The Interplay of R&D, Digitalisation, and GDP: Insights from Fuzzy Logic Analysis

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Abstract

Technological development is recognised as a key factor in long-term economic growth, and R&D activity is a key driver of this process. In the context of ongoing digital transformation, it is necessary to understand the links between R&D spending, the level of digitisation and the level of GDP per capita in an integrated manner. While existing studies examine these variables separately using classical statistical methods, they fail to capture the indirect and uncertain relationships between them. Therefore, this paper aims to develop a model of the relationship between R&D expenditures, Digital Economy and Society Index (DESI) level and GDP per capita using fuzzy logic. The practical application of the method is presented in the example of the EU-27 countries. The results prove the usefulness of the method for analysing real causal relationships. The model based on fuzzy logic makes it possible to identify differences between countries that could go unnoticed using traditional classification methods.

Keywords: digital transformation, economic indicators, fuzzy logic, dependency modelling public intervention

1. Introduction

In 2022, the EU's overall spending on research and development (R&D) was around €352 billion (i.e. 2.22% of EU GDP) [6]. At the same time, M. Draghi's report, published in September 2024, highlighted the significant challenges facing the European Union (EU) in terms of digital transformation. According to this report, EU countries need to increase investment in digital technologies to avoid marginalisation from global technology leaders [47]. The EU's ‘Digital Transformation Plan 2030 – The Digital Decade’ outlines goals in four areas, monitored through the Digital Economy and Society Index (DESI).

The DESI level is closely linked to technology availability and adoption. Studies show that digital development positively impacts economic growth [41]. Growth theory highlights technological progress, driven by R&D, as a key factor for long-term economic growth [20]. There are proven relationships between R&D spending, the level of digitalisation and the value of GDP per capita in the literature, but most studies focus on analysing only one of these relationships and use classical statistical methods [9–11, 29, 42]. They do not identify the direct and indirect relationships that condition a better understanding of the mechanisms supporting economic development in EU countries.

In addressing these challenges, this paper aims to develop a model of the relationship between R&D investment, DESI level and GDP per capita using fuzzy logic. The adopted method fills an important research gap and brings a new perspective to innovation and digital policy analysis, enabling a better understanding of the synergies between knowledge investment, digital transformation and economic development. Creating a model that describes causal relationships between variables, and the sequence of their reactions requires the consideration of three key aspects: the relevance of the variables in the analysis, the type of relationships between them, and the level of uncertainty the model is intended to handle. Parameter values are often unknown and are determined based on estimates from historical data, which leads to simplifications and a loss of information. Fuzzy set theory [44] and fuzzy logic offer a new approach that allows the imprecision of economic phenomena to be preserved in the modelling process [14, 18, 27].

In fuzzy logic, the truth value of a proposition is a predicate that can take values in the interval [0, 1]. The truth domain is not limited to the classical true and false values. Therefore, intermediate truth values are allowed, and the order relation -- as true as -- is interpreted. The implication A → B quantifies the degree to which B is at least as true as A [40]. In this paper, a model based on fuzzy implications and logical operators is proposed to quantify the degree of the relationship between investments in research and development, the level of digitalisation, and GDP per capita. This approach allows us to better represent real cause-effect relationships and flexibility in building expert models. The practical application of the proposed framework is presented using the example of the EU-27 countries.

The paper consists of five sections: section 2 reviews the literature, section 3 outlines the methodology, section 4 presents and interprets the results, and section 5 concludes with key findings and future research directions.

2. Theoretical framework

The relationship between R&D spending and the DESI (R&D→DESI) is crucial to understanding the economic impact of the digital transformation. The DESI serves as an important tool for measuring the economic impact of digital transformation in EU countries. It covers areas such as human capital, connectivity, digital integration and digital public services, which together affect each other and economic performance. These investments can enhance digital capabilities [34], increase innovation [11], economic complexity and overall competitiveness. Advanced technologies such as artificial intelligence, data analytics and the Internet of Things are integrated into the digital transformation process [1]. An inverse relationship analysis (DESI→R&D) would verify the feedback effect that a country with a high DESI may have a better research environment, but it is not the level of DESI that determines the level of R&D spending, but a country's innovation policy.

The positive impact of digital development on economic growth and/or GDP per capita (DESI→GDP) is widely discussed in the literature [9, 12, 25, 41]. Analysis of the impact of DESI components, such as human capital and digital integration, on GDP highlights their importance in economic performance during the digital transformation [2]. A high DESI fosters innovation in companies which leads to the creation of new products and services and new jobs [21]. Research shows that a 1% increase in digitisation (as measured by the DESI index) correlates with a 0.3838% increase in GDP [33], a 10% increase in Internet connectivity increases GDP growth by 1.38%, and high rates of Internet access contribute 2% to GDP growth [19].

Existing research proves that R&D spending has a crucial role in influencing GDP per capita (R&D→GDP) through increased productivity and technological progress. However, its impact on overall economic growth is not always straightforward. A broader approach shows that public spending on R&D, along with a skilled scientific workforce and patents, contributes significantly to economic growth and thus has a positive impact on GDP [15]. In less developed countries, simply increasing R&D spending is insufficient without an enabling environment for innovation, the basis for creating an innovation ecosystem is capacity building, and in its absence, a whole range of innovation opportunities remain untapped [30]. From the perspective of digital transformation, this potential, consists of all areas included in the DESI.

Faced with evidence suggesting both direct and indirect effects in different economies, the need for a model that considers additional conditions that determine the occurrence of these relationships has been identified. Given the complexity and interdependence of the variables describing the DESI (33 aggregate indicators for each year), fuzzy logic-based modelling was deemed reasonable. The most important arguments in favour of using this method are related to the need to evaluate multiple interdependent variables [3]. Researchers use it for economic modelling [37] and to assess the development of the digital economy [26]. They also argue that while traditional methods of analysing interdependence are deterministic, fuzzy logic models consider the uncertainty of variables caused by past behaviour, current actions, and changing forecasts [5, 13].

We have identified relationships between R&D spending and DESI level and DESI level and GDP per capita, as well as between R&D spending and GDP per capita. We also know that in the digital economy, value added from R&D activities materialises primarily through digital channels, which enable the scaling of innovations and increase their impact on productivity and GDP [45]. Based on this, we formulated a hypothesis:

H: Fuzzy logic can effectively model the nonlinear relationship between R&D investment, digitalisation level (the DESI), and GDP per capita in EU countries, taking into account their stage of digital transformation.

3. Methodology

The main goal of our research is to develop a model of the relationship between R&D investment, DESI level and GDP per capita using fuzzy logic. Identifying the degree of relationship will allow us to determine how strongly the elements of the system influence each other. The analysis focuses on the years 2022 and 2023, as the structure of the DESI index underwent significant changes prior to 2022, making earlier data incomparable; in total, the model was based on 1,890 input data points.

In the proposed approach to modelling and assessing the relationships between the aforementioned variables, fuzzy multi-valued logic was used, in particular implication and aggregation operators. In our research, we use the fact that implication reflects the degree of dependence between an antecedent and a consequent. In multi-valued logic, Łukasiewicz proposed the following implication:

$$a \rightarrow b = \min(1 - a + b;\ 1) \tag{1}$$

which allows for modelling vague relationships in fuzzy logic and determining how much one value influences another. At the same time, Łukasiewicz's t-norm is one of the triangulation norms used to model conjunctions in fuzzy logic, in particular when there is a need to model gradual dependence:

$$T(a,\ b) = max\ (a + b - 1;\ 0) \tag{2}$$

In our approach Łukasiewicz's t-norm it plays the role of an aggregation function, aggregating values in accordance with the rules of fuzzy logic. The model adopts the following analysis directions:

R&D → DESI　　　DESI → GDP　　　R&D → GDP

The relationship was based on causal logic assumption on the reasoning described in the theoretical part. The dependencies were defined separately for each country. The implications R&D → DESI and DESI → GDP incorporate all four groups of DESI indicators listed on Heatmap 1-2. The value of the causal relationship was quantified through the conjunction of two fuzzy implications (R&D → DESI & DESI → GDP). At the same time, it was assumed that the joint occurrence of the first two conditions (R&D → DESI & DESI → GDP), determines the fulfilment of the third condition (R&D→ GDP).

In consequence, to determine the relationship between research and development

(R&D) investments, the level of digitalisation (the DESI) and GDP per capita (GDP), the following model was proposed:

$$[(R\&D \rightarrow DESI) \,\&\, (DESI \rightarrow GDP)] \rightarrow (R\&D \rightarrow GDP) \quad (3)$$

Let's assume that p = R&D, q = DESI and r = GDP, then $[(p \rightarrow q)\&(q \rightarrow r)] \rightarrow (p \rightarrow r)$. In classical logic, this is a law of logic. In fuzzy logic it corresponds to $[(p \rightarrow q)\&(q \rightarrow r)] \leq (p \rightarrow r)$ so in Łukasiewicz's logic we also obtain a tautology [17].

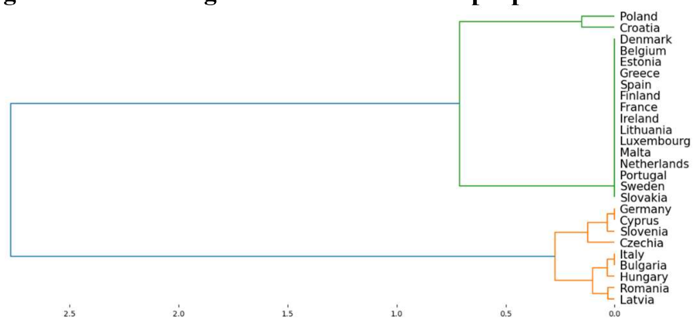
The application of Łukasiewicz logic in analysis results from its unique mathematical properties, which are well suited to the nature of the analysed relationships between investments in R&D, the DESI, and GDP per capita. The implication operator in Łukasiewicz's logic is linear and continuous, what makes it more interpretable in economic models. This form of implication well captures the idea that the truer the premise is, the greater the *burden of proof* is placed on the truth of the conclusion. Moreover, Łukasiewicz logic allows for modeling various levels of inconsistency between the premise and the conclusion. This is useful when there are inconsistencies between economic variables that are not simply *true or false* but have partial agreement. Łukasiewicz implication allows for expressing relationships in the form of IF-THEN rules with intermediate values, what is crucial when modeling complex relationships.

4. Results

4.1. Cluster Analysis of R&D, DESI, and GDP per capita in the EU

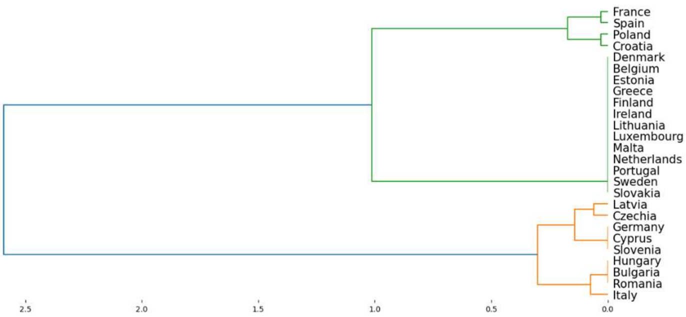
Dendrograms 1 and 2 represent hierarchical relationships between the considered data for both 2022 and 2023, which were included in the study. The clusters represent a group of EU countries defined by the degree of dependence if R&D→DESI & DESI→GDP, then R&D→GDP.

Dendrogram 1. Clustering of countries based on proposed model for 2022



Source: Own elaboration.

Dendrogram 2. Clustering of countries based on proposed model for 2023



Source: Own elaboration.

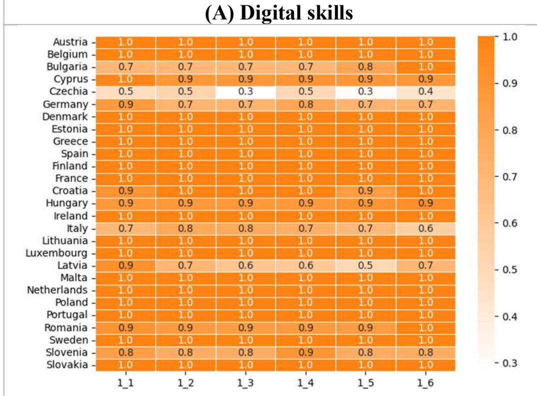
In 2022, for 16 countries (Austria, Belgium, Denmark, Estonia, Finland, France, Greece, Ireland, Lithuania, Luxembourg, Malta, the Netherlands, Portugal, Slovakia, Spain and Sweden), and in 2023, for 14 countries (excluding France and Sweden), a complete dependence (value of 1.000) between the components of the model (i.e. R&D, the DESI and GDP per capita) was confirmed. These countries formed the first cluster in which four groups of variables, comprising a total of 33 DESI indicators, described the relationship between the analysed components at the level of 1.000. They were mostly original EU countries, except: Estonia, Lithuania, Malta and Slovakia, which joined the EU in 2004. The second cluster included countries with slightly lower numbers of the most significant links (also with a value of 1.000) between model components. In 2022 it included Poland and Croatia, and in 2023 France and Spain joined. The third cluster was formed by countries for which the number of complete dependencies between model components ranged from 0 to 9 DESI indicators. These were: Bulgaria, Italy, Hungary, Romania, Latvia, Slovenia, Cyprus, Germany and the Czech Republic. Apart from Italy and Germany, these were new EU states. Despite a common accession date, the cluster was characterized by internal diversity. Bulgaria, Italy, Hungary and Romania stood out positively, while the Czech Republic (in both years) ranked last in the group.

4.2. The results of fuzzy logic-based modelling

The results presented in the previous section, due to their aggregated nature, provide an overall picture of the links between R&D, the DESI, and GDP per capita. The specific degree of these relationships was determined based on the model we proposed in the Methodology section. The analysis included 33 DESI components grouped into four categories: (A) Digital skills, (B) Digital infrastructure, (C) Digital transformation of businesses, and (D) Digitalisation of public services. The results for 2022 are presented in heatmap 1 and for 2023 in heatmap 2.

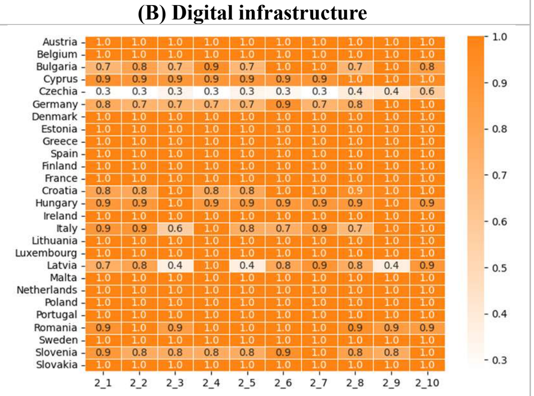
Heatmap 1. Degree of relationship between R&D, DESI and DGP per capita for 2022

(A) Digital skills



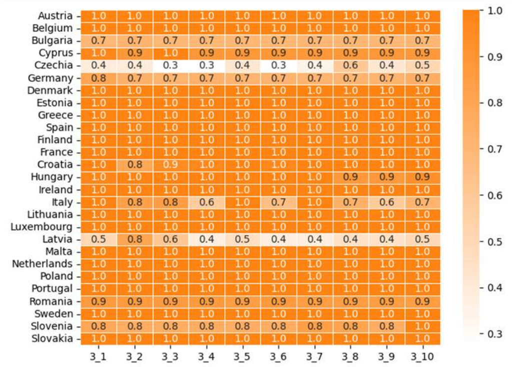
1.1. Internet use (16-74) % of individuals, 1.2. At least basic digital skills, 1.3. Above basic digital skills, 1.4. Enterprises providing ICT training, 1.5. ICT specialists, 1.6. ICT graduates

(B) Digital infrastructure



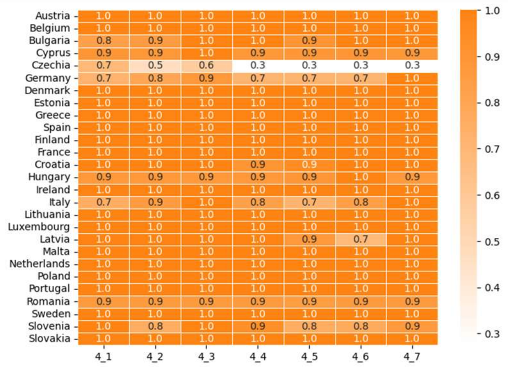
2.1. Overall internet take-up, 2.2. At least 100 Mbps fixed broadband take-up, 2.3. At least 1 Gbps fixed broadband take-up, 2.4. Share of fixed broadband subscriptions >= 100 Mbps, 2.5. Share of fixed broadband subscriptions >= 1 Gbps, 2.6. Fixed Very High Capacity Network (VHCN) coverage, 2.7. Fibre to the Premises (FTTP) coverage, 2.8. Mobile broadband take-up, 2.9. Overall 5G coverage, 2.10. 5G spectrum.

(C) Digital transformation of businesses



3.1. SMEs with at least a basic level of digital intensity, 3.2. Electronic information sharing, 3.3. Social media, 3.4. Big data, 3.5. Cloud, 3.6. Artificial intelligence, 3.7. e-Invoices, 3.8. e-Commerce turnover, 3.9. SMEs selling online, 3.10. SMEs selling online cross-border

(D) Digitalisation of public services



4.1. e-Government users, 4.2. Digital public services for citizens, 4.3. Digital public services for businesses, 4.4. Pre-filled Forms, 4.5. Transparency of service delivery, design and personal data, 4.6. User support, 4.7. Mobile friendliness

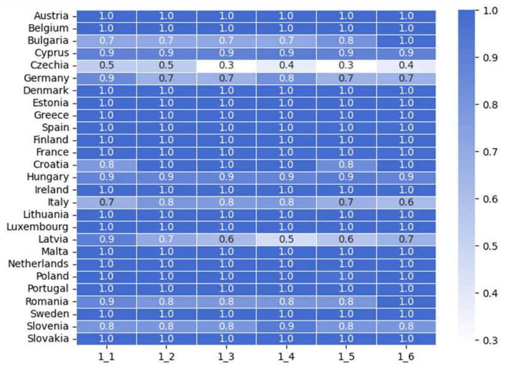
Source: Own elaboration.

Analysis of the four DESI (2022) component groups shows a clear digital division in the

EU. In 16 to 17 countries (depending on the DESI components) of Western and Nordic Europe (including Austria, Denmark, the Netherlands, Finland), all indicators reached complete dependence with a value of 1.000. In **digital skills**, the highest values (1.000) for *ICT graduates* and *At least basic digital skills* were achieved by 17 to 20 countries (relative to the component under analysis), including Poland, Ireland and Finland. Hungary and Cyprus report slightly lower but still high indicator values (e.g., *ICT specialists* - 0.935, *Enterprises providing ICT training* - 0.898). In contrast, Romania and Bulgaria lag behind (e.g. *Above basic digital skills* in Romania - 0.854). In **digital infrastructure**, complete dependence (1.000) occurred in 16 countries. Hungary (*Overall 5G coverage* - 0.995) and Latvia (*fixed broadband ≥ 100 Mbps* - 0.991) are near the top. Germany and Slovenia also have high scores (e.g., *VHCN coverage* - 0.914 and 0.927 respectively). In Cyprus and Romania, on the other hand, indicators such as *5G spectrum* and *Internet take-up range* between 0.884 and 0.934. In **digital transformation of businesses**, Poland stands out (1.000) for *e-Commerce turnover*, *Electronic information sharing* and *SMEs with basic digital intensity*. Hungary shows a high value for *Cloud* (0.995). Romania and Slovenia, on the other hand, have indicators below 0.870 (e.g., *AI* in Romania - 0.854). In the **digitalisation of public services**, 16 countries have achieved complete dependence (1.000). *Mobile friendliness* and *Digital public services for businesses* scored 1.000 in 22 countries. Hungary and Croatia have high *User support* values (1.000 and 0.998), while Romania and Cyprus are outliers (*e-Government users* - 0.854; *Pre-filled Forms* - 0.884).

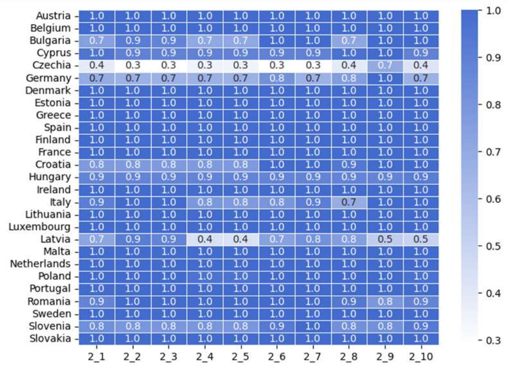
Heatmap 2. Degree of relationship between R&D, DESI and DGP per capita for 2023

(A) Digital skills



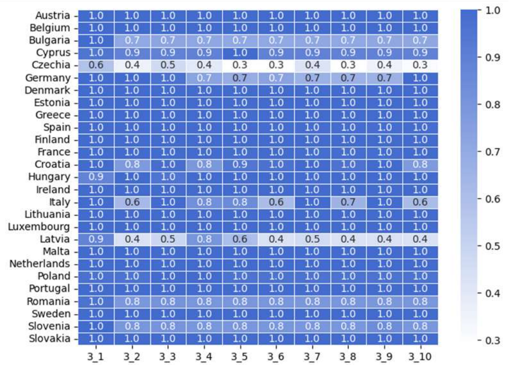
1.1. Internet use (16-74) % of individuals, 1.2. At least basic digital skills, 1.3. Above basic digital skills, 1.4. Enterprises providing ICT training, 1.5. ICT specialists, 1.6. ICT graduates

(B) Digital infrastructure



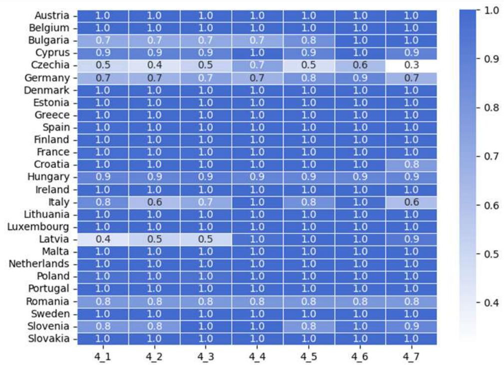
2.1. Overall internet take-up, 2.2. At least 100 Mbps fixed broadband take-up, 2.3. At least 1 Gbps fixed broadband take-up, 2.4. Share of fixed broadband subscriptions >= 100 Mbps, 2.5. Share of fixed broadband subscriptions >= 1 Gbps, 2.6. Fixed Very High Capacity Network (VHCN) coverage, 2.7. Fibre to the Premises (FTTP) coverage, 2.8. Mobile broadband take-up, 2.9. Overall 5G coverage, 2.10. 5G spectrum.

(C) Digital transformation of businesses



3.1. SMEs with at least a basic level of digital intensity, 3.2. Electronic information sharing, 3.3. Social media, 3.4. Big data, 3.5. Cloud, 3.6. Artificial intelligence, 3.7. e-Invoices, 3.8. e-Commerce turnover, 3.9. SMEs selling online, 3.10. SMEs selling online cross-border

(D) Digitalisation of public services



4.1. e-Government users, 4.2. Digital public services for citizens, 4.3. Digital public services for businesses, 4.4. Pre-filled Forms, 4.5. Transparency of service delivery, design and personal data, 4.6. User support, 4.7. Mobile friendliness

Source: Own elaboration.

Analysis of the DESI component groups for 2023 again shows a clear divide between the digitally advanced countries and the rest of the EU. In terms of **digital skills**, complete dependence (1.000) for all 6 indicators was achieved by 14 countries, mostly from Western and Nordic Europe. The highest values were observed for: *At least basic digital skills* and *Above basic digital skills* (18 countries), as well as for *ICT graduates* and *Internet use* (17 countries). High indicators' values were also recorded in Spain (0.991), France (0.989), Poland (0.975), Bulgaria (0.995) and Cyprus (0.917). In the **digital infrastructure** group, France joined the leading countries. Key indicators, such as *Overall 5G coverage*, *FTTP coverage* and *VHCN coverage*, reached complete dependence in more than 20 EU states. Poland stands out in terms of *5G spectrum* (0.970) and Cyprus in *mobile broadband usage* (0.975), among others. Latvia, Hungary, Slovenia, Romania also record high values of DESI indicators. Mobile infrastructure outpaces fixed infrastructure, especially in Central and Eastern Europe. In terms of **digital transformation of business**, 14 countries achieved complete dependence (1.000). The indicator - *SMEs with at least a basic level of digital intensity* - confirmed this relationship in 21 countries. France and Spain recorded very high values for most of the DESI indicators. Poland reached 1.000 for *Social med*ia and *Big data*, while the other indicators oscillated around 0.961. Cyprus and Croatia also recorded good results (up to 0.952). In the **digitalisation of public services** category, complete dependence (1.000) was achieved by 14 countries. *The Pre-filled Forms* and *User support indicators* reached this level in 21 countries. France, Spain and Poland scored very high (e.g., 0.991 - 1.000), while Cyprus and Hungary scored slightly lower (0.891-0.924). Countries with advanced e-government are the leaders, but Central and Southern European states are gradually catching up in the digitalisation of public services.

Fuzzy logic-based analysis confirmed full and partial relationships between R&D expenditure, DESI indicators, and GDP per capita in EU-27 (2022–2023). Despite EU ambitions, clear digital divides remain. Countries with mature digital policies and education systems, e.g., Sweden, Denmark, Finland, Netherlands show full alignment in digital skills [36]. Southern and Eastern Europe progress more slowly [7]. Poland, Hungary, and Romania improve [8], but need stronger educational [4] and structural support. Spain and Portugal still face gaps in advanced digital skills [38]. In digital infrastructure, countries like Spain, France [31], and the Netherlands [35] lead with full broadband and 5G coherence. CEE states (e.g., Poland [23], Latvia [24]) excel in mobile tech, but lag in fixed-line networks. Infrastructure gaps in Bulgaria and Romania still limit growth [16].

Digital business transformation is most advanced in states with strong SMEs and public support [46], such as Spain, France, and Sweden. AI and Big Data are well integrated. In CEE and Southern Europe [22], adoption is rising but uneven. Poland and Hungary show high SME digitisation, but full integration remains limited. Cyprus and Romania still lack coherence in digital tool use [43]. Western and Northern countries (e.g., Denmark, Finland, Netherlands) lead in digital public services [39]. CEE and Southern states like Poland advance, though personalisation is still partial [28]. Cyprus and Bulgaria remain behind, needing more investment [32].

5. Conclusions

Fuzzy logic enables identification of country differences often missed by traditional methods, confirming Besri and Boulmakoul's view on its effectiveness in handling digital transformation uncertainties [3]. The model offers a robust basis for designing targeted, multidimensional policies supporting countries at various digitalisation stages. Countries with moderate or low DESI levels, such as Bulgaria, Croatia, and the Czech Republic, typically show persistent low R&D spending alongside low GDP per capita. Higher R&D expenditures alone do not directly increase GDP per capita, highlighting the need for strategic allocation of public funds that supports specific DESI components and narrows digitisation gaps across the EU.

This model underlines the necessity of tailored, multifaceted digital interventions adapted to each country's context. Fuzzy logic is particularly valuable in analysing relationships among R&D spending, digital transformation indicators (i.e. the DESI), and GDP per capita, where data often remain ambiguous or hard to measure precisely. Unlike traditional quantitative methods, it captures fuzzy category boundaries and variable interdependencies, thus better reflecting complex economic realities. This facilitates more accurate innovation policy decisions and more efficient public fund allocation.

Overall, fuzzy logic not only mirrors the complexity of the modern economy more faithfully but also yields more precise and actionable analytical insights, making it highly suited for studying complex, dynamic socio-economic phenomena.

The presented analysis has certain limitations. First, it is based on cross-sectional data from 2022 and 2023, which limits the ability to capturing changes over time and considering the delayed effects of R&D investments. The fairly high level of aggregation of the DESI index may lead to a loss of detail, the model does not include other important factors of socio-economic development, such as the quality of institutions, the structure of the labour market, or the level of education. These areas may provide an interesting scope for further analysis.

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