

Evolution of the Digital Economy and Society Index in the European Union: A Socioeconomic Perspective

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Abstract: The rapid development of information and communication technologies (ICT) in recent years has brought about significant changes in many social sectors such as communication, economy, entertainment, and others. To define the key role that ICT plays in its development course, the European Union (EU) has developed a composite indicator, the Digital Economy and Society Index (DESI), to assess the digital policy performance of its Member States. In the current work, an attempt is made to evaluate the performance of the EU countries on the digital economy and society with respect to implemented EU digital policies by studying the five dimensions of the DESI for the years 2014–2019, using the corresponding DESI reports (DESI 2015 – DESI 2020). Moreover, the digital convergence among EU Member States, in terms of similarity of their performance in the five dimensions of the DESI by grouping them according to the optimal number of clusters, is also examined. Since the optimal number of clusters is two, EU Member States are classified in two groups, one of high and one of low performance in the five dimensions of the DESI. The evolution of each member country and the possible transitions from one group to another during the years 2014–2019 is also a point of interest. The grouping of EU Member States into the two clusters showed that socioeconomic factors may affect the overall DESI. Linear mixed effect models confirm the positive effect of Gross Domestic Product per capita, the public expenditure for education

and research and development (R&D) on the DESI and the negative effect of the average number of weekly working hours. The results could be used to reform the existing EU digital policies and identify areas where further improvement is needed.

Keywords: *digital economy, digital society, digital transformation, DESI, European Union, k-means clustering, linear mixed effect models*

1. Introduction

In recent years, the development of technology and networks has been rapid, and this has a direct impact on the evolution of society. Increasing exposure to new digital technologies has brought about significant changes in many social sectors, and the concept of digitization lies at the heart of all (Castells, 2009). Digitization and development of information and communication technologies are restructuring various aspects of social life such as work, business administration, communication, entertainment, education, and the economy (Parviainen *et al.*, 2022). Even in the field of education, a lot has changed, as learning can be provided without the physical presence of the teachers and/or students. The evolution of society through the development of new technologies and globalization processes is pushing the economy to undergo radical changes. The digital dimension of society and economy has been a huge advantage in COVID-19 lockdown, as without digital technologies, the economic hardships would have been even greater. The concept of digitization is dominating and, in combination with the development of ICTs, changing the way we work, communicate, entertain ourselves, and the way of life in general.

In March 2010, the European Union (EU) set forth the Europe 2020 Strategy for Smart, Sustainable and Inclusive Growth in order to lift Europe out of the economic crisis and prepare its Member States' economies for the challenges of the next decade (Communication COM(2010) 2020; Bánhidi, Dobos & Nemeslaki, 2020). To achieve this, specific actions were proposed. One of them is the Digital Agenda for Europe (DAE), which aims to define the key role that ICT will play in Europe's development. The DAE aims to strengthen European economy by providing sustainable economic and social benefits from a digital single market (DSM) (Communication COM/2010/0245 final). To that end, a communication and a recommendation

from the Commission were released in order to propose ways to update and improve the EU networks bringing the basic broadband to all Europeans by 2013 (Communication COM(2010) 472 final) and very fast internet by 2020 (Recommendation 2010/572/EU). Part of the DAE's targets were e-government and the re-use of public sector information, which are addressed in an action plan. It was set to exploit the ICTs to support the transition to a new generation of open, flexible, and collaborative e-government services and re-use of public data at local, regional, national, and European levels (Communication COM (2010) 743 final; Directive 2013/37/EU). The DSM is a prerequisite for EU's transformation towards the digital revolution of the 21st century (Troitiño, 2022). It is one of the EU policy priorities and provides businesses, particularly entrepreneurs, with new opportunities to scale up across Europe. It can expand markets and create opportunities for new start-ups, fostering better services at better prices and creating new sources of employment where advanced digitally skilled employees will be valuable (Communication COM/2015/0192 final). To strengthen human capital, a Communication was released in 2016, focusing on improving the quality and relevant skills formation by enhancing both basic and higher, more complex digital skills of citizens. More opportunities will be available when everyone is equipped with a broad range of skills (Communication COM/2016/0381 final).

As digital competence has become key for citizens to participate in today's social, economic and civic life, the Digital Education Action Plan, adopted in 2020, will reset education and training for the digital age (Communication COM/2020/624 final). In 2021, the EU presented its vision for a successful digital transformation of Europe by 2030, putting forward four cardinal points: digitally skilled citizens and highly skilled digital professionals, secure, performant and sustainable digital infrastructures, digital transformation of businesses and digitalization of public services (Communication COM/2021/118 final). Digital competitiveness in our new digital era is challenging and each EU member is required to invest in digital economy and society.

The European Commission has gradually developed several indicators to assess the digital performance of its Member States. One of the most popular indices is the Digital Economy and Society Index (DESI). The significant innovation of the DESI is that it represents an overall index that tracks the evolution of EU Member States' (Giannone & Santaniello, 2019). The DESI is a composite index consisting of five dimensions corresponding to five EU principal policy areas: Connectivity, Human Capital, Use of Internet

Services, Digital Technology Integration and Digital Public Services (European Commission, 2020a). It summarizes relevant indicators related to the EU digital performance and monitors the development of its Member States in the field of digital competitiveness. Since 2014, the DESI has been a key analytical tool for the annual measurement of EU countries' progress towards the digital economy and society (OECD, 2018).

As the DESI is the indicator that the EU uses to monitor the digital progress of its EU Member States in five dimensions, it undoubtedly plays a significant role in the decision-making process regarding the digital transformation of the EU. Many researchers used the DESI to study the digital progress of an individual country compared with the rest of EU members or with the average digital performance in the EU (Stoica & Bogoslov, 2017; Nagy, 2017; Moroz, 2017; Česnauskė, 2019; Russo, 2020), pointing out digital policies that should be formed to enhance the digital progress at the country level. Moreover, the DESI has been also studied at the EU level (Bogoslov & Stoica, 2019; Rakićević, Rakićević & Poledica, 2019; Bánhidi, Dobos & Nemeslaki, 2020; Borowiecki *et al.*, 2021; Sevgi, 2021; Liu, 2022; Andrei *et al.*, 2023) and the effect of several socio-economic factors on the DESI is also examined (Scupola, 2019; Stavitsky, Kharlamova & Stoica, 2019; Marino & Pariso, 2021; Andrei *et al.*, 2023).

The current work extends the previous literature in the field by studying the evolution in time of each DESI dimension during the whole period of 2014–2019, using Repeated Measures ANOVA to highlight statistically significant inter-year differences on each dimension. To that end, the five dimensions of the DESI are studied over a six-year period (2014–2019), using the corresponding DESI reports (DESI 2015 – DESI 2020). In the current work, an attempt is made to evaluate the performance of the EU countries on the digital economy and society with respect to the implemented EU digital policies. Moreover, the digital convergence among EU Member States in terms of similarity of their performance in the five dimensions of the DESI, by grouping them according to their optimal number of clusters, is examined. Another novelty of our study is that the optimal number of clusters is determined on the basis of 30 indicators (Charrad *et al.*, 2014). In addition, the countries' interchanges are also a point of interest. Finally, the impact of some important socioeconomic factors on the DESI was also studied using linear mixed effect models, allowing the incorporation of fixed and random effects into the models since the existing literature is rather limited (Scupola, 2019; Stavitsky, Kharlamova & Stoica, 2019; Marino & Pariso, 2021; Andrei *et al.*, 2023). In the current study, more factors were

selected to cover a wider area in the social and economic field, to represent the whole of society in a more comprehensive manner. More specifically, the effect of the Gross Domestic Product (GDP) per capita, the average number of weekly working hours, the unemployment rate, the consumption of renewable sources, the lack of corruption, the public expenditures on education and the percentage of gross domestic product spent on basic and applied research and experimental development on the overall DESI was studied. The results reveal the strengths and weaknesses in the countries' digital transformation that are of a great importance for policymakers at the national and European level to plan long-term policies.

The rest of the paper is organized as follows. The relevant literature on the DESI and its structure are presented in Section 2 and Section 3, respectively. Methodology and methods are discussed in Section 4. The main results are presented in Section 5 and the discussion and implications are presented in Section 6. Recommendations are provided in Section 7 and some concluding remarks in Section 8.

2. Literature review

The DESI has gained a lot of research attention in recent years as a global index capable of evaluating states' digital performances related to society and economy, and it has caught the attention of policymakers. The rest of this section presents the most recent related literature.

Bogoslov and Stoica (2019) studied the digital evolution of EU Member States during 2014–2019. They also examined the position of the EU at a global level, comparing the digital progress of the EU with non-EU countries. Rakićević *et al.* (2019) studied the overall index in the DESI 2018 report, using logical clustering to measure the proximity among countries forming five (5) groups. Their aim was to identify directions of digital policies to enhance each Member States' digital competitiveness, based on their proximity with the rest of the EU countries. Bánhidi *et al.* (2020) studied the correlations and partial correlations of the five dimensions in the DESI 2018 report. Moreover, they also grouped EU Member States in five (5) clusters, using hierarchical clustering. According to these results, adequate knowledge of the partial correlation between the dimensions of the DESI will help policymakers in decision-making process to improve competitiveness at local, regional, and European level. Sevgi (2021) used data from the

DESI 2020 report and, by applying the k -means algorithm, grouped the EU Member States into four (4) groups, according to their performance in the five dimensions of the DESI. They also examined whether there were similarities between these groups and the classification of the welfare state regimes by Esping-Andersen (1990) in South Europe (Kammer, Niehues & Peichl, 2012), Central and Eastern Europe (Lauzadyte-Tutliene, Balezentis & Goculenko, 2018). According to the welfare of EU Member States, there are six types of welfare regimes: the Social Democratic, Conservative, Liberal, Southern, Central, and Eastern Europe. Each type of welfare state is characterized by the political situation (eligible government or not), social situation (labor market, gender differences in the labor market, demographic situation, population education, living conditions), and financial situation (real GDP) of a country, also government programs provided to citizens. According to their results, comparing the DESI clustering and the first welfare regime, countries applying the social democratic welfare regime (Finland, Sweden, Denmark, the Netherlands, and Norway) are better prepared for the digitization of the economy and future digital competition compared to other EU countries, as they have higher values in all dimensions of the DESI index. They are followed by the countries of liberal welfare regimes (United Kingdom and Ireland), with a small difference from the first category, and by the countries of conservative welfare regimes (Germany, Luxembourg, Belgium, Austria, and France). Finally, the rest of the countries (Italy, Spain, Greece, Portugal, Croatia, Poland, Slovakia, Slovenia, Bulgaria, Estonia, Latvia, Lithuania, and Romania) belong in the last three categories and have the lowest values in all dimensions of the DESI and are more likely to face problems in the future in terms of technological transformation and digital competition with other EU countries.

Borowiecki *et al.* (2021) present the development of digital economy and society in the light of the digital convergence of EU markets using data from DESI 2015 and 2020 reports. They applied dynamic time series models to determine the dynamics of changes in DESI values and classified countries in terms of the similarity of DESI value, forming five clusters. Their results highlight the strengths as well as weaknesses in the Member States' digitization efforts to shape proper domestic governance and strengthen competitiveness in various areas of the economy. Liu (2022) intended to analyze the digital policy performance of EU countries based on the DESI and determined the similarities and differences between their digital performance using data from DESI 2017 report. A graphical analysis co-plot technique was used to categorize EU Member States based on the five DESI

variables, creating four groups. Based on this classification, policymakers will design appropriate policies to boost digitization and economic development at national level.

Scupola (2019) tried to investigate factors contributing to the digital transformation regarding digital public administration in Denmark. Using the longitudinal case study methodology, they concluded that low unemployment and well-educated population, revenues from exports and public administration which is supported by central government's policies, and political initiatives seem to be the key factors of success. Stavvytskyy, Kharlamova and Stoica (2019) studied the effect of per capita expenditures based on purchasing power parity and unemployment on each DESI dimension. A panel regression model was constructed for 28 EU countries, using DESI reports from 2014–2018. Their analysis confirmed that a more prosperous society leads to more advanced digital services. They concluded that there is a certain positive effect of economic development and a negative effect of unemployment on all DESI dimensions apart from Integration of Digital Technology.

Marino and Pariso (2021) studied the effect of four socio-economic factors on the DESI and on its dimensions in 2016–2018, performing a statistical regression analysis. They concluded that Social Progress, Corruption Perception, Global Innovation, and Doing Business indices positively affect DESI and most of its dimensions. Andrei *et al.* (2023) investigated the convergence of digitalization in the EU in terms of the DESI in each Member State during 2015–2020, taking into account indicators representing each country's economy. In their study, econometric models were used to estimate the σ and β convergence of the DESI. They also examined the effect of the gross value added and the education index during the convergence process. They concluded that, during the studied period, digital convergence was observed and that gross value added had a positive effect on the DESI, while education appeared not to be statistically significant.

The adding value of the current paper is the study of the digital performance of European countries and the evolution of digital competitiveness over a six-year period, from 2014 to 2019, using Repeated Measures ANOVA to highlight statistically significant inter-year differences on them. Moreover, EU Member States are grouped into the optimal number of classes based on 30 indicators applying the *k*-means clustering method. The stability of the grouping per year is also studied. Finally, several factors, such as income, the average number of weekly working hours, unemployment rate, consumption of renewable sources, lack of corruption, public expenditures on education,

and percentage of gross domestic product spent on basic and applied research and experimental development that may affect the DESI were studied. To that end, linear mixed effect models were utilized, which allow for fixed and random effects—an effective tool when there is dependence in the data.

3. The structure of the DESI

The DESI has a three-level structure, with five dimensions. Each dimension consists of subdimensions and these, in turn, of indicators. In total, the 5 dimensions consist of 12 sub-dimensions and these in total of 37 indicators. The **Connectivity** dimension examines both the demand and supply of fixed and mobile broadband. As to fixed broadband, it assesses the overall and ultrafast broadband (at least 100 Mbps), the availability of fast broadband access (next generation access (NGA), providing at least 30 Mbps), and the availability of very high-capacity fixed networks (VHCNs) while taking into account retail prices. Mobile broadband includes 4G coverage, mobile broadband adoption (3G and 4G) and 5G connectivity readiness indicator. Digital connectivity is considered a social right in the EU (European Commission, 2020b). The **Human Capital** concerns the digital skills of EU citizens, ranging from basic skills that enable people to participate in activities involving the use of digital devices and the internet consuming digital goods and services, to advanced skills such as those of ICT specialists (ICT service managers, professionals, and technicians) and ICT graduates that empower the workforce to develop new digital goods and services (European Commission, 2020d). The **Use of Internet Services** dimension measures the percentage of people who use internet services, and which of the available services they use. Activities include online content consumption (e.g., entertainment, such as music, movies, TV, or games, downloading multimedia-rich information, or engaging in online social interaction) using modern communication activities (e.g., participating in video calls) and activities transactions such as online shopping and banking (European Commission, 2020f). The **Integration of Digital Technology** dimension measures the digitization of businesses and e-commerce. Digital technologies allow businesses to be more competitive, improving their services and products and expanding their markets. The digital transformation of businesses opens up new opportunities and fosters the development of new and reliable technologies (European Commission, 2020e). Finally, the **Digital Public Services** dimension concerns both the demand and

supply of digital public services, as well as open data management policies (European Commission, 2020c).

To calculate the five dimensions of the DESI as well as the total DESI, the initial 37 indicators are standardized using the min–max method. The DESI is a weighted sum of the five aforementioned dimensions of the initial 37 indicators. Some dimensions and individual indicators are more important than others with respect to the priorities of EU digital policy and, therefore, have a greater effect on the calculation of the final DESI (European Commission, 2020a). The weights used in dimension level are Connectivity: 25%, Human Capital: 25%, Use of Internet Services: 15%, Integration of Digital Technology: 20%, and Digital Public Services: 15% (European Commission, 2020a).

4. Methodology and methods

The data used in the current study has been collected from the annual DESI 2015 – DESI 2020 EU reports. The annual DESI reports cover the period from 1 February of the previous year to 31 January of the following one. To determine the socioeconomic factors affecting the DESI for the period 2014–2019, data from both the European Statistical Office (Eurostat) and the World Open Data Bank (Word Data Bank) were used. Real Gross Domestic Product per capita (GDP) were retrieved from the World Open Data Bank and the consumption of renewable sources (RNRGconsumption), the lack of corruption (CORRlack), the percentage of GDP spent on basic and applied research and experimental development (GERD), the average weekly working hours (WORKINGhours), the percentage of GDP for pre-primary to tertiary education (EDUexpend), and the unemployment rate (UNEMPLOYMENT) were retrieved from Eurostat. The data refer to 28 countries that belonged to the EU in 2019, observed over a period of six (6) years. The statistical analysis was conducted using R (version 4.2.0) and all the tests were implemented at 5% significance level.

Initially, the main descriptive statistics of each of the five dimensions of the DESI are computed for the period 2014–2019. To study the evolution of the five dimensions of the DESI, first, the normality assumption of the data was tested by the Shapiro-Wilk normality test (Shapiro & Wilk, 1965). When the normality assumption was met, as in our case, the ANOVA test in a repeated measures design (Repeated Measures ANOVA) was utilized (Salkind, 2010).

When the null hypothesis of Repeated Measures ANOVA was rejected, a post-hoc analysis was performed to explore differences between all possible group pairs using Tukey's test (Tukey, 1977).

To group the EU Member States with respect to their performance in the five dimensions of the DESI, the k -means clustering method was implemented, as it is simple, fast, and efficient. Moreover, k -means leads to tighter clusters than the hierarchical clustering and it is easy to interpret the clustering results. As a measure of distance, the Euclidean distance was used. To determine the optimal number of clusters, NbClust package in R was used which "provides 30 indicators for determining the number of clusters and proposes to use the best clustering scheme from the different results obtained by varying all combinations of number of clusters, distance measures, and clustering methods" (Charrad *et al.*, 2014). The performance in the five DESI dimensions was compared between the two groups.

Finally, the effect of some main economic and social variables on the DESI was also examined. To that end, linear mixed effect models (LMM) were constructed, which are parametric linear models for repeated-measures data (West, Welch & Galecki, 2014). LMMs are an extension of simple linear models containing fixed and random effects in some analysis and are used when there is dependence in the data, such as repeated measurements on each subject over time, as in our case. The R's lme4 package (Bates *et al.*, 2015) was used to construct an LMM with the DESI as a dependent variable and the aforementioned socioeconomic factors as fixed effects. A model with fixed effect of years and a randomized intercept per country was initially constructed. The fitted model would be expressed as

$$y_i = X_i\beta + Z_ib_i + \varepsilon_i, i = 1, \dots, 28$$

$$b_i \sim N(0, \sigma_b^2), \quad \varepsilon_i \sim N(0, \sigma^2 I)$$

where

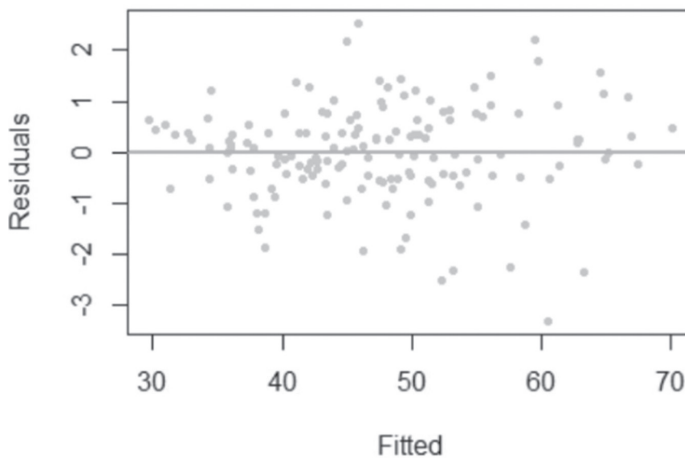
$$X_1 = \dots = X_{28} = \begin{bmatrix} 1 & 1 \\ 1 & 2 \\ \vdots & \vdots \\ 1 & 5 \end{bmatrix}, \quad Z_1 = \dots = Z_{28} = \begin{bmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix}.$$

The two-dimensional fixed-effect vector β consists of the mean intercept, β_1 , and the common slope β_2 . The one-dimensional random-effects vectors, b_i , $i = 1 \dots 28$ describe a shift in the intercept for each country. Due to there being a common slope, these shifts are preserved for all values of year. A model with random effects for both the intercept and the slope was also constructed (Model 2). The above two models were compared using the function anova in R (Chambers & Hastie, 1992), and Model 2 was selected

as optimal based on the Akaike criterion (Burnham & Anderson, 2004). In this model, independent variables were added (Model 3).

The basic assumptions of the model, such as independence of data points, absence of measurement errors, independence of random effects from explanatory variables, linearity, and homoscedasticity of residuals (Fig. 1), are satisfied. The normality of the residuals and random effects has not been tested since it has been shown that mixed models are very resistant to the violation of the normality assumption of the residuals and the random effects (Schielzeth *et al.*, 2020). The normality test of random effects is very difficult to implement as it requires additional assumptions for the model without which determining their distribution is impossible (Alonso, Litière & Laenen, 2010).

Figure 1. Residuals vs. fitted models



5. Results

5.1 Evolution of the DESI

The main descriptive statistics of each of the five dimensions of the DESI are presented in Table 1, where a steady upward trend through the dimensions of Connectivity, Use of Internet Services, Integration of Digital Technology, and Digital Public Services is observed over time. It is noticed that the median and average performance of the above dimensions are steadily increasing every year. Moreover, it is evident that the median of the Human

Capital dimension remains stable in the first years and then an increase from 2018 is observed. Regarding the standard deviation, it remains stable in the Connectivity dimension, while decreasing steadily in the Digital Public Services dimension. For the rest of the dimensions, the standard deviation is stable at the beginning, whereas towards the end of the studied period, an increase is observed.

Since the five dimensions of the DESI fulfil the normality assumption, Repeated Measures ANOVA was performed for each dimension and a statistically significant difference in the average performance is observed in all dimensions of the DESI during the studied period. The Tukey's test, which was implemented next, determined between which years these statistically significant differences were observed.

As mentioned above, **Connectivity** evolves very quickly over time, which was also confirmed by the corresponding Tukey tests (Table 2), as in all DESI reports from 2015 to 2020, there is a statistically significant difference to the average performance of EU Member States in this dimension, from year to year. No statistically significant difference in the average performance of EU Member States was observed in the **Human Capital** dimension between the DESI 2015, 2016, and 2017 reports. A statistically significant difference appeared for the first time between the DESI 2017 – DESI 2018 reports, and between the DESI 2019 – DESI 2020. A delay in the appearance of a statistically significant difference between the average performance of the **Use of Internet Services** dimension in the EU Member States was also observed, as it appeared from the DESI 2018 report onwards. A statistically significant difference was observed in the average level of the **Integration of Digital Technology** dimension almost every second year. An exception is the year 2015, where there is a statistically significant difference from the very next year. A statistically significant difference was observed in the average performance of EU Member States in the **Digital Public Services** dimension in all DESI reports from 2017 to 2018, while it was first observed in the DESI reports from 2015 to 2016.

5.2 Clustering

The results of the NbClust package suggest that the optimal number of clusters is two (2) for each year. Figure 2 shows, by year, the map of Europe where the countries with high performance in the DESI are highlighted in darker grey (cluster1) and the countries with low performance in light grey (cluster2). Countries such as Belgium, Denmark, Estonia, Finland, Ireland,

Malta, Netherland, Sweden, and the United Kingdom have maintained a high level of performance in the DESI over the years. On the other hand,

Table 1. Descriptive statistics of the five dimensions of the DESI for the period 2015–2020.

DESI dimen- sions	year	mean	stdev	min	Q1	median	Q3	max
Connectivity	2015	39.9174	7.7814	23.23	35.14	39.6486	46.16	54.19
	2016	42.2325	7.4879	24.82	37.44	41.6606	47.98	56.38
	2017	43.9315	7.1306	30.12	38.55	42.8125	50.13	56.04
	2018	46.7801	7.6538	28.14	43.66	45.8654	52.23	52.23
	2019	48.5581	7.0797	32.22	44.78	48.3406	52.74	60.64
	2020	53.6205	7.7477	36.43	48.93	52.6956	60.8	65.95
Human Capital	2015	45.5404	11.4415	28.11	36.18	44.406	54.55	73.6
	2016	44.7214	11.4165	27.12	34.62	43.5734	55.16	72.7
	2017	45.5353	11.5996	26.99	34.75	43.6286	54.7	73.92
	2018	47.3008	11.8119	31.15	36.81	44.9486	56.39	75.38
	2019	47.8184	12.4603	28.23	37.37	45.7846	57.07	76.76
	2020	49.2868	12.6325	32.13	37.02	48.0113	59.91	77.66
Use of Internet Services	2015	44.5937	6.4921	30.97	39.21	43.4983	50.66	57.37
	2016	45.1928	6.7067	31.48	39.99	45.8058	51.52	56.6
	2017	45.7061	6.9835	30.48	40.51	45.3347	51.93	59.89
	2018	47.5729	7.3865	33.64	42.44	46.1701	53.69	62.11
	2019	49.4192	7.8195	34.14	44.72	47.4025	54.37	64.58
	2020	51.0165	8.0533	33.09	46.31	50.1588	56.03	65.3
Integration of Digital Technology	2015	33.2732	10.6554	16.56	26.21	31.4885	40.91	51.72
	2016	36.0594	11.8749	16.57	27.69	34.7421	45.17	60.61
	2017	36.6312	10.2904	18.38	29.27	35.4833	46.19	57.6
	2018	38.7205	11.9113	18.27	29.2	38.0323	47.08	63.18
	2019	40.9177	13.7662	16.85	30.85	39.3795	49.45	68.8
	2020	43.4246	15.021	17.81	31.46	40.8778	53.87	73.97
Digital Public Services	2015	58.9803	16.4951	28.58	45	59.4677	72.49	85.39
	2016	63.0707	16.0617	32.77	49.3	64.1562	75.9	88.54
	2017	64.5462	14.3618	38.25	54.19	64.1392	77.57	87.03
	2018	67.2339	13.0767	45.04	58.69	67.231	79.37	87.62
	2019	69.9412	12.2691	47.17	61.66	68.4749	81.54	87.53
	2020	72.12	11.5488	48.41	63.38	72.7364	80.93	89.33

Table 2. Tukey pairwise comparisons (p-values) five dimensions of the DESI for the period 2015–2020.

DESI dimensions	year	2015	2016	2017	2018	2019
Connectivity	2016	0.0008				
	2017	<.0001	0.0315			
	2018	<.0001	<.0001	<.0001		
	2019	<.0001	<.0001	<.0001	0.0208	
	2020	<.0001	<.0001	<.0001	<.0001	<.0001
Human Capital	2016	0.4031				
	2017	1	0.4105			
	2018	0.001	<.0001	0.001		
	2019	<.0001	<.0001	<.0001	0.8341	
	2020	<.0001	<.0001	<.0001	0.0001	0.0106
Use of Internet Services	2016	0.8109				
	2017	0.1924	0.8918			
	2018	<.0001	<.0001	0.0021		
	2019	<.0001	<.0001	<.0001	0.0024	
	2020	<.0001	<.0001	<.0001	<.0001	0.0138
Integration of Digital Technology	2016	0.0173				
	2017	0.0018	0.985			
	2018	<.0001	0.0268	0.1484		
	2019	<.0001	<.0001	<.0001	0.1115	
	2020	<.0001	<.0001	<.0001	<.0001	0.0445
Digital Public Services	2016	0.0001				
	2017	<.0001	0.5168			
	2018	<.0001	<.0001	0.0245		
	2019	<.0001	<.0001	<.0001	0.0229	
	2020	<.0001	<.0001	<.0001	<.0001	0.1173

Bulgaria, Cyprus, Greece, Czechia, Croatia, Hungary, Italy, Luxemburg, Poland, Romania, Slovenia, and Slovakia remain consistently at a low level of performance. Countries such as Spain, Lithuania, Portugal, and Austria maintain high levels of performance for long periods of time, whereas in 2020, they transpire with a low performance level. Finally, there are countries such as France, Latvia, and Germany that do not maintain a steady course over the years and alternate between low- and high-performance group of the DESI.

Figure 2. Cluster Maps of EU Member States based on the five dimensions of the DESI. The countries with high performance in DESI are highlighted in dark grey and the countries with low performance in light grey.

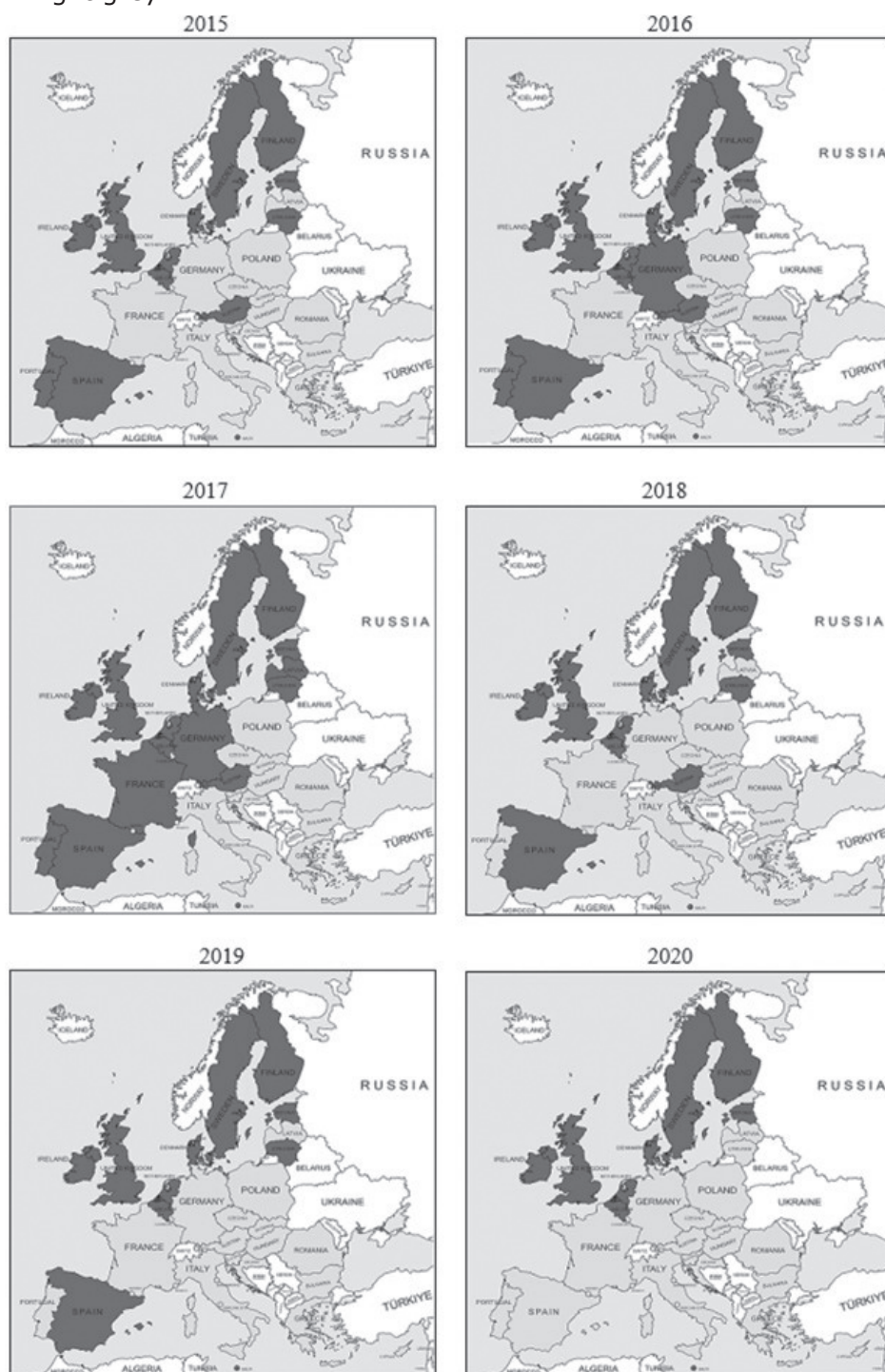
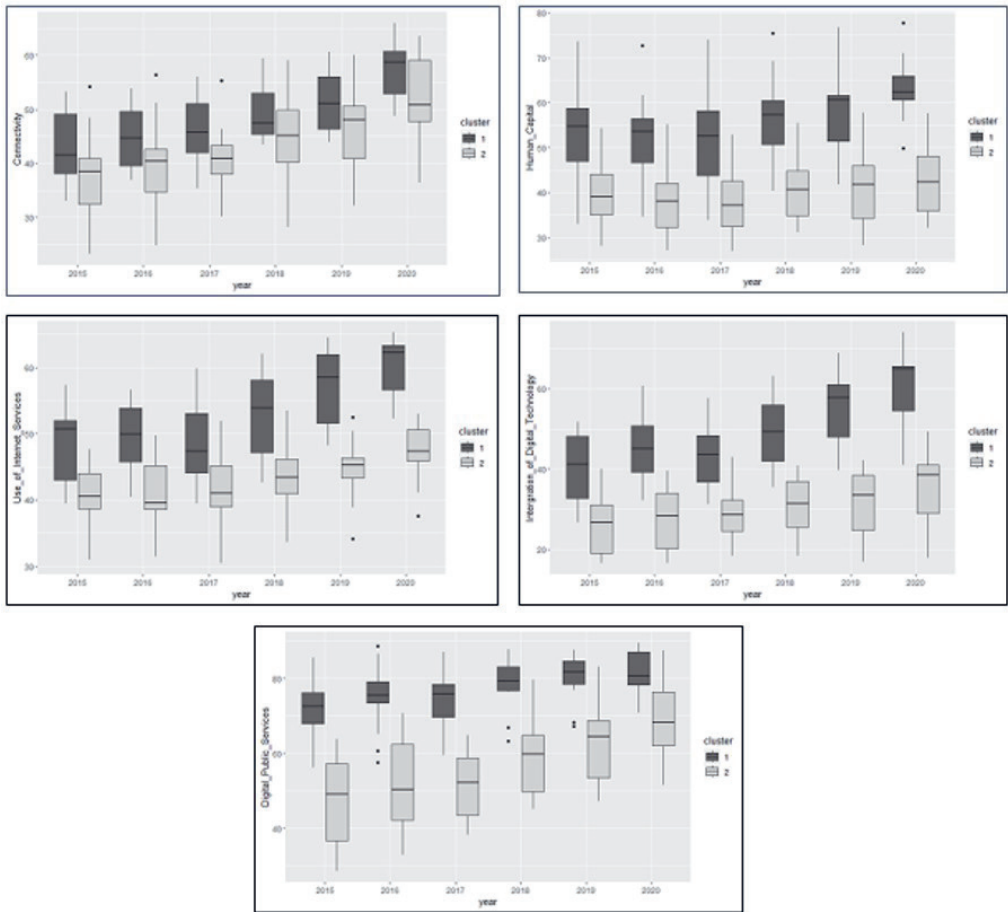


Figure 3. Boxplots of five DESI dimensions in cluster 1 and 2.



Additionally, a statistically significant difference is observed in the mean performance on four of the five dimensions of the DESI between the two groups each year. The boxplots of the course of the five DESI dimensions in the two groups are depicted in Figure 3. The Connectivity dimension in both clusters follows the same course with very small differences in the median values. The Human Capital seems to have no development in the countries of the second cluster during the studied period, contrary to the countries of the first cluster which show a significant development, especially in the last years. The Use of Internet Services seems to have a faster development in the countries of the first cluster which is also the case of the Integration of Digital Technology. However, the difference that exists between the two

clusters regarding the evolution of these dimensions is clear. For the Digital Public Services dimension, the countries of the second cluster are quite behind compared to the countries of the first cluster.

5.3 Impact of the socioeconomic factors on the DESI

Using LMMs, two models were formed, one with fixed effect of years and a randomized intercept per country and the other with random effects for both the intercept and the slope. The two models were compared using AIC and Model 2 was selected as the optimal (Model 1: AIC 674.84, Model 2: AIC 669.12). In this model, independent variables were added (Model 3). In model 3, the variables, RNRGconsumption (p-value = 0.58), UNEMPLOYMENT (p-value = 0.76) and CORRLack (p-value = 0.7) are not statistically significant and were sequentially removed from the model that leads to the final one (Model 4). It is observed that all factors have a statistically significant impact on the DESI in Model 4 (Table 3). The average DESI increases by 1.72 per year for constant values of the variables GDP per capita, average working hours, education expenditure, and R&D expenditure, and by 1.99 for each unit of GDP per capita growth for constant values for the rest of parameters. It also increases by 0.81 for each unit of increase in the percentage of education expenditure and by 1.99 for each unit of increase in the percentage of R&D expenditure, while it decreases by 1.57 for each unit of increase of the average working hours provided that the values of the remaining explanatory variables of the model remain constant.

Table 3. Model 4: Final model.

Model 4	Est	S.E.	t-value	p	Random Effect Std. Dev
Intercept	41.40	0.85	48.95	0.00	1.03
YEAR	1.72	0.08	21.32	0.00	
GDP	1.99	0.78	2.56	0.01	
WORKINGhours	-1.57	0.68	-2.30	0.02	
EDUexpend	0.81	0.39	2.09	0.04	
GERD	1.99	0.60	3.32	0.00	

6. Discussion and implications

Considering the **evolution in the five DESI** dimensions for EU-28, the digital evolution of EU Member States is monitored under EU digital policies, established since 2010 by the DAE (Communication COM/2010/0245 final) and Europe Strategy 2020 (Communication COM(2010) 2020). Our findings show a clear increasing trend of the five dimensions of the DESI over time. However, some dimensions are evolving faster than others. The **Connectivity** dimension is the basis that will give the necessary space for the other dimensions to unfold, as it concerns the technological infrastructure but also the supply and demand of technological benefits. It evolves very quickly over time. EU digital policies seem to fulfil their goal in terms of infrastructure, bringing the basic broadband to all Europeans (Communication COM(2010) 472 final; Recommendation 2010/572/EU). Although the technological infrastructure appears to be present, the **Human Capital** and the **Use of Internet Services** dimensions, related to digital skills and using internet services, respectively, are delayed. It is likely that the population may need time to get acquainted with the new technology, to understand how they could use it and get familiar with internet services such as digital communications and transactions, this is also the case for Borowiecki *et al.* (2021) and Grigorescu *et al.* (2021). The **Integration of Digital Technology** dimension shows signs of improvement every second year. It is commonly recognized that a reasonable timeframe is required for the e-commerce and the digital transformation of businesses to take place. To formulate and implement a digital transformation strategy is a time-consuming task (Chanias, Myers & Hess, 2019). Finally, due to the priorities set by each country, whether it focuses on the modernization of its national portals or on an open data policy, the development trajectory of the **Digital Public Services** dimension is disrupted. The organizational and the technical support in e-government systems is rather challenging (Al-Sebie & Irani, 2005).

Furthermore, the EU Member States were grouped in two clusters based on their performance in the five dimensions of the DESI, contrary to Rakićević, Rakićević and Poledica (2019), Bánhidi, Dobos and Nemeslaki (2020), Borowiecki *et al.* (2021) and Sevgi (2021) and Liu (2022), where they formed five and four clusters, respectively. A cluster consisting of countries with high performance (cluster1) and a cluster of countries with low performance (cluster 2) in all dimensions of the DESI were formed. Considering that the North-European countries are more digitally developed compared to

the rest of the EU countries, these results are not surprising (Castells & Himanen, 2002; Sevgi, 2021; Andrei *et al.*, 2023). Over the six-year period of our study, some countries alternate from one group to another. This is due to the different pace at which each country is evolving in relation to the rest. This is also confirmed by other researchers (Kyriakidou, Michalakelis & Spicopoulos, 2011; Borowiecki *et al.*, 2021). In addition, our results indicate that the grouping of EU-28 is not affected by the Connectivity dimension even though it evolves quickly and steadily over the studied period. It is revealed that the Connectivity dimension in both clusters follows the same trajectory. However, all the other dimensions are evolving faster in high performance countries than in low performance. Countries in cluster 1 have higher values in all dimensions of the DESI, as they are better prepared for the digitization of the economy and future digital competition compared to countries in cluster 2, as Sevgi (2021) has also indicated.

Finally, it is observed that the division into two clusters also matches the economic profile of the countries. According to the **proposed model**, the DESI is indeed significantly positively affected by GDP, as Scupola (2019), Stavytskyy, Kharlamova and Stoica (2019), and Andrei *et al.* (2023) have also concluded. The most economically developed countries seem to invest more in the digital transformation of both the economy and society (Castells & Himanen, 2002; Sevgi, 2021; Andrei *et al.*, 2023). Moreover, the DESI is positively affected by educational expenditures, as Scupola (2019) also suggests in contrast to Marino and Pariso (2021). Countries which invest more in education from pre-primary to tertiary level seem to have better digital performance, which is also the case for countries which spend a greater percentage of GDP on basic and applied research and experimental development. A decrease in the DESI values is observed as the average number of usual weekly working hours in main job increase. While the working hours are on the rise, population have less time to get acquainted with the new technology either for training or to be involved in other leisure activities. Regarding the other studied factors—the unemployment rate, the consumption of renewable sources and the lack of corruption—it is found that they do not have a statistically significant impact on the DESI in the current study.

7. Recommendations

As the DESI is the core index, used by the EU to assess the digital progress of its Member States, policymakers may rely on it to form appropriate digital policies at international, regional, and national level to strengthen the countries' digital transformation.

As indicated, the Connectivity dimension evolves very rapidly over the six-year period, while both Human Capital and Use of Internet Services keep following the evolution of the Connectivity dimension, even with a two-year delay. The Integration of Digital Technology and Digital Public Services dimensions do not show a rapid evolution. More effective strategies should be implemented to strengthen the more slowly evolving dimensions. Moreover, policymakers at global and domestic level should focus on the countries in cluster 2 to encourage their digital transformation. Long-term policies and supportive initiatives need to be implemented to foster digital transition, considering each country's characteristics. Our research has identified factors that affect the DESI. This knowledge is used by policymakers to develop appropriate policies to promote digital transformation.

Policies towards the enhancement of citizens' basic and advanced digital skills need to be implemented to close the digital division across EU Member States (Janssen, Charalabidis & Zuiderwijk, 2012; Grigorescu *et al.*, 2021). The related Communication released in 2016 does not seem to fulfil its target (Communication COM/2016/0381 final). Policymakers have to carefully design digitally based strategies in order to provide appropriately focused learning programs at basic and advanced digital skills. In addition to face-to-face education, distance education could be improved. Also, the gender and the age of citizens should be taken into account so that educational training will be inclusive and accessible to everyone. The Digital Education Action Plan was adopted in 2020 to enhance Human Capital and Use of Internet Services as these dimensions fell behind during the DESI evolution (Communication COM/2020/624 final). In the new digital era, acquiring the relevant knowledge will make citizens active participants, who are able to use internet services such as e-banking, video calling, online shopping, or social interaction. In addition, policies should be designed to foster business and public services digitalization. The digitization of business processes for products and services has helped companies to be more flexible in competitiveness. However, there is still a need to enhance the use of digital technologies such as digital platforms (Apple's iOS and Google's Android platform) and infrastructures (cloud computing, data analytics,

online communities, social media, 3D printing, digital marketspaces) in business digital transformation (Nambisan, 2017). Digital Public Services is also a dimension left behind on the evolution path. Strategies for digital governance, such as transparency and openness of government processes to the public, should be developed. DSM also prompts the need for international cooperation with other governments to better serve citizens and businesses across borders (OECD, 2014). In addition, attention must be given to open data policies regarding reusable and available data in national data portals (Janssen, Charalabidis & Zuiderwijk, 2012).

8. Conclusion

The evolution of the society through the development of new technologies and globalization processes is pushing the economy into radical changes. Digital competitiveness in the new digital era is challenging and investing in the digital economy and society is required of every EU member. Since 2010, the EU has put in place strategies, action plans, communications, and recommendations related to digital advances, with the aim to support EU Member States on their path in digitalization and digital convergence. The EU introduced the DESI in 2014 as a key analytical tool for the annual measuring of EU countries' digital progress. The DESI is used to evaluate and shape Europe's digital policy towards the digital convergence of all EU countries, as it is presenting the digital performance of each Member State.

In the current work, the evolution of the five dimensions of the DESI for the period 2014–2019, using the respective reports DESI 2015 to DESI 2020 was studied. Our study was conducted in the light of how policymakers at national or global level may be influenced by the DESI in their decision-making processes. The results revealed the current state of EU Member States' digital performance and highlighted the strengths and weaknesses in the digital progress. Also, the EU Member States were grouped based on their performance in the five dimensions of the DESI and factors that affect the overall DESI were examined. Two groups were created, one including countries with high and one with low performance on the DESI. Finally, socioeconomic factors such as GDP, EDUexpend, and GERD have a positive effect on the DESI, while the WORKINGhours have a negative effect. Our research may help policymakers worldwide to develop innovative strategies in facing digital economy challenges.

For a more detailed study of the DESI, other socioeconomic factors could be incorporated in the proposed model and more complex models with interactions could be studied. As the digital economy is a global concern, a review of digital performance of the EU on a global level could be also studied. A study of the International Index of Digital Economy and Society (I-DESI) would help in that direction.

Modern society and economy are changing as ICT has developed rapidly in recent years. When taking into consideration the new needs for work, leisure, communication, education, and online shopping, arising from the COVID-19 pandemic, it is commonly recognized how urgent it is for the EU to monitor, understand, and follow the digital evolution.

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