

DIGITAL PROGRESS AND CONVERGENCE IN EUROPE: A CLUSTER ANALYSIS OF DIGITAL ECONOMY AND SOCIETY INDEX DIMENSIONS FROM 2016 TO 2020

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DOI: 10.7906/indecs.23.6.10
Regular article

Received: 27 August 2025.
Accepted: 8 December 2025.

ABSTRACT

The Digital Economy and Society Index (DESI) assesses the digital progress of selected European countries based on five main dimensions: connectivity, human capital, internet usage, digital technology integration, and digital public services. Since 2014, the European Commission has published annual DESI reports to track the digital development of EU Member States.

This study employs a cluster analysis to examine changes in DESI scores from 2016 to 2020 and to evaluate digital convergence across the selected European countries. It seeks to identify disparities in digital growth and determine whether less developed countries are narrowing the gap with more advanced ones, recognizing the pivotal role of digitalization in driving economic growth and technological adaptation.

The results indicate that digital development has generally improved across the examined European countries, with the most significant progress observed in technologically advanced Scandinavian states. Although southern and eastern countries remain behind, all have experienced growth in digitalization since 2016. The study concludes that accelerating digital transformation through effective policy measures is crucial to enhancing socioeconomic development and fostering digital progress throughout Europe.

KEY WORDS

digital divide, DESI index, European countries, cluster analysis, digital progress

CLASSIFICATION

JEL: D83, L86, M15, O14

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INTRODUCTION

The rapid advances of information and communication technologies (ICTs) have become a key driver of economic growth and social development, accelerating the economy's and society's transition to digitalization [1]. The digitalization of economies and societies inevitably shapes the future trajectory of all countries. Technological transformation and digitalization at the socio-economic level advance at varying speeds, slower in some countries and faster in others. The primary determinant of this pace is the set of policies and investments a country implements in the digital domain [2].

The digital transformation of society and economy plays a key role in shaping the economic potential and technological adaptability of European countries. Yet, significant and concerning inequalities in ICTs access and usage present risks to this transition [3, 4]. The term digital divide (DD) refers to these gaps in ICTs availability, usage, and the capacity of individuals and economies to engage in the global information society [5].

To systematically track and assess this transformation, the European Commission introduced the Digital Economy and Society Index (DESI), a composite indicator that evaluates five key dimensions: Connectivity, Human Capital, Use of Internet Services, Integration of Digital Technology, and Digital Public Services [6]. Since 2014, DESI has served as a main tool for measuring digital progress, supporting evidence-based policymaking, and identifying areas for strategic intervention [7].

This study explores the evolution of DESI scores across selected European countries between 2016 and 2020, a period marked by increasing digitalization efforts and policy emphasis on closing the digital divide. Through a combination of cluster analysis and Pearson correlation, the research aims to uncover patterns of digital convergence and divergence among countries.

Findings reveal that, although selected European countries have made measurable progress in digital development, Scandinavian nations consistently lead in all five DESI dimensions, establishing themselves as benchmarks in digital innovation. In contrast, Eastern and Southern European countries continue to lag behind, despite showing notable improvements over time. The digital divide remains a significant challenge, with disparities not only between countries but also within them – underscoring the need for sub-national analysis and tailored policy responses [8].

The cluster analysis applied in this study identifies distinct groups of countries based on their digital performance trajectories, highlighting limited signs of convergence [9]. While some countries have advanced rapidly, the catch-up effect among lagging nations appears weaker than anticipated, raising concerns about the effectiveness of current digital policies.

This study examines changes in the Digital Economy and Society Index (DESI) from 2016 to 2020 to assess how European countries are progressing toward digital convergence. It focuses on identifying differences in digital development across European countries and evaluating whether less advanced countries are narrowing the gap with leading performers, recognizing digitalization as a key driver of economic growth and technological advancement. This article contributes to the ongoing discourse on digital transformation in European countries. The implications of the findings are important for the future, suggesting that unless targeted efforts are intensified, the digital gap may continue to widen, threatening the European countries' goals of economic cohesion and technological leadership.

The article consists of seven sections. After the Introduction, there are two sections regarding the digital divide and the DESI index. The fourth section is Methodology and includes subsections Data and Statistical analysis. In the fifth section, results are presented. Discussion is presented in the sixth section. The last section concludes the article.

DIGITAL DIVIDE

The concept of the digital divide emerged in the 1990s to describe disparities in access to and use of computers and the Internet. Early studies focused on infrastructure, availability, and affordability, while modern research evaluates information and communication development through indicators such as market penetration, household and business use, education, and e-government [10, 11].

Differences in access to and use of ICTs are commonly referred to digital divide [12]. In other words, the digital divide refers to inequalities between individuals, organizations, regions, and countries in accessing and using information and communication technologies, often linked to social, demographic, and economic factors. It is a key indicator of disparities within the global information society, influencing both economic growth and technological advancement [5, 13]. Multiple factors have been identified as contributing to the digital divide, including poverty, limited literacy, lack of interest or motivation to engage with technology, and restricted access to it [14]. These challenges exist worldwide, making the digital divide a global concern. Barriers to technology access often stem from high costs, inadequate broadband coverage, poorer accessibility for individuals with disabilities, and reliance on lower-performing devices such as outdated computers or tablets [15].

Both developed and developing nations strive to build inclusive information societies to improve the quality of life and stimulate growth. However, unequal progress creates significant differences in information and communication technologies adoption [6]. In the European countries, initiatives like eEurope 2005, following the Lisbon strategy – the 2010 digital agenda for Europe that continues with the Strategy on shaping Europe’s digital future in 2020 that led to Digital Decade policy programme with concrete targets and objectives for 2030 for Europe’s digital transformation aimed to promote modern online public services [16, 17]. However, studies confirm persistent gaps, especially between older EU members and newer entrants. In the last document, the Digital Decade policy programme for 2030 focuses on digital transformation in the area of business, government, skills, and infrastructure [18].

Interestingly, some older members lag in ICT use, while certain newer states outperform them.

Closing the digital divide is central to the EU Digital Agenda, which seeks to maximize ICT’s social and economic impact, particularly in business. Information and communication technologies adoption boosts productivity, competitiveness, and structural innovation, with enterprises gaining opportunities to connect globally and integrate into larger supply chains [19, 20].

MEASURING DIGITAL DIVIDE USING DESI INDEX

Several composite indices, including the Digital Divide Index, Digital Access Index, Network Readiness Index, and DESI index, have been developed to measure digital divide gaps. In this article, data regarding the DESI index dimension for the years 2016 and 2020 are used in order to better understand differences among selected European countries and to investigate progress after five years.

The European Commission created the multifaceted composite index known as the Digital Economy and Society Index (DESI) to assess and contrast the digital performance of EU member states. The DESI index compiled data on Europe’s digital performance and monitored the advancements of EU member states. To comprehend and research digital development in Europe, it tracks advancements in five key areas: connectivity, human capital, internet service usage, digital technology integration, and digital public services [1]. The Human Capital dimension examines factors such as citizens’ basic and advanced digital skills, the proportion of information and communication technologies (ICTs) specialists in the workforce, and the number of ICT graduates. Connectivity assesses the quality, coverage, and capacity of

broadband networks, including both fixed and mobile infrastructure, as well as readiness for future technologies. Use of Internet Services captures the extent to which individuals engage in online activities such as e-commerce, communication, media consumption, banking, and other internet-enabled behaviors. Integration of Digital Technology focuses on the adoption of digital tools in enterprises, including cloud computing, e-invoicing, artificial intelligence, big data analytics, and online commerce. Digital Public Services evaluates the availability and uptake of e-government tools, such as pre-filled online forms, open data initiatives, and electronic communication with public administrations [6].

The findings serve as a reference for public institutions, regional authorities, and politicians as they develop evidence-based digital plans, allocate funds, and assess advancements at the national and EU levels. Finland had the best overall DESI score in 2022 (about 69,6), higher than the EU average of 52,3. Denmark came in second, with a strong Connectivity score, and Estonia was first in Digital Public Services [21]. While Denmark's edge comes from sophisticated broadband infrastructure, Finland's dominant position is ascribed to its high levels of digital proficiency, widespread use of e-government, and robust integration of digital technology in business [22]. In previous years, like 2015, Finland and Denmark often dominated DESI results, but in 2020, based on 2019 data, Finland once again topped the rating, followed by Sweden, Denmark, and the Netherlands.

Wide-ranging effects of DESI include improved inclusiveness, a decrease in digital divides, the digital transformation of SMEs, and the modernization of public services. In order to connect its measures with the EU's 2030 digital ambitions, DESI has been incorporated into the State of the Digital Decade framework since 2023. With over 26% of national funds designated for digital transformation, one observable result has been the allocation of significant investment through the Recovery and Resilience Facility. The recalculation of previous rankings and modifications to DESI's structure throughout time show a continuous improvement in methodology and conformity with changing EU digital policy priorities [23].

METHODOLOGY

The methodology in the article consists of two parts. In the first part, the collected data will be presented. Data include DESI index values for the years 2016 and 2020 for the 28 European countries. In the second part, statistical analysis, which includes descriptive analysis and a Pearson correlation matrix together with cluster analysis, will be defined.

DATA

Data were collected from the Digital Economy and Society Index (DESI) for the years 2016 and 2020 for the 28 European countries (Denmark, Estonia, Finland, Netherlands, Sweden, Germany, Latvia, Luxembourg, United Kingdom, Austria, Belgium, Czech Republic, France, Ireland, Lithuania, Malta, Portugal, Slovenia, Spain, Bulgaria, Croatia, Cyprus, Greece, Hungary, Italy, Poland, Romania, and Slovakia). Table 1 presents a variable list that contains five DESI dimensions. There are five main DESI dimensions: *Connectivity*, *Human Capital*, *Use of Internet Services*, *Integration of Digital Technology*, and *Digital Public Services*. According to its index structure, DESI adopts basic weighted arithmetic averages as part of a bottom-up aggregation strategy to assess the EU's digital progress.

Table 1. Variable list – DESI dimensions.

DESI dimension	Variable name	Time coverage
Connectivity	desi_1_conn	2016 and 2020
Human Capital	desi_2_hc	2016 and 2020
Use of Internet Services	desi_3_ui	2016 and 2020
Integration of Digital Technology	desi_4_idt	2016 and 2020
Digital Public Services	desi_5_dps	2016 and 2020

DESI *Connectivity* Dimension is determined by calculating a weighted average of five components: (i) Fixed broadband take-up (25%), (ii) Fixed broadband coverage (25%), (iii) Mobile broadband (35%), (iv) Broadband price index (15%). DESI *Human Capital* Dimension is based on a weighted average of two components: (i) Internet user skills (50%), (ii) Advanced skills and development (50%). DESI *Use of Internet* Dimension is assessed using a weighted average of three components: (i) Internet usage (25%), (ii) Online activities (50%), (iii) Online transactions (25%). DESI *Integration of Digital Technology* Dimension is calculated from a weighted average of: (i) Business digitalisation (60%), (ii) E-commerce (40%). DESI *Digital Public Services* Dimension is measured solely based on the score of E-Government.

STATISTICAL ANALYSIS

Descriptive and cluster analysis were used to examine the data that were collected from the DESI index for the years 2016 and 2020. First, a descriptive statistical analysis was undertaken on the characteristics of 28 European countries, aiming to better understand the differences between selected countries. The mean, minimum, maximum, standard deviation, and correlation analysis are used to describe the results of descriptive analysis for the years 2016 and 2020. Column graphs were used to present the collected data for 28 European countries. Examining descriptive statistics provides the basis for conducting cluster analysis.

Cluster analysis was employed to identify homogeneous groups of selected European countries based on collected variables. Variable selection was theoretically guided, with attention to maintaining an appropriate ratio between the number of variables and the sample size.

Given the large number of possible data partitions, a non-hierarchical clustering approach was adopted. The k-means algorithm was selected due to its computational efficiency and widespread use in empirical research [24]. In k-means clustering, initial centroids are specified in a p-dimensional space, and countries are assigned to the nearest centroid using squared Euclidean distance. Centroids are then iteratively recalculated, and units are reassigned until no further membership changes occur, yielding a stable solution [25].

To determine the optimal number of clusters, a v-fold cross-validation procedure ($v = 10$) was applied [26]. The dataset was divided into ten subsamples; each was omitted in turn while the remaining subsamples were used to predict its values. The average prediction error across folds was compared across competing solutions, and the solution with the lowest error was selected. To ensure interpretability, the number of clusters was restricted to the range of 2 to 25, and a solution with $k + 1$ clusters was retained only if it improved the error function by at least 5% relative to the k-cluster solution [27]. Descriptive statistics were first computed for 28 European countries to provide a basis for clustering. All analyses were conducted using Statistica 13.1. All 28 selected European countries were divided into four clusters based on DESI index values for the year 2016, and into three clusters for the year 2020, according to the results of a cluster study.

Cluster analysis has been shown to be an effective method in educational and social research for identifying meaningful patterns in behavioural, motivational, and structural data. Its application here enables the systematic classification of European countries based on the chosen indicators.

RESULTS

Results of the conducted statistical analysis include descriptive analysis results and cluster analysis results. Descriptive analysis results focus on five DESI index dimensions and differences for 28 selected European countries for the years 2016 and 2020. The Pearson correlation matrix presents a possible significant correlation between five DESI index

dimensions. A non-hierarchical statistical cluster analysis was applied to classify the selected European countries, for both years (2016 and 2020), in order to see progress and differences between countries for the period of five years.

DESCRIPTIVE ANALYSIS

The column graph compares the DESI Connectivity dimension scores for 27 EU member states and the UK for the years 2016 and 2020, Figure 1.

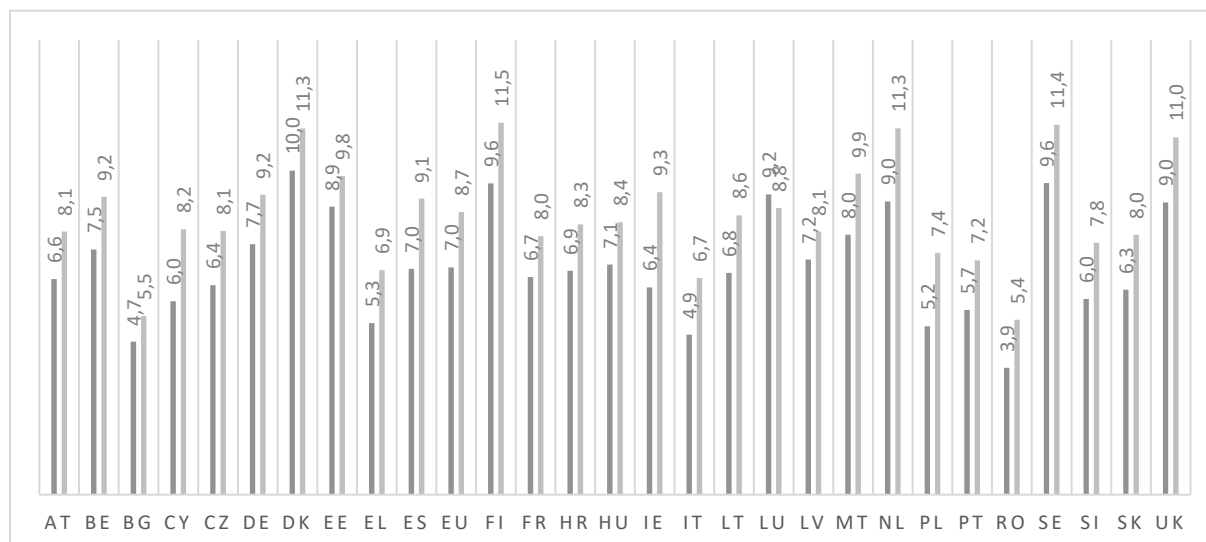


Figure 1. Connectivity in European countries – 2016 (dark grey) and 2020 (light grey).

Values for the DESI Connectivity dimension range from approximately 3,0 to 12,0. According to the given results, all countries show improvement in DESI Connectivity values from 2016 to 2020. The highest value of the DESI index for *Connectivity* dimension in 2020 have: Denmark (DK): 11,3, Netherlands (NL): 11,3, Sweden (SE): 11,4, Finland (FI): 11,5, United Kingdom (UK): 11,0. The lowest values of DESI index in 2020 have: Greece (EL): 6,9, Italy (IT): 6,7, Romania (RO): 5,4, Bulgaria (BG): 5,9, Poland (PL): 7,4. Largest relative improvements could be seen for Greece (EL): from 5,3 (2016) to 6,9 (2020), Romania (RO): from 3,3 (2016) to 5,4 (2020), Italy (IT): from 4,9 (2016) to 6,7 (2020). High scores in both years are for the following countries: Finland, Sweden, Denmark, the Netherlands, Luxembourg, and the United Kingdom.

Figure 1 highlights significant progress across all countries in improving broadband connectivity and infrastructure between 2016 and 2020, with Northern and Western European countries generally leading, and Southern and Eastern European countries showing notable improvements but still lagging behind.

The column graph compares the DESI *Human Capital* dimension scores for 27 EU member states and the UK for the years 2016 and 2020, Figure 2. Values for the DESI *Human Capital* dimension range from approximately 6,0 to 20,0. It can be seen that all countries improved their *Human Capital* scores from 2016 to 2020. The EU average increased from 11,2 in 2016 to 12,3 in 2020. The highest value of the DESI index for *Human Capital* dimension in 2020 have: Denmark (DK): 15,3, Netherlands (NL): 16,0, Sweden (SE): 17,9, Finland (FI): 19,6, United Kingdom (UK): 15,8, Estonia (EE): 16,7. These countries demonstrate strong digital skills and educational development in their populations. The lowest values of the DESI index in 2020 are for the following countries: Greece (EL): 8,3, Italy (IT): 7,8, Romania (RO): 6,9, Bulgaria (BG): 7,1, and Poland (PL): 8,0. These countries are still catching up in terms of digital skills and training. Noteworthy changes (2016-2020) are for the following countries: Romania (RO): from 6,9 to 8,3, Estonia (EE): 13,9 to 16,7, Sweden (SE): 15,6 to 17,9.

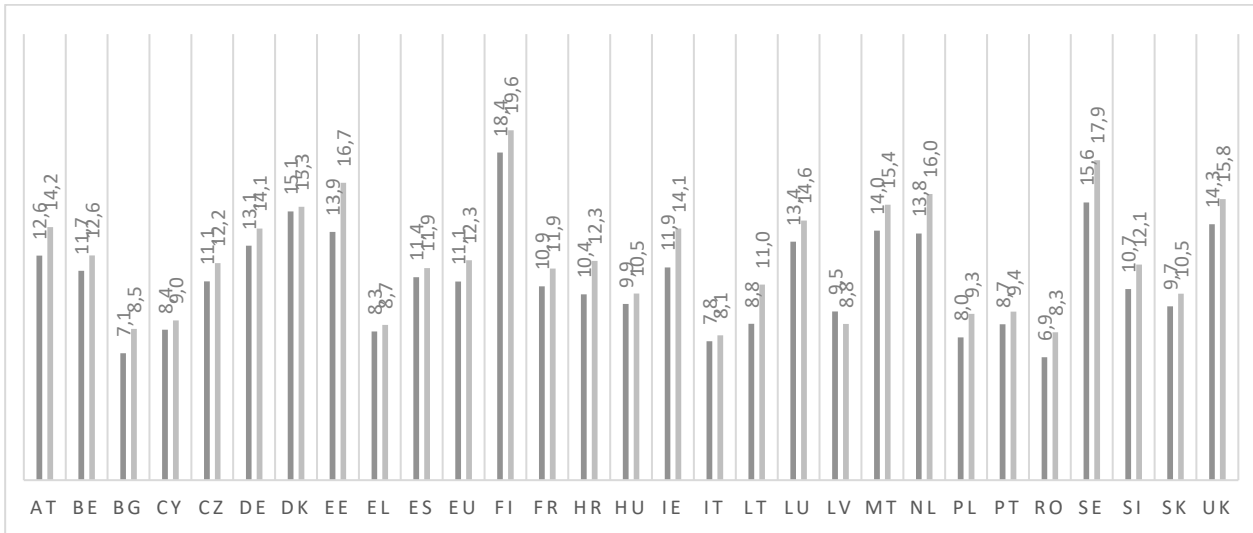


Figure 2. Human Capital in European countries – 2016 (dark grey) and 2020 (light grey).

Figure 2 highlights that *Human capital* has improved across Europe, with Nordic and Western European countries leading, while Eastern and Southern European countries show slower but steady progress. The results reflect broader trends in education, digital inclusion, and workforce development.

The column graph compares the DESI *Internet services* dimension scores for 27 EU member states and the UK for the years 2016 and 2020, Figure 3. Values for the DESI *Internet services* dimension range from approximately 3,9 to 11,5. Every country shows a higher score in 2020 than in 2016, indicating an increase in online activities such as social media use, video calls, online banking, and streaming. The EU average increased from 7,0 in 2016 to 8,7 in 2020. The highest value of the DESI index for *Internet services* dimension in 2020 are for the following countries: Denmark (DK): 11,3, Netherlands (NL): 11,3, Sweden (SE): 11,4, Finland (FI): 11,5, United Kingdom (UK): 11,0. These countries had the highest levels of *Internet service* use by individuals in 2020. The lowest values of the DESI index in 2020 are for the following countries: Greece (EL): 6,9, Italy (IT): 6,7, Romania (RO): 5,4, Bulgaria (BG): 5,0, and Poland (PL): 7,4. These countries lag behind, but show noticeable progress compared to 2016. Noteworthy changes (2016-2020) are for the following countries: Romania (RO): from 6,9 to 8,3, Estonia (EE): from 13,9 to 16,7, Sweden (SE): from 15,6 to 17,9. The largest relative improvement could be seen for Poland (PL): from 5,2 to 7,4.

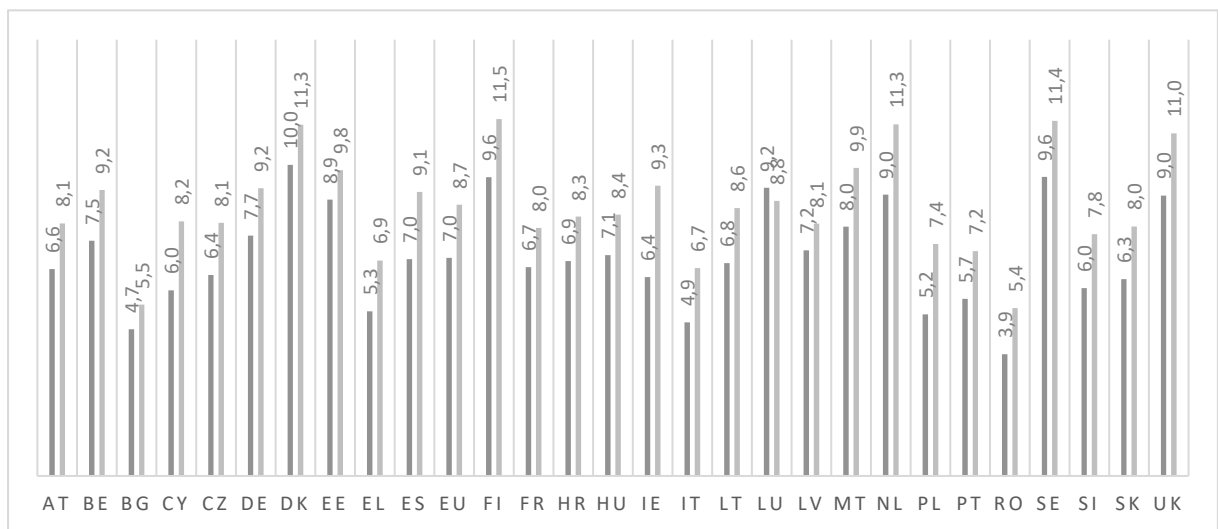


Figure 3. Use of Internet Services in European countries – 2016 (dark grey) and 2020 (light grey).

Figure 3 demonstrates a clear upward trend in the use of *Internet services* across all 28 European countries between 2016 and 2020. This indicates that individuals across Europe are increasingly engaging in digital activities such as online communication, entertainment, transactions, and social media. Northern and Western European countries consistently show the highest DESI scores, reflecting widespread and advanced Internet usage. Meanwhile, Eastern and Southern countries like Romania, Bulgaria, and Greece, though still lagging behind, exhibit notable progress over the four years.

The column graph compares the DESI *Integration of Digital Technology* dimension scores for 27 EU member states and the UK for the years 2016 and 2020, Figure 4. Values for the DESI *Integration of Digital Technology* dimension range from approximately 3,2 to 14,9. Every country shows a higher score in 2020 than in 2016, indicating an increase in the *Integration of digital technology* in everyday life and business. The EU average increased from 6,6 in 2016 to 8,3 in 2020. The highest values of the DESI index for *Integration of digital technology* dimension in 2020 are for the following countries: Belgium (BE): 13,2, Denmark (DK): 13,0, Netherlands (NL): 13,1, Sweden (SE): 12,4, Finland (FI): 13,4. These countries had the highest levels of *Integration of digital technology* in 2020. The lowest values of the DESI index in 2020 are for the following countries: Latvia (LV): 3,7, Romania (RO): 3,7, Bulgaria (BG): 3,2, and Poland (PL): 3,7. These countries lag behind, but show noticeable progress compared to 2016. Noteworthy changes (2016-2020) are for the following countries: Ireland (IE): from 11,3 to 14,9, Finland (FI): from 9,1 to 13,4, Sweden (SE): from 15,6 to 17,9. The largest relative improvement could be seen for Ireland (IE): from 11,3 to 14,9.

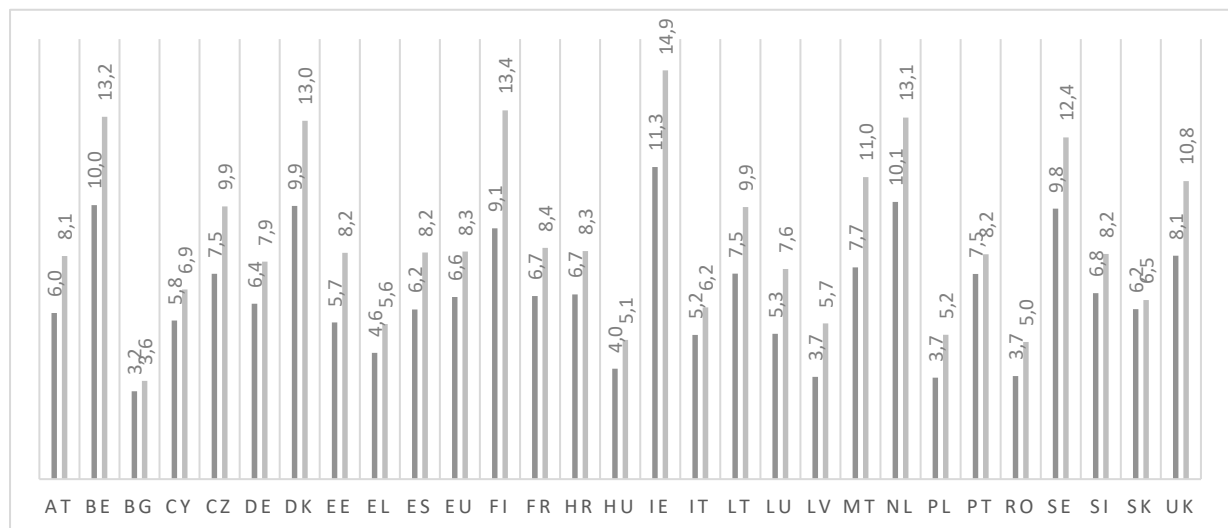


Figure 4. Integration of Digital Technology in European countries – 2016 (dark grey) and 2020 (light grey).

Between 2016 and 2020, all EU countries improved their *Integration of digital technologies*, though the extent varied significantly. Ireland, Finland, and the Netherlands lead in digital progress, while some countries, particularly in Eastern Europe, showed remarkable improvement despite starting from lower levels.

The column graph compares the DESI *Digital Public Services* dimension scores for 27 EU member states and the UK for the years 2016 and 2020, Figure 5. Values for the DESI *Digital Public Services* dimension range from approximately 4,0 to 13,4. Every country shows a higher score in 2020 than in 2016, indicating an increase in *Digital Public Services*. The EU average increased from 8,1 in 2016 to 10,8 in 2020. The highest values of the DESI index for the *Digital Public Services* dimension in 2020 are for the following countries: Denmark (DK): 13,1, Estonia (EE): 13,4, Spain (ES): 13,1, Finland (FI): 13,0, and Latvia (LV): 12,8. These countries

had the highest levels of *Digital Public Services* in 2020. The lowest values of the DESI index in 2020 are for the following countries: Greece (EL): 4,0, Hungary (HU): 4,3, and Slovakia (SK): 4,7. These countries lag behind, but show noticeable progress compared to 2016. Noteworthy changes (2016-2020) are for the following countries: Bulgaria (BG): from 6,2 to 9,3, Greece (IE): from 4,0 to 7,7, Czech Republic (CZ): from 5,6 to 9,4.

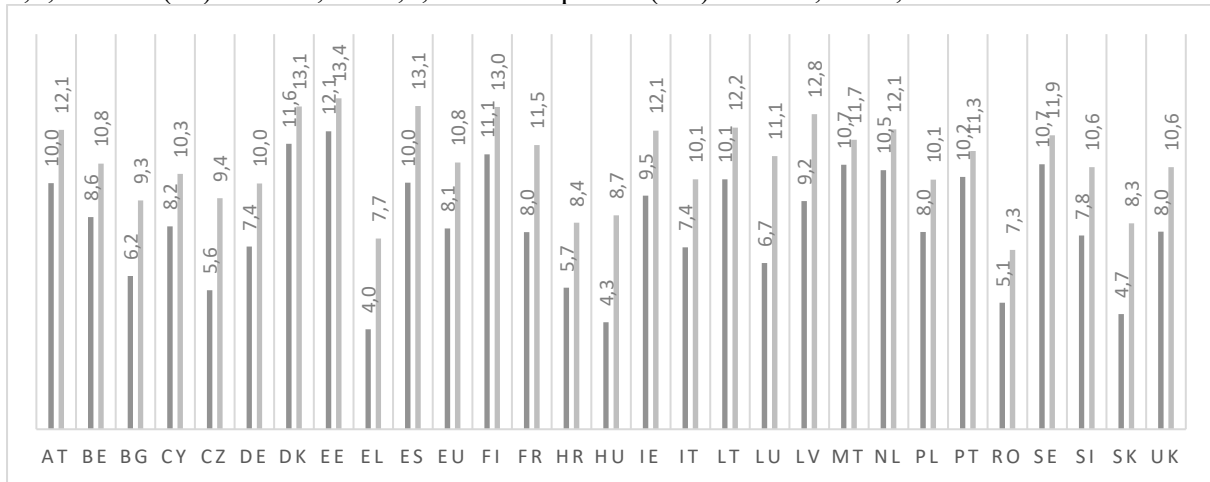


Figure 5. Digital Public Services in European countries – 2016 (dark grey) and 2020 (light grey).

European countries have greatly increased and enhanced their *Digital Public Services* between 2016 and 2020. While countries like Germany and Romania exhibit slower adoption, leaders like Estonia, Finland, and Malta demonstrate what can be achieved with robust digital governance. According to the data, e-government activities around Europe are accelerating broadly but unevenly.

Table 2 presents changes in DESI dimensions from 2020 to 2016 in percentage. Analysis includes data for 28 European countries across the five DESI dimensions: *desi_1_conn*: Connectivity, *desi_2_hc*: Human Capital, *desi_3_ui*: Use of Internet, *desi_4_idt*: Integration of Digital Technology, and *desi_5_dps*: Digital Public Services. Each value represents the number of countries that fall within a given percentage deviation from the EU average.

Regarding the first DESI dimension, *desi_1_conn*: Connectivity, most countries are concentrated in the 21-60% above EU average range (47%). Eight countries perform 51-60% above the EU average, showing strong infrastructure progress. Only one country is in the 71-90% range, and none of the selected countries are underperforming.

Values for the second DESI dimension, *desi_2_hc*: Human Capital, are significantly below the EU average (11%) in most countries (16 countries are 0-10% below, 11 countries are 11-20% below). There are no countries that exceed the EU average, which indicates a widespread shortfall in digital skills across the region.

Regarding the third DESI dimension, *desi_3_ui*: Use of Internet most of the selected countries is below the EU average (24%). Results showed that 11 countries are 21-30% below, and 9 are 11-20% below, which indicates that Internet usage among citizens is still catching up in most countries.

Values for the fourth DESI dimension, *desi_4_idt*: Integration of Digital Technology, showed mixed distribution. Most of the countries are below the EU average (25%) (9 countries are 31-40% below, 8 countries are 21-30% below). Five countries are above the average (41-60%), which implies that digital tech adoption in business is progressing unequally.

Regarding the fifth DESI dimension, *desi_5_dps*: Digital Public Services, most of the selected countries are above the EU average (33%). There are only six countries that are 21-40% below

the average. Four countries are 41-50% above, five countries exceed the EU average by more than 60% and one country is over 91% above the average. Results showed a relatively high level of digital government service development in several countries.

Table 2. DESI dimensions – change in 2020 to 2016. Change at the country level is in Appendix 1.

	desi 1 conn	desi 2 hc	desi 3 ui	desi 4 idt	desi 5 dps
EU-average, %	47%	11%	24%	25%	33%
-10%-1%	0	1	1	0	0
0-10%	0	16	0	1	2
11-20%	0	11	9	4	5
21-30%	6	0	11	8	6
31-40%	5	0	5	9	6
41-50%	4	0	2	5	4
51-60%	8	0	0	1	0
61-70%	3	0	0	0	2
71-80%	1	0	0	0	1
81-90%	1	0	0	0	1
91-100%	0	0	0	0	1
Total	28	28	28	28	28

It can be concluded that two dimensions of the DESI index: *desi_1_conn* – Connectivity and *desi_5_dps* – Digital Public Services are the strongest performing DESI dimensions across Europe, with many countries exceeding the EU average.

Table 3 presents the mean and standard deviation values for the year 2016. Analysis includes five dimensions of the Digital Economy and Society Index (DESI) across European countries: *desi_1_conn*: Connectivity; *desi_2_hc*: Human Capital; *desi_3_ui*: Use of Internet; *desi_4_idt*: Integration of Digital Technology and *desi_5_dps*: Digital Public Services.

The mean values were used as a measure for the central tendency. The mean value of the five variables ranges from 6,73 for *desi_4_idt*: Integration of Digital Technology to 11,26 for *desi_2_hc*: Human Capital. Furthermore, standard deviation ranges from the 1,63 for *desi_3_ui*: Use of Internet to 2,86 for *desi_2_hc*: Human Capital. The highest mean value and the highest standard deviation value has dimension *desi_2_hc*: Human Capital (Mean = 11,26, SD = 2,86).

The Pearson correlation matrix for the five observed variables is shown in Table 3. The correlation matrix presents a significant association between the five dimensions of the DESI index. Notably, the correlation between *desi_2_hc*: Human Capital and *desi_3_ui*: Use of Internet ($r = 0,912^{**}$) suggests a strong alignment. Furthermore, moderate correlation is shown between *desi_1_conn*: Connectivity and *desi_3_ui*: Use of Internet ($r = 0,658^{**}$) and *desi_2_hc*: Human Capital and *desi_4_idt*: Integration of Digital Technology ($r = 0,662^{**}$). In addition, the relatively lower correlation between *desi_1_conn*: Connectivity and *desi_2_hc*: Human Capital ($r = 0,535^{**}$) and *desi_1_conn*: Connectivity and *desi_5_dps*: Digital Public Services ($r = 0,478^{**}$) warrants further investigation regarding different possibilities of connectivity services. There are no statistically significant correlations between dimensions *desi_4_idt*: Integration of Digital Technology and *desi_1_conn*: Connectivity ($r = 0,223$).

The data suggested that dimension *desi_2_hc*: Human Capital is a central factor in digital development, strongly associated with both *desi_3_ui*: Use of Internet and *desi_4_idt*: Integration of Digital Technology. Overall, the DESI dimensions are interrelated, implying that progress in one area (e.g., digital skills or connectivity) likely supports growth in others.

Table 3. Descriptive statistics and correlation analysis – 2016.

Variable	Mean	St.Dev.	desi_1_conn	desi_2_hc	desi_3_ui	desi_4_idt	desi_5_dps
desi_1_conn	8,99	1,84	1	0,535**	0,658**	0,223	0,478**
desi_2_hc	11,26	2,86		1	0,912**	0,662**	0,587**
desi_3_ui	7,06	1,63			1	0,584**	0,569**
desi_4_idt	6,73	2,21				1	0,551**
desi_5_dps	8,27	2,31					1

Table 4 presents mean and standard deviation values for the year 2020. Analysis includes five dimensions of the Digital Economy and Society Index (DESI) across European countries: *desi_1_conn*: Connectivity; *desi_2_hc*: Human Capital; *desi_3_ui*: Use of Internet; *desi_4_idt*: Integration of Digital Technology and *desi_5_dps*: Digital Public Services.

The mean values were used as a measure of the central tendency. The mean value of the five variables ranges from 8,66 for *desi_3_ui*: Use of Internet to 13,06 for *desi_1_conn*: Connectivity. Furthermore, standard deviation ranges from 1,64 for *desi_3_ui*: Use of Internet to 3,19 for *desi_2_hc*: Human Capital.

Table 4. Descriptive statistics and correlation analysis – 2020.

Variable	Mean	St.Dev.	desi_1_conn	desi_2_hc	desi_3_ui	desi_4_idt	desi_5_dps
desi_1_conn	13,06	2,12	1	0,460**	0,525**	0,309	0,498**
desi_2_hc	12,45	3,19		1	0,887**	0,764**	0,582**
desi_3_ui	8,66	1,64			1	0,806**	0,637**
desi_4_idt	8,74	3,02				1	0,569**
desi_5_dps	10,82	1,73					1

The Pearson correlation matrix for the five observed variables is shown in Table 4. The correlation matrix presents a significant association between the five dimensions of the DESI index. Notably, the correlation between *desi_2_hc*: Human Capital and *desi_3_ui*: Use of Internet ($r = 0,887^{**}$) and between *desi_3_ui*: Use of Internet and *desi_4_idt*: Integration of Digital Technology ($r = 0,806$) suggests a strong alignment. Furthermore, moderate correlation is shown between *desi_3_ui*: Use of Internet and *desi_5_dps*: Digital Public Services ($r = 0,637^{**}$). In addition, the relatively lower correlation between *desi_1_conn*: Connectivity and *desi_2_hc*: Human Capital ($r = 0,460^{**}$) and *desi_1_conn*: Connectivity and *desi_5_dps*: Digital Public Services ($r = 0,498^{**}$) warrants further investigation regarding different possibilities of connectivity services. There are no statistically significant correlations between dimensions *desi_4_idt*: Integration of Digital Technology and *desi_1_conn*: Connectivity ($r = 0,309$).

The data showed that *desi_2_hc*: Human Capital is a key factor to digital development, highly correlated with all other DESI dimensions. In terms of internet usage, technological integration, and public digital services, nations with higher levels of digital literacy and education typically perform better.

CLUSTER ANALYSIS

Table 5 presents cluster analysis parameters for 2016 and 2020 using five DESI dimensions. A non-hierarchical statistical cluster analysis was applied to classify the selected European countries, using the k-means algorithm for both years (2016 and 2020). Initial centroids were determined through the greatest average distance method, after which all countries were assigned to their nearest centroid. Squared Euclidean distances served as the distance metric, giving greater weight to countries farther from the centroid [28].

The clustering process was repeated 10 times to ensure stability. Before computation, all variables were individually normalized using the software’s built-in feature, which transforms data into a predefined range based on the minimum and maximum values. This normalization

step enhances the precision of the clustering algorithm and improves the quality of the resulting groups [29]. In this article, the final number of clusters was selected using the v-fold cross-validation procedure, which resulted in four (4) clusters for the year 2016 and three (3) clusters for the year 2020.

Figure 6 presents a graph of cost sequences and indicates that for the year 2016, the four-cluster solution is the best, while for 2020, the three-cluster solution is the best. This graph displays the error function for various clustering options, where the error is defined as the average distance of observations within subsamples to their respective cluster hubs [30].

Results of Anova analysis and k-means clustering for five variables regarding DESI index dimensions for the year 2016 are presented in Table 6. All of the selected variables are statistically significant at 1%, which implies that the decision of dividing selected European countries into four clusters is acceptable.

Table 5. Cluster analysis parameters for 2016 and 2020 using DESI dimensions.

2016	2020
Algorithm: k-Means	Algorithm: k-Means
Distance method: Euclidean distances	Distance method: Euclidean distances
Initial centers: Maximize initial distance	Initial centers: Maximize initial distance
Cross-validation: 10 folds	Cross-validation: 10 folds
Training error: 0,324602	Training error: 0,357296
Number of clusters: 4	Number of clusters: 3

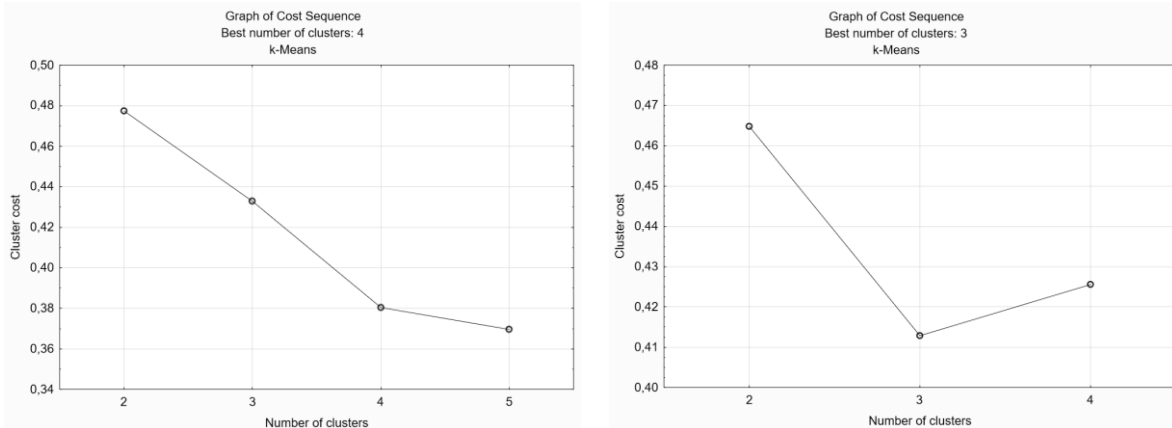


Figure 6. Graphs of cost sequences, for 2016 (left) and 2020 (right).

Table 6. Anova analysis for 2016; k-means clustering; 5 variables, 4 clusters, $n = 28$ countries.

	Between SS	df	Within SS	df	F	p value
desi 1 conn	60,1241	3	31,459	24	15,290	0,000***
desi 2 hc	158,4959	3	62,624	24	20,247	0,000***
desi 3 ui	54,5529	3	16,721	24	26,100	0,000***
desi 4 idt	70,3874	3	61,882	24	9,100	0,000***
desi 5 dps	97,5139	3	46,672	24	16,715	0,000***

Table 7. Anova analysis for 2020; k-means clustering; 5 variables, 3 clusters, $n = 28$ countries.

	Between SS	df	Within SS	df	F	p value
desi 1 conn	48,275	2	73,171	25	8,247	0,002***
desi 2 hc	180,262	2	94,496	25	23,845	0,000***
desi 3 ui	48,000	2	24,892	25	24,104	0,000***
desi 4 idt	154,152	2	92,309	25	20,874	0,000***
desi 5 dps	51,160	2	29,866	25	21,412	0,000***

Results of Anova analysis and k-means clustering for five variables regarding DESI index dimensions for the year 2020 are presented in Table 7. All of the selected variables are statistically significant at 1%, which implies that the decision of dividing selected European countries into three clusters is acceptable.

Table 8 and Table 9 present cluster distances for the years 2016 and 2020. The measure of how similar or dissimilar data are within a cluster or between clusters is explained by cluster distance. Cluster distances should be small, indicating that data points within a cluster are close to each other and highly similar, which can be seen in Tables 8 and 9.

Figure 7 presents standardized mean values for the years 2016 and 2020. These distributions show how much each observed variable varies between nations within a cluster. A more compact distribution is the outcome of a smaller gap between countries. It can be seen that the highest mean values for all five variables and for both years (2016 and 2020) are in Cluster 2.

Figure 8 presents distributions of the observed variables regarding DESI index dimensions across four given clusters for the year 2016. A graph where the distribution is more narrow showed that more similar variable values have countries in the same cluster.

For example, if the graph of distributions for variable *desi_5_dps: Digital Public Services* (2016) in Figure 5, the last graph, is observed, it can be concluded that countries in cluster 2 have more similar values of the observed variable than countries in other clusters. That conclusion can be brought because cluster 2 has a lower standard deviation and a more narrow distribution than the other clusters. However, at the same time, it can be concluded that countries in cluster 2 have a statistically significant higher *desi_5_dps: Digital Public Services* (2016) than countries in other clusters, which have wider distribution.

Table 8. Cluster distances – 2016.

	Cluster 1	Cluster 2	Cluster 3	Cluster 4
Cluster 1	0	0,732	0,631	0,496
Cluster 2		0	1,306	0,639
Cluster 3			0	0,795
Cluster 4				0

Table 9. Cluster distances – 2020.

	Cluster 1	Cluster 2	Cluster 3
Cluster 1	0	0.676	0.675
Cluster 2		0	1.313
Cluster 3			0

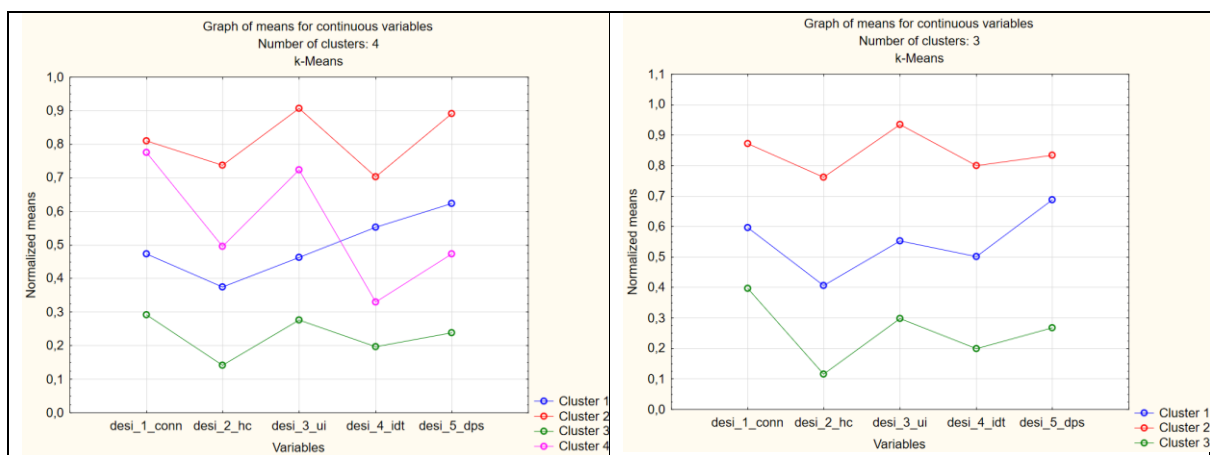


Figure 7. Standardized mean values – 2016 (left graph) and 2020 (right graph).

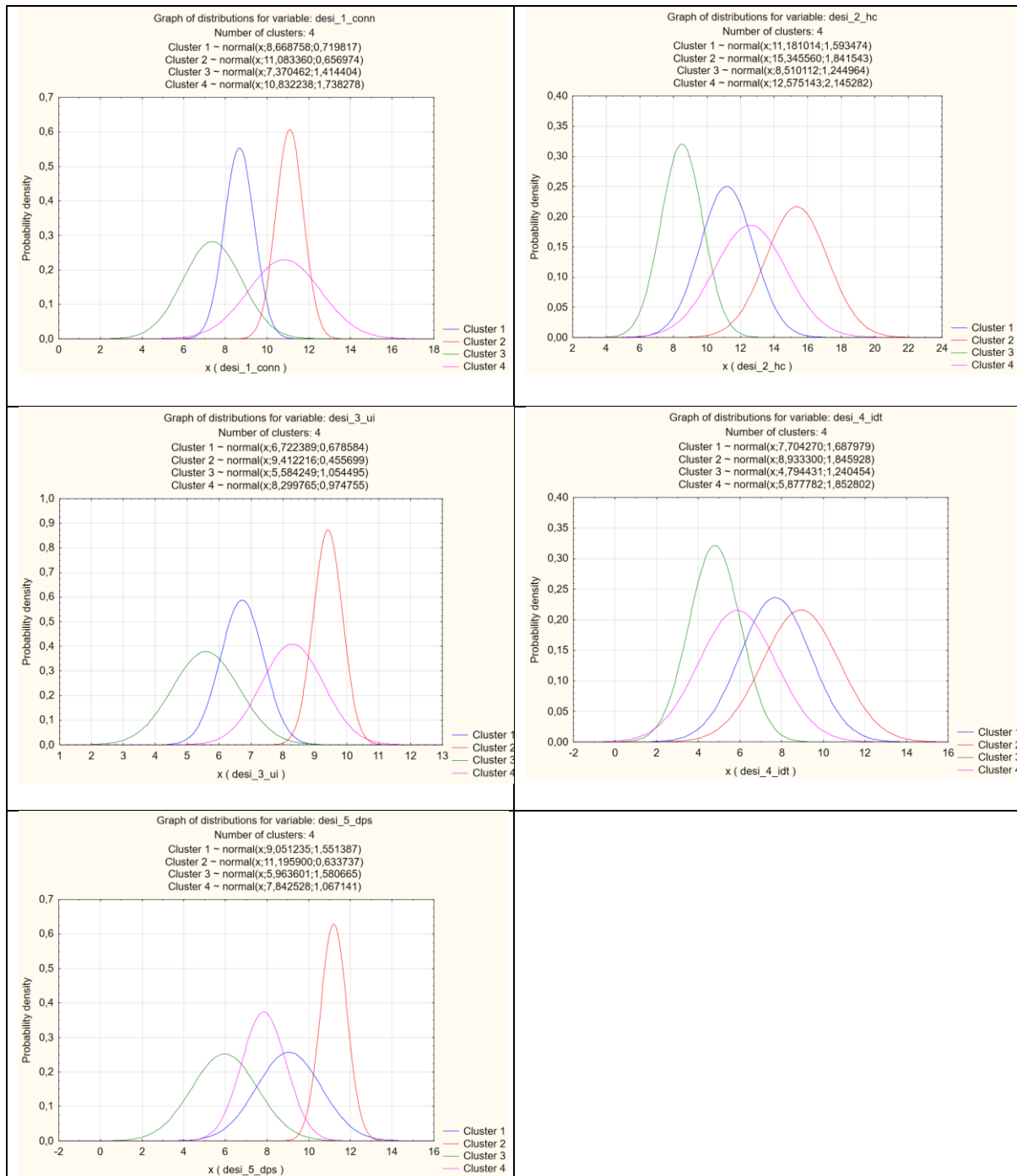


Figure 8. Distribution of variables – 2016.

Figure 9 presents distributions of the observed variables regarding DESI index dimensions across three given clusters for the year 2020. A graph where the distribution is more narrow shows that more similar variable values have countries in the same cluster.

For example, if the graph of distributions for variable *desi_1_conn* – *Connectivity* (2020) in Figure 9, the first graph, is observed, it can be concluded that countries in cluster 3 have more different values of the observed variable than countries in cluster 2. That conclusion can be brought because cluster 3 has a higher standard deviation and wider distribution than cluster 2. However, at the same time, it can be concluded that countries in cluster 3 have a statistically significant higher *desi_1_conn* – *Connectivity* (2016) than countries in cluster 2.

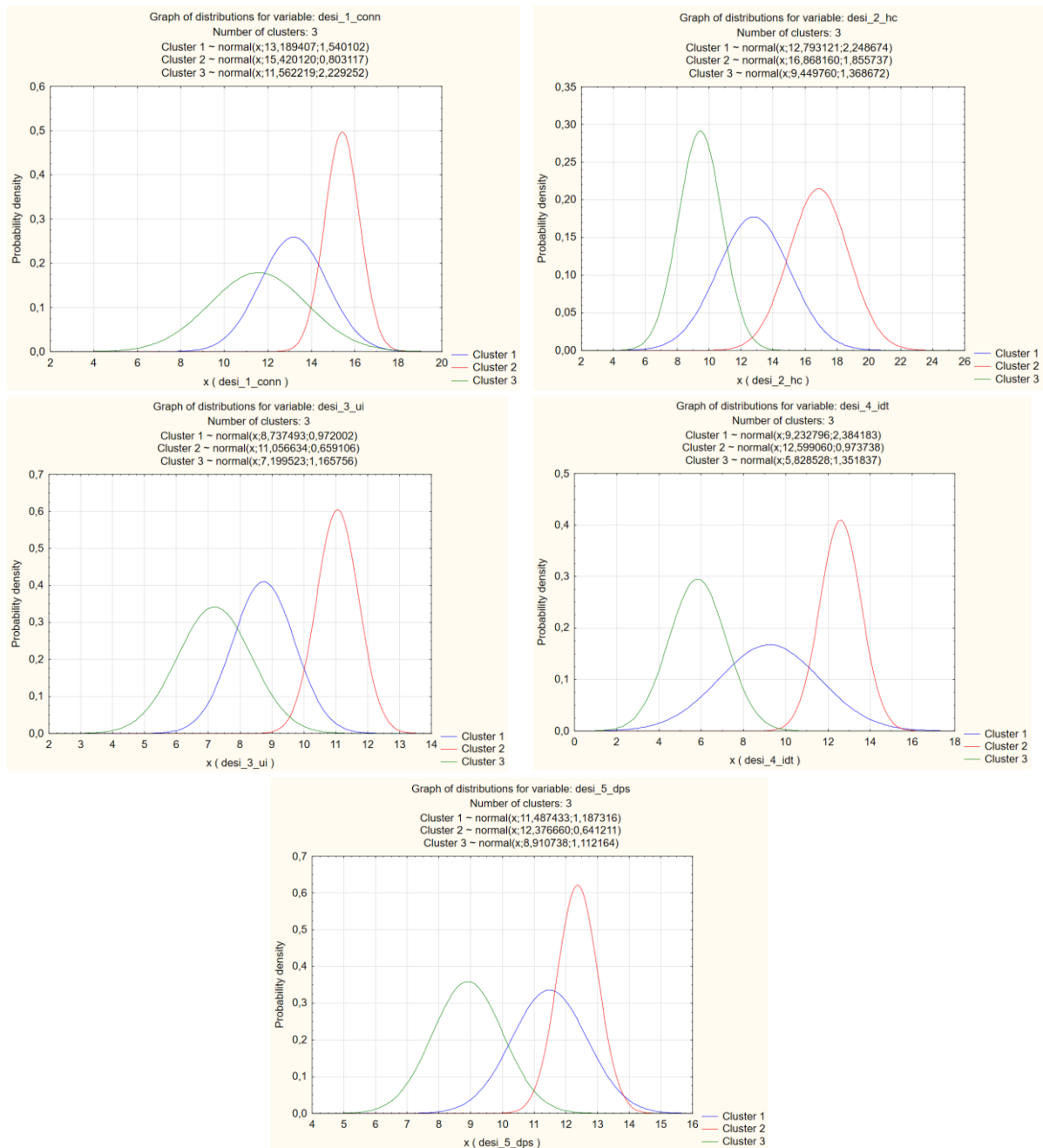


Figure 9. Distribution of variables – 2020.

DISCUSSION

Table 10 presents cluster means for five selected variables regarding DESI index dimensions for the years 2016 and 2020.

The highest mean values for all five variables are in Cluster 2, which is followed by Cluster 4, lower mean value has Cluster 1, and the lowest mean values are in Cluster 3. It could be concluded that Cluster 2 includes countries that are leaders in digital development regarding all five dimensions.

The same situation is regarding cluster means for the year 2020. The highest mean values for all five variables are in Cluster 2, which is followed by Cluster 1, and the lowest mean values are in Cluster 3. It could be concluded that Cluster 2 includes countries that are very successful in using and investing in information and communication technologies regarding connectivity, human capital, use of Internet services, integration of digital technology, and digital public services.

Table 10. Cluster means, k-means clustering; five variables, $n = 28$ countries, 4 clusters for 2016, and 3 clusters for 2020. Country allocation to cluster – 2016 and 2020 is in Appendix 2.

Variable	2016				2020		
	C1	C2	C3	C4	C1	C2	C3
desi_1_conn	8,67	11,08	7,37	10,83	13,19	15,42	11,56
desi_2_hc	11,18	15,35	8,51	12,58	12,79	16,87	9,45
desi_3_ui	6,72	9,41	5,58	8,30	8,74	11,06	7,20
desi_4_idt	7,70	8,93	4,79	5,88	9,23	12,60	5,83
desi_5_dps	9,05	11,20	5,96	7,84	11,49	12,38	8,91
Number of cases	10	5	9	4	14	5	9
Percentage, %	35,71	17,86	32,14	14,29	50,00	17,86	32,14

Figure 10 presents country membership in clusters in 2016 and 2020. In this article, data from the years 2016 and 2020 are used for cluster analysis for 28 European countries. According to the results, four clusters with significant differences are found for the year 2016, and three clusters with significant differences are found for the year 2020. Data for five dimensions of the DESI index are analysed: *desi_1_conn*: Connectivity, *desi_2_hc*: Human Capital, *desi_3_ui*: Use of Internet, *desi_4_idt*: Integration of Digital Technology, and *desi_5_dps*: Digital Public Services.

For the year 2016, Cluster 2 has the highest mean values and includes five countries: Denmark, Estonia, Finland, the Netherlands, and Sweden. All five countries are northern European countries, mostly Scandinavian countries, and one Baltic country (Estonia). All five countries are members of the European Union. These countries are leaders in digital development in Europe. Finland and Denmark mostly have a higher DESI score than the European Union average. These countries are leaders regarding sophisticated broadband infrastructure, a high level of digital proficiency, widespread use of e-government, and strong integration of digital technology in business.

Cluster 4 follows Cluster 2, and there are countries like Germany, Latvia, Luxembourg, and the United Kingdom. These countries belong to different geographical regions, such as Central Europe (Germany, Luxembourg), Eastern Europe (Latvia), and Western Europe (the United Kingdom). These countries invest a lot in the development of information and communication technologies, especially in Latvia. With an emphasis on fostering its digital infrastructure, improving digital skills, and encouraging the digitization of businesses and governmental services, Latvia is aggressively pursuing digital development. With more than 91% of services now accessible online, the nation has made great progress in digitizing public services and is now leading the EU in this area. There are still issues with digital skills, though, especially with the adoption of cloud computing and the rollout of 5G and high-capacity networks.

Cluster 1 consists of ten European countries: Austria, Belgium, the Czech Republic, France, Ireland, Lithuania, Malta, Portugal, Slovenia, and Spain. This Cluster is the most diverse with regard to the geographical position of the countries, while it includes Central, Eastern, Southern, and Western European countries. This cluster includes some of the largest European economies, like France and Spain. However, more investments are required in the ICT sector.

Cluster 3 has the lowest level of cluster mean, as shown in Figure 7. This cluster consists of nine European countries: Bulgaria, Croatia, Cyprus, Greece, Hungary, Italy, Poland, Romania, and Slovakia. These countries are mostly lagging behind. All countries are members of the European Union. To improve the quality of information and communication technologies, the European Union offers different sets of policy instruments that stimulate EU countries to invest in their digital development and foster it.

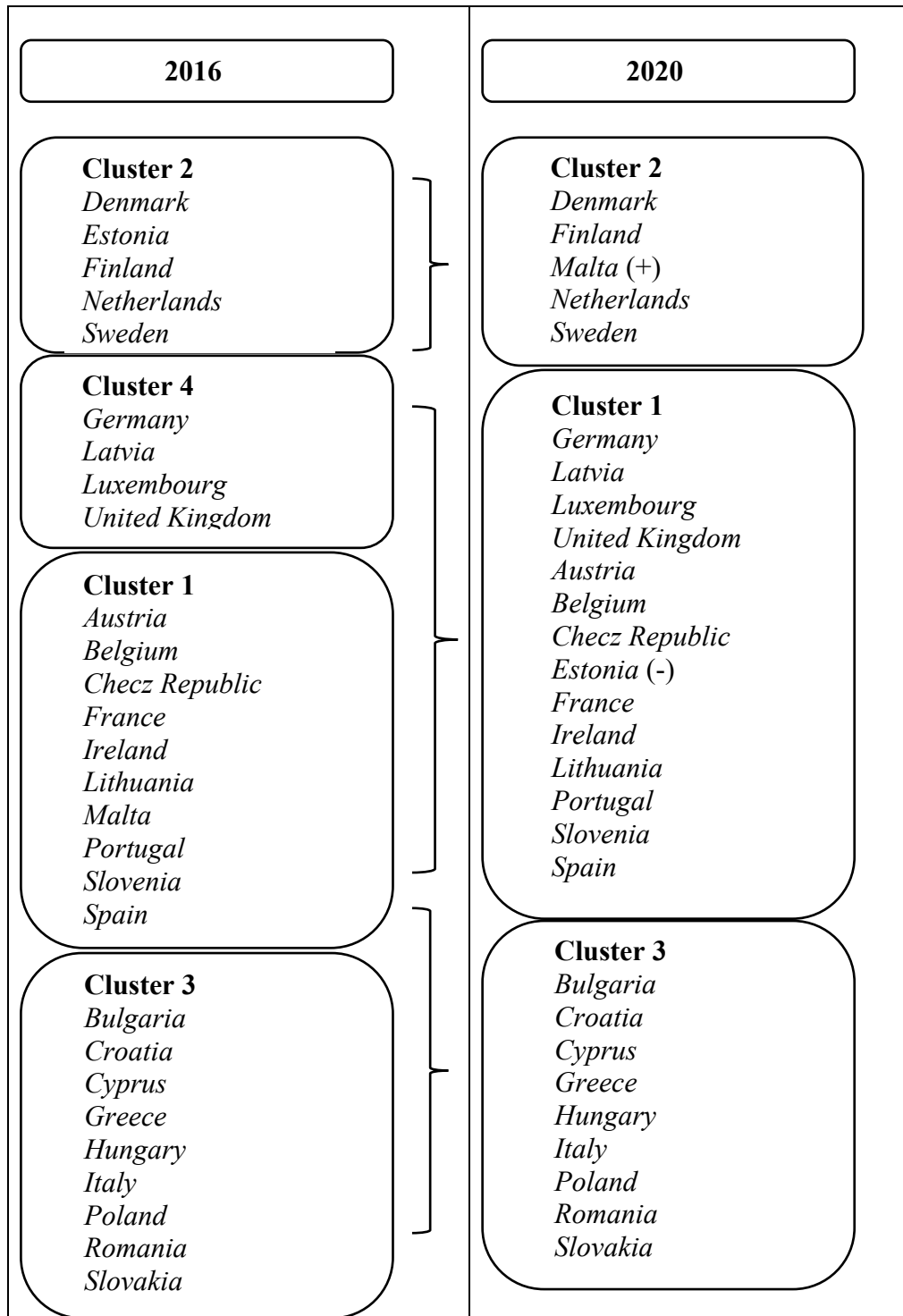


Figure 10. Country membership in clusters in 2016 and 2020.

For the year 2020, some differences between clusters could be seen. Cluster 2 has the highest mean values and includes five countries: Denmark, Malta, Finland, the Netherlands, and Sweden. All countries are Northern European countries, except Malta, a Southern European country. All five countries are members of the European Union and are leaders in digital progress in Europe. Compared to five years ago, Estonia is no longer in the top five, replaced by Malta. Information and communications technologies have advanced significantly in Malta, especially in fields like connection and commercial digitization in the last few years. Malta is a leader in broadband infrastructure and commercial adoption of cutting-edge technology, but it struggles to acquire fundamental digital skills and hire more ICT specialists.

Cluster 1 follows Cluster 2, and there are 14 countries: Germany, Latvia, Luxembourg, the United Kingdom, Austria, Belgium, the Czech Republic, Estonia, France, Ireland, Lithuania, Portugal, Slovenia, and Spain. These countries belong to different geographical regions such as Central Europe (Germany, Austria, Slovenia), Eastern Europe (Estonia, Latvia, Lithuania), Western Europe (Ireland, United Kingdom, Belgium, Luxembourg, France), and Southern Europe (Spain, Portugal). Compared to cluster analysis for the year 2016, it comprises countries from Cluster 4 and Cluster 1. It could be concluded that most countries have made significant progress regarding digital development.

Cluster 3 has the lowest level of cluster mean, as shown in Figure 7 for both years (2016 and 2020). Although some progress could be seen as mean values are slightly higher in 2020 than in 2016. This cluster consists of nine European countries: Bulgaria, Croatia, Cyprus, Greece, Hungary, Italy, Poland, Romania, and Slovakia. Most of the countries have finally joined the European Union and are part of Eastern European countries. Information and communication technology is advancing rapidly in Eastern European nations, with some emerging as major global tech hubs. The area is known for its robust reservoir of IT expertise, rising digital infrastructure expenditures, and expanding software development outsourcing industry. Emerging as major innovation hubs in the area, Romania and Poland are drawing talent and investments. Poland scores highly in terms of IT competitiveness and tech talent. The region's developing digital infrastructure is being aided by investments in data centers and cloud services.

CONCLUSION

The competitiveness of the European economy relies on fostering a knowledge-based system through human capital development and qualitative improvement, alongside advancing research and development that depends on the integration and growth of information and communication technologies.

In this article, changes in the Digital Economy and Society Index (DESI) between 2016 and 2020 were examined using a cluster analysis approach to assess patterns of digital convergence among 28 European countries. The analysis revealed that while all countries improved across the five DESI dimensions – Connectivity, Human Capital, Use of Internet Services, Integration of Digital Technology, and Digital Public Services – significant disparities persist between leading and lagging nations. Scandinavian countries consistently outperformed the rest, demonstrating strong infrastructure, high digital skills, and advanced e-government services, whereas many Eastern and Southern European countries, although progressing, remained below the EU average. The clustering results confirmed limited convergence, indicating that without targeted policy interventions, regional gaps in digital development may persist.

When compared with previous research, these findings confirm earlier observations that Nordic countries have maintained leadership in digital performance for over a decade, with only minor changes in the top tier of performers. Earlier studies had also noted the persistent underperformance of several Eastern and Southern EU members, and this study shows that while their DESI scores have risen, the relative distance to the leaders has narrowed only modestly. This aligns with prior conclusions that organic catch-up is slow and requires substantial policy-driven investment in infrastructure, digital skills, and technological adoption.

The practical implications of this research are substantial for policymakers and regional authorities. By identifying specific clusters of countries with similar digital performance profiles, the results can guide the allocation of resources and the design of tailored digital transformation strategies. For lagging countries, targeted measures to strengthen human capital, improve broadband infrastructure, and promote business digitalisation are particularly critical. For leading countries, the focus may shift toward sustaining innovation capacity and ensuring that high digital maturity translates into inclusive economic and social benefits.

However, the article has several limitations that should be addressed in future research. The analysis was restricted to two time points, 2016 and 2020, limiting the ability to capture finer-grained trends or the influence of short-term policy interventions. The study also focused exclusively on selected European countries, excluding South Eastern European countries and non-EU members, whose inclusion might provide a broader comparative perspective. Furthermore, the reliance on DESI as a sole measurement framework may overlook other relevant dimensions of digitalisation not captured in its indicators. Future research could expand the temporal scope, incorporate complementary indices, and investigate causal relationships between policy measures and digital performance. This would allow for a deeper understanding of the mechanisms driving convergence or divergence in Europe's digital transformation.

APPENDIX 1

Table 11. DESI dimensions – change in 2020 to 2016 (%) at the country level.

Country code	desi_1_conn	desi_2_hc	desi_3_ui	desi_4_idt	desi_5_dps
AT	48%	13%	22%	34%	22%
BE	52%	7%	22%	32%	25%
BG	30%	19%	17%	12%	49%
CY	60%	6%	37%	20%	26%
CZ	29%	9%	26%	33%	66%
DE	59%	7%	20%	24%	35%
DK	41%	2%	13%	31%	13%
EE	20%	20%	11%	44%	11%
EL	58%	4%	31%	23%	91%
ES	62%	5%	31%	34%	31%
FI	47%	7%	19%	47%	17%
FR	55%	9%	19%	26%	44%
HR	54%	18%	21%	23%	46%
HU	75%	6%	18%	26%	100%
IE	53%	18%	46%	31%	28%
IT	84%	4%	35%	19%	37%
LT	31%	25%	26%	32%	21%
LU	29%	9%	-5%	45%	64%
LV	24%	-7%	12%	52%	38%
MT	68%	10%	24%	43%	9%
NL	34%	16%	25%	30%	16%
PL	68%	16%	44%	42%	27%
PT	55%	8%	27%	10%	10%
RO	40%	20%	38%	33%	42%
SE	39%	15%	19%	26%	11%
SI	28%	13%	29%	21%	35%
SK	49%	7%	27%	5%	79%
UK	31%	10%	22%	33%	33%

APPENDIX 2

Table 12. Country allocation to cluster – 2016 and 2020.

Country code	2016		2020	
	Final classification	Distance to centroid	Final classification	Distance to centroid
AT	1	0,282	1	0,276
BE	1	0,318	1	0,377
BG	3	0,274	3	0,431
CY	3	0,365	3	0,386
CZ	1	0,430	1	0,443
DE	4	0,246	1	0,371
DK	2	0,183	2	0,223
EE	2	0,441	1	0,501
EL	3	0,382	3	0,449
ES	1	0,247	1	0,384
FI	2	0,300	2	0,290
FR	1	0,206	1	0,191
HR	3	0,374	3	0,419
HU	3	0,389	3	0,476
IE	1	0,488	1	0,573
IT	3	0,237	3	0,273
LT	1	0,267	1	0,240
LU	4	0,303	1	0,394
LV	4	0,505	1	0,595
MT	1	0,384	2	0,305
NL	2	0,223	2	0,110
PL	3	0,300	3	0,259
PT	1	0,311	1	0,399
RO	3	0,514	3	0,521
SE	2	0,148	2	0,157
SI	1	0,277	1	0,254
SK	3	0,297	3	0,197
UK	4	0,399	1	0,510

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