	9.8	65.4	30.4	47.0	42.6	30.0	23.7	29.3
SD	6.8	9.2	7.6	14.8	7.5	10.9	6.0	7.1	9.5	10.6	7.4
2019											
Mean	32.3	45.1	27.6	54.7	79.5	46.0	58.1	52.7	47.2	39.3	41.9
Max	43.9	65.8	42.9	76.0	93.6	63.4	69.1	66.9	68.8	61.8	56.2
Min	16.3	28.0	12.1	11.8	67.1	29.1	50.5	43.2	32.4	24.4	25.8
SD	6.9	9.2	8.5	15.1	7.6	10.5	5.1	6.3	10.7	10.9	8.0
2020											
Mean	36.6	46.1	30.5	58.8	79.1	46.0	55.1	51.4	43.8	39.6	37.9
Max	48.0	67.5	49.0	80.8	93.5	62.9	64.6	66.3	68.0	59.8	55.0
Min	19.1	28.5	13.1	14.9	68.0	27.7	47.0	42.2	26.4	26.8	20.3
SD	7.4	9.4	9.5	15.5	7.1	10.6	4.2	5.9	11.9	9.5	9.3
2021											
Mean	45.0	47.0	33.8	63.6	79.2	47.1	54.8	52.1	43.5	39.0	39.4
Max	72.1	70.5	53.4	86.3	93.3	64.1	62.6	68.0	68.1	60.3	54.4
Min	31.1	30.1	14.1	18.2	68.1	28.9	45.1	44.7	25.9	25.2	22.2
SD	9.3	9.6	10.7	16.0	6.8	10.4	4.4	6.8	11.9	9.9	9.2

Table 4
Descriptive statistics of the determinants of the SIDI.

Environmental variables	Mean	Max	Min	SD	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(1) EP.	9.09	26.35	0.19	5.57	1						
(2) GHG	8.66	17.52	4.09	2.86	0.12	1					
(3) PM	33.94	99.37	0.00	34.54	−0.01	−0.31	1				
(4) WG	486.08	845.00	247.00	116.23	0.01	0.15	−0.35	1			
(5) MR	24.79	49.59	5.67	9.48	−0.13	0.46	−0.20	0.22	1		
(6) RE	21.28	53.10	3.99	11.87	−0.15	−0.30	−0.29	−0.01	0.11	1	
(7) MF	25.87	103.41	11.28	15.68	0.01	0.41	−0.42	0.36	0.12	−0.06	1
Social variables	Mean	Max	Min	SD	(1)	(2)	(3)	(4)	(5)		
(1) NR	14.13	29.10	4.10	5.04	1						
(2) G	29.81	40.80	20.90	4.07	0.45	1					
(3) GE	28.42	47.43	10.10	9.69	−0.22	−0.13	1				
(4) LS	6.51	7.86	4.84	0.69	−0.65	−0.50	0.50	1			
(5) GWG	10.74	28.34	1.55	5.90	−0.24	−0.18	0.08	0.16	1		
Economic variables	Mean	Max	Min	SD	(1)	(2)	(3)	(4)			
(1) GDPpc	43638	114481	20489	18631	1						
(2) E	68.2	78.2	52.0	5.7	0.3	1					
(3) R	8.5	16.9	2.1	3.8	0.5	0.3	1				
(4) I	4.7	6.3	3.0	0.7	0.6	0.3	0.6	1			

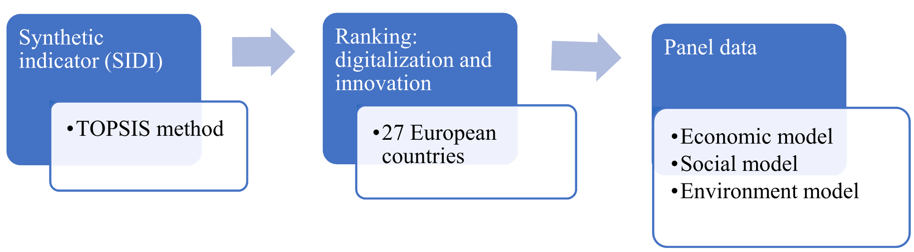

Fig. 1. Research method.

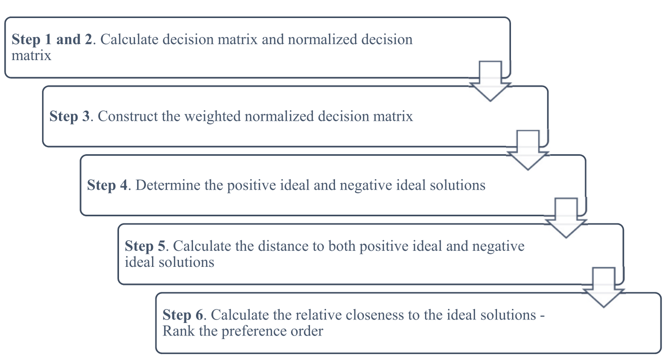

Fig. 2. TOPSIS algorithm.

ideal solutions and negative ideal solutions consist of the highest and the lowest values, respectively, of the rows in the weighted normalized decision matrix. In this paper, the ideal solution is identified by maximizing each criterion.

Step 5. The distance to the positive ideal solution (A^+) and to the negative ideal solution (A^-) is determined. The final ranking for decision-making will be obtained by comparing distances. The distance separating each alternative from the positive ideal solution (S^+_i) and the negative ideal solution (S^-_i) is measured by means of the Euclidean distance.

Step 6. The relative closeness of each alternative to the ideal solution is computed.

$$CC_i = \frac{S_i^-}{S_i^* + S_i^-}, (0 < CC_i < 1, i = 1, 2, \ldots m)$$

The preference order of the alternatives is then established, based on their relative closeness to the ideal solution. A higher value of relative closeness represents a higher preference order among the generated alternatives [71].

Once the SIDI has been calculated, the most influential economic, social and environmental factors are identified by estimating three regression models with panel data. The logarithmic form of the relationship between the variables considered is expressed as follows (equations (1)–(3)):

$$SIDI = \beta_0 + \beta_1 \, Ln(GPDpc_{,it}) + \beta_2 \, Ln(E_{it}) + \beta_3 \, Ln(R_{it}) + \beta_4 \, Ln(I_{it}) + \omega_0 \quad (1)$$

$$SIDI = \beta_0 + \beta_1 \, Ln(G_{,it}) + \beta_2 \, Ln(NR_{it}) + \beta_3 \, Ln(GE_{it}) + \beta_4 \, Ln(LS_{it}) + \beta_5 \, Ln(GWG_{it}) + \omega_0 \quad (2)$$

$$SIDI = \beta_0 + \beta_1 \, Ln(EP_{,it}) + \beta_2 \, Ln(GHG_{it}) + \beta_3 \, Ln(PM_{it}) + \beta_4 \, Ln(WG_{it}) + \beta_5 \, Ln(MR_{it}) + \beta_6 \, Ln(RE_{it}) + \beta_5 \, Ln(MF_{it}) + \omega_0 \quad (3)$$

where, SIDI is the Synthetic Indicator of Digitalization and Innovation; GDPpc, Gross domestic product per capita; E, Employment; R, Total researchers; I, Quality of overall infrastructure; G,: Gini coefficient; NR, NEET rate; GE, Gender equality in parliaments; LS, Life satisfaction; GWG, Gender wage gap; EP, Energy productivity; GHG, Greenhouse gas emissions; PM, Particulate matter; WG, Waste generation; MR, Material recycling; RE, Renewable energy; MF, Material footprint. In addition, ω, i, and t are the error term, some countries, and time, respectively.

Different econometric tests are applied to the data to identify the best way to conduct the estimation and the possible presence of problems related to autocorrelation and heteroskedasticity. First, the *Breusch-Pagan test*, also known as the *Lagrange multiplier test* for random effects, is applied to determine whether it is more appropriate to perform a pooled OLS or random effects estimation [72]. The *Wooldridge test* is used to test for autocorrelation [73]. For the case of heteroskedasticity, the *modified Wald test* is applied [74]. If the tests were to confirm the presence of the two problems, estimating a panel data model with fixed or random effects would yield biased results; the use of *Feasible Generalized Least Squares* (FGLS) or *Panel Corrected Standard Errors* (PCSE) would therefore be appropriate. Beck and Katz [75] showed that the standard errors of PCSE are more accurate than those of FGLS.

PCSE has been applied in other studies in the context of digitalization or innovation [76–79]. Regarding digitalization, Hung et al. [56] explain the nexus between digitalization and environmental innovations, while Thanh et al. [80] analyse the relationship between digital transformation and energy security. In the area of innovation, Rahman and Alam [81] study the role of corruption, technological innovation, globalization, renewable energy, and economic growth in CO_2 emissions in Asian countries. In this research, we use the Prais-Winsten regression with PCSE to obtain robust estimators [82].

4. Results and discussion

Focusing on 2021, the GII and the DESI show the interrelationship of digitalization and innovation for the 27 EU members (Fig. 3). These results coincide with the findings of Nagy and Somosi [83], who conclude that the capacity for social innovation is having a positive impact on the digitalization of the economy and society.

In the group of EU member states, we see a dispersion of points depicting a positive trend, revealing the direct relationship between innovation and digitalization (Fig. 3). Group II, which leads the way in the EU, is made up of countries located in northern Europe, all of which registered above-average values in both indices (Denmark, Finland, the Netherlands, Sweden, Ireland, Luxembourg, Austria and Estonia). According to Aytekin et al. [1], these are countries where the GII pillars confirm the efficiency of their innovative capacity, with Denmark standing out for the highest value in digitalization. Brodny and Tutak [66] report that Danish companies are characterized by a notable willingness to use new technologies and introduce changes in the work system.

Regarding the less advanced nations, Group III is made up of countries from the east and south of Europe, which register low values in the analysed indices (Romania, Greece, Bulgaria, Poland, Hungary, Slovakia, Cyprus, Italy, Croatia, Portugal, Latvia and Lithuania). However, these countries are making progress in digitalization; for example, in 2020, Bulgaria and Romania started working on various initiatives based on blockchain technology, establishing a node to connect to the European Blockchain Infrastructure for Services Network [26]. It is important to clarify that the contrast between the south-eastern European countries and the north-central ones reveals the presence of a digital divide creating different conditions for economic growth [84].

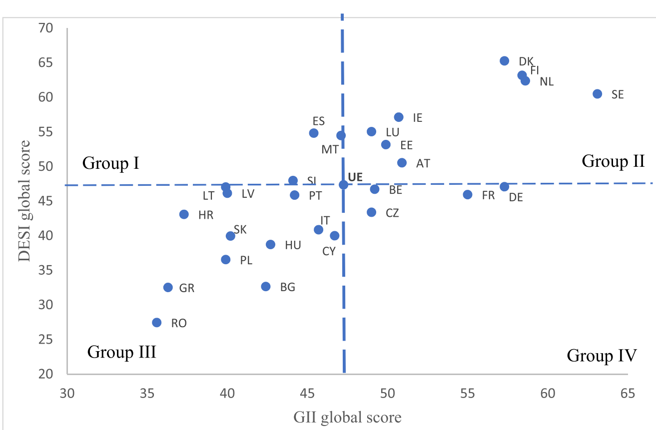

Fig. 3. Levels of digitalization and innovation of EU members (2021).

In Group I are Spain, Malta and Slovenia, with high levels of digitalization but low levels of innovation, while the opposite is true for Belgium, France, Czechia and Germany (Group IV). Based on the results obtained with the SIDI, it is possible to accurately identify countries' positions and make comparisons among them. The research results are structured in line with the research questions posed.

Q1. Has there been progress in EU digitalization and innovation between 2017 and 2021?

In Europe, innovation and technological progress are understood to be the main sources of countries' competitiveness [85]. Specifically, innovation in the digital field and the application of new technologies in the value chains of the different productive activities give rise to smarter industry, referred to as Industry 4.0 [86]. By producing the SIDI, we can establish a ranking of countries revealing the European countries that show the greatest competitiveness (Table 5).

The results of the ranking point to stability in countries' positions over the five years analysed. This fact is confirmed by calculating the Spearman correlation coefficient between the SIDI of 2017 and that of 2021, which gives a value of 0.98, indicating a very close similarity between the positions in these two years. These results are in line with the study by Onea [87] relating to the field of innovation, and that by Paraschiv et al. [88] for digitalization, where it is pointed out that there have been no major changes between countries in recent years due to a slowdown in the public sector relative to the private sector, and progress in some pillars that has offset a decline in others. Thus, we confirm that no significant change is found in the levels of digitalization and innovation of the analysed countries (answer to Q1).

The SIDI puts Sweden in first place (as with the GII) and Denmark in third (whereas it tops the ranking with the DESI), leaving the Netherlands in second place due to its high score in the GII. In brief, these are three very competitive countries that have been able to develop new tools and the ability to innovate in society. This situation is not surprising, considering that northern European countries are pioneers in promoting digital development. This group of countries, referred to by Cruz-Jesus et al. [89] as Digital Leaders, are characterized by having the highest levels in ICT infrastructure and adoption by population, and e-business and internet access costs.

If we compare the GII and the DESI of the group of major European powers such as France and Germany against Spain and Slovenia (Fig. 3), the former is better at innovation while the latter is better at digitalization. However, the SIDI in 2021 places the former in significantly more prominent positions, demonstrating its capacity to provide a more instructive ranking in these two areas.

Among the least competitive countries are Romania, Greece and Poland, where there are certain barriers to digitalization and innovation, especially in the public sector, with shortcomings such as a lack of specialized labour or inadequate infrastructures [21]. However, the first two are starting to make changes to improve this situation. In Romania, the National Coalition for Digital Skills and Jobs promotes computer classes, cybersecurity and educational events focused on developing digital skills [90]. The Greek government's efforts to improve human capital are on the right track. However, its policymakers should focus on infrastructure and developing regulation to improve its performance further [91]. The results for Poland can be attributed to the fact that 15% of its population is not online and almost 50% still lacks basic digital skills [92].

Q2. What economic, social and environmental factors are determinants of the modernization of European countries?

Table 5
Ranking of European countries according to the synthetic indicator (SIDI).

	SIDI 2017	Rank	SIDI 2018	Rank	SIDI 2019	Rank	SIDI 2020	Rank	SIDI 2021	Rank	SIDI Average	Rank
Sweden	0.85	1	0.87	1	0.88	1	0.89	1	0.83	1	0.86	1
Netherlands	0.83	2	0.84	2	0.82	3	0.83	2	0.81	2	0.82	2
Finland	0.77	4	0.80	3	0.84	2	0.81	3	0.77	4	0.79	3
Denmark	0.77	3	0.78	4	0.80	4	0.81	4	0.80	3	0.79	4
Ireland	0.68	5	0.69	5	0.69	5	0.68	5	0.63	5	0.67	5
Luxembourg	0.66	6	0.65	6	0.64	6	0.63	6	0.57	8	0.62	6
Germany	0.59	7	0.59	7	0.62	7	0.62	7	0.61	6	0.60	7
Malta	0.58	8	0.59	8	0.58	8	0.59	10	0.55	10	0.58	8
France	0.54	13	0.55	13	0.58	9	0.59	8	0.55	9	0.56	9
Austria	0.55	11	0.55	12	0.56	12	0.57	11	0.57	7	0.56	10
Estonia	0.57	9	0.57	10	0.57	11	0.55	12	0.54	11	0.56	11
Belgium	0.54	12	0.56	11	0.56	13	0.59	9	0.53	12	0.55	12
Spain	0.56	10	0.58	9	0.58	10	0.54	13	0.51	13	0.55	13
Slovenia	0.48	15	0.50	14	0.49	14	0.47	15	0.45	15	0.48	14
Czechia	0.48	14	0.46	16	0.48	15	0.49	14	0.46	14	0.47	15
Portugal	0.47	16	0.48	15	0.47	16	0.46	16	0.42	16	0.46	16
Lithuania	0.44	18	0.46	18	0.46	17	0.43	17	0.39	19	0.43	17
Latvia	0.46	17	0.46	17	0.44	18	0.43	18	0.36	20	0.43	18
Italy	0.39	20	0.39	20	0.42	19	0.42	19	0.40	17	0.40	19
Cyprus	0.40	19	0.40	19	0.41	20	0.40	20	0.39	18	0.40	20
Hungary	0.32	22	0.37	21	0.36	21	0.35	21	0.32	22	0.34	21
Slovakia	0.35	21	0.35	22	0.33	22	0.31	22	0.29	23	0.33	22
Croatia	0.32	23	0.33	23	0.32	23	0.31	23	0.32	21	0.32	23
Poland	0.26	25	0.27	25	0.28	24	0.29	24	0.26	24	0.27	24
Bulgaria	0.27	24	0.28	24	0.25	25	0.26	25	0.26	25	0.26	25
Greece	0.24	26	0.24	26	0.23	26	0.22	26	0.23	26	0.23	26
Romania	0.24	27	0.23	27	0.21	27	0.20	27	0.14	27	0.20	27

Note: Average represents the mean of values in the analysed period 2017–2021. Ranking based on the average value.

The estimation of the panel data models (equations (1)–(3)) requires several tests to be carried out beforehand to identify the characteristics of the sample and decide on both the correct specification and the appropriate econometric method. First, Table 4 shows the absence of collinearity between the three groups of variables considered, as indicated by the low correlation coefficients. Second, the *Breusch-Pagan test* is applied, allowing us to reject the null hypothesis (p-value <0.05) in the three models, thus indicating that random effects estimation is more suitable than pooled OLS. Next, the presence of autocorrelation and heteroskedasticity are confirmed by the *Wooldridge test* and the *modified Wald test*, respectively (Table 6).

The results of the tests applied above facilitate the choice of the method for estimating the equations, the Prais-Winsten regression model, and the analysis of the relationship between the SIDI and the economic, social and environmental factors during the period 2017–2021 (Table 7).

All three estimates present a good fit, registering an R^2 of over 0.8 in all cases. In the economic model, the coefficients referring to the explanatory factors are positive and significant, that is, *GDPpc*, *Employment*, *Researchers* and *Infrastructures* all have a direct relationship with countries' ranking according to the SIDI. These findings coincide with those of other studies that have individually analysed either innovative capacity or digitalization. De Noni et al. [93] and Sharma et al. [94] show that GDP is a positive and significant determinant of innovation. However, Leogrande et al. [95] go a step further by indicating that the positive relationship between technological innovation and per capita income exists only for low and medium-low levels of per capita income, and tends to become negative as per capita income rises.

In turn, the study by Zhu et al. [96] on businesses in China reports ambiguous evidence of the impact of innovation on employment: process innovation exerts a positive effect on the hiring of workers, whereas product innovation has a negative effect. In addition, Piva and Vivarelli [97] specify that the medium and high-tech sectors in Europe have a positive effect on the relationship between innovative development and the employment rate, but this is not the case for more technologically backward industries. Leogrande [98] concludes that the influence of technological innovation on employment in Europe has increased by 10.6% between 2014 and 2021. Meanwhile, Kučera and Fiľa [2] confirm a significant interdependence between R&D expenditure, innovation

Table 6
Model fit test.

Economic model	Social model	Environment model
Breusch and Pagan test		
Chibar2(01) = 102.19	Chibar2(01) = 100.68	Chibar2(01) = 185.00
Prob > chibar2 = 0.000	Prob > chibar2 = 0.000	Prob > chibar2 = 0.000
Wooldridge test for autocorrelation in panel data		
F(1, 26) = 18.707	F(1, 26) = 30.310	F(1, 26) = 44.732
Prob > F = 0.000	Prob > F = 0.0000	Prob > F = 0.0000
Modified Wald test for groupwise heteroskedasticity		
chi2 (27) = 708.05	chi2 (27) = 3062.56	chi2 (27) = 3803.42
Prob > chi2 = 0.000	Prob > chi2 = 0.0000	Prob > chi2 = 0.0000

Table 7
Prais-Winsten regression, heteroskedastic panel corrected standard errors.

	Economic model.	Social model	Environment model
Ln(GPDpc)	0.146***		
Ln(Employment)	0.532***		
Ln(Researchers)	0.038*		
Ln(Infrastructure)	0.481***		
Ln (Gini coefficient)		0.154**	
Ln (NEET rate)		−0.148***	
Ln (Gender equality)		0.057**	
Ln (Life satisfaction)		0.717***	
Ln (Gender wage gap)		0.023	
Ln (Energy prod.)			0.013
Ln (Greenhouse emis.)			−0.070*
Ln (Particulate matter)			−0.010***
Ln (Waste generate)			0.190***
Ln (Material recycling)			0.065***
Ln (Renewable energy)			−0.016
Ln (Material footprint)			0.033**
R-squared	0.866	0.827	0.817
Number of obs	135	135	135

Note: Dependent variable: synthetic indicator; ***p < 0.01, **p < 0.05, *p < 0.1.

and countries' level of economic development.

In the social inclusion model, all the coefficients are significant except for *Gender wage gap*. Regarding their signs, a negative value was found for the variable capturing the population that neither studies nor work (*NEET rate*) because having a critical mass of unproductive citizens adversely affects digitalization and innovation. Conversely, a positive sign indicates that greater wealth inequality (Gini index), a more satisfactory life, and greater gender equality improve the position in the SIDI. In line with these results, Elmassah and Hassanein [3] have shown that internet connectivity and use, as well as integrated digital technology, are positively related to people's satisfaction, as assessed through the *Life Satisfaction Index*.

Lastly, in the environmental factors model, all the coefficients turn out to be significant except for *Energy productivity* and *Renewable energy*. The more sustainable societies have a greater drive to modernize, paying substantial attention to innovation and digitalization. The relationship between digitalization and sustainable development is currently an important line of research. Denicolai et al. [99] and Jovanović et al. [100] show that digitalization and sustainability are positively related; they are growth paths that compete with one other when companies internationalize. Also, Perez-Martinez et al. [101] highlight the need to guarantee global progress, breaking down barriers to effective sustainability. Their study shows that despite the strong correlation between digitalization, sustainability and economic growth, two of the SDGs do not align with this relationship. The synergies between economic and social sustainability make up for the depletion of natural resources and the generation of waste.

In short, the results confirm that for countries to modernize, decision-makers must foster the introduction of policies that support economic growth, education and the installation of better infrastructure. All this should be accompanied by social and environmental inclusion policies, as they are determinants of European countries' positioning in terms of innovation and technology.

5. Conclusions

Digital technologies are having a major impact on people's lives when it comes to communication media, ways of living and ways of working. They offer solutions for countries' growth, promoting job creation, educational progress, improvements in competitiveness and environmental protection. Taken together with the advances in innovation achieved by nations, not only in the digital context but in all areas of the economy, this makes it possible to identify the level of competitiveness of countries. The Digital Europe concept, for which the European Commission has set aside € 9.2 billion in the 2021–2027 budget, seeks to boost the EU's competitiveness and provide citizens with all the skills and infrastructure needed to use the latest technologies. In this regard, the aim of the present paper has been to produce a ranking of EU member states to assess their capacity for innovation and digitalization, using the TOPSIS multicriteria decision analysis technique to do so. In addition, we have analysed the determinants of countries' position in the ranking using variables related to the economy, the social sphere and the environment.

We conclude that the positions obtained in the ranking remain very similar throughout the period 2017–2021, reflecting European countries' stable development in terms of digitalization and innovation, despite having suffered the effects of the COVID-19 pandemic between 2020 and 2021. Sweden, the Netherlands, Finland and Denmark have managed to remain among the top positions during the analysed period, thus representing the leading group of countries in digital skills and innovation. However, there is a significant digital and innovation gap between north-central and south-eastern Europe. Indeed, Poland, Greece, Bulgaria and Romania are in the bottom positions, as these are countries that face major financial barriers and obstacles relating to human capital. This gives rise to two deployment speeds, which is an important issue when it comes to fostering economic growth in the countries most in need.

Regarding the factors that determine a country's position in the ranking, the present research indicates that European governments should commit to promoting economic policies that bolster wealth, the employment rate, and research, as well as increasing funding targeted at infrastructure investments. Sustainable development also plays a relevant role in countries' modernization process: respect for the environment and social inclusion policies improve the innovative capacity of countries. Countries all around the world continue to strive to introduce advanced technologies, fostering socio-economic development and encouraging care of the environment.

Credit author statement

Luisa Marti: Conceptualization, Methodology, Data, Writing – original draft, Supervision,Writing- Reviewing and Editing, Rosa Puertas: Conceptualization, Methodology, Data, Writing – original draft, Supervision,Writing- Reviewing and Editing

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Declaration of competing interest

None.

Data availability

The authors are unable or have chosen not to specify which data has been used.

Abbreviations

BS	Business sophistication
CO	Creative outputs
CON	Connectivity
DESI	Digital Economy and Society Index
DPS	Digital public services
EU	European Union
FGLS	Feasible Generalized Least Squares
GDP	Gross domestic product
GII	Global Innovation Index
HC	Human capital
HCR	Human capital and research
IDT	Integration of digital technology
INF	Infrastructure
INS	Institutions
KTO	Knowledge and technology outputs
MS	Market sophistication
NEET	Neither in education nor employed
PCSE	Panel Corrected Standard Errors
SGI	Sustainable Governance Indicators
SIDI	Synthetic Indicator of Digitalization and Innovation
TOPSIS	Technique for Order Preference by Similarity to an Ideal Solution

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