
CHAPTER 2

Digital drivers of business model transformation in the circular economy paradigm

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Abstract

This study provides a quantitative assessment of the digital drivers influencing business model transformation within the circular economy paradigm, using data from European Union countries. An integrated framework for evaluating the level of digital-circular integration is developed and implemented. The methodological approach includes the construction of a composite index, correlation and regression analyses, K-means clustering, principal component analysis (PCA), and scenario modelling. The study introduces the Integrated Digital Circular Economy Index (IDCEI), which comprises five core indicators reflecting digital intensity and resource efficiency. It is hypothesized that operational digital integration particularly through enterprise resource planning (ERP) systems and the Circular Material Use (CMU) rate are key drivers of the circular transition. The analysis reveals asymmetries in digitalization levels and investment structures across EU member states. The robustness of the IDCEI is validated through empirical verification. Based on digital-circular transformation trajectories, three clusters of countries are identified. The study outlines three development scenarios: intensive digital integration, fragmented implementation, and digital stagnation. A typology of transition models is proposed and visualized, facilitating the identification of transformation pathways. The findings provide a foundation for policy development in digital-environmental transformation, cross-country benchmarking, and integration monitoring. The IDCEI shows potential for broader application in international comparative studies. The scientific contribution lies in the formalization of a novel index for measuring digital-circular transformation and the methodological integration of quantitative and qualitative tools. Research implications include expanding the data set, refining digital indicators (e.g., AI, IoT, DPP), and applying the framework to sectoral analyses.

This chapter is empirical in nature.

Keywords

Circular economy, digital transformation, business models, ERP systems, digital integration, cluster analysis, composite index, sustainable development.

2.1 Introduction

At the current stage of economic development, the significance of the integrated twin transition concept is increasingly evident. This concept entails simultaneous and interlinked transformations along two critical dimensions – ecological and digital – which compel businesses to reconsider their development strategies and fundamentally redesign operational models.

The transition from a linear to a circular economy requires profound transformations in business models, prioritizing reuse, recovery, recycling, and resource efficiency. According to OECD data [1], global material consumption rose from 37 billion tons in 1990 to 88 billion tons in 2017, with projections suggesting it may double by 2060. These figures underscore the urgent need to adopt resource-efficient economic practices.

Within this framework, digital technologies play a crucial role. They enhance supply chain transparency and traceability, enable advanced product lifecycle analytics, support personalized services, and facilitate the adoption of service-oriented business models. Additionally, digital solutions reduce communication and coordination barriers among value chain stakeholders, promote partnerships, and foster the development of shared services and innovative business models.

However, research indicates that service-based circular economy models do not always guarantee sustainability due to potential risks, such as load redistribution and unintended consequences.

As a result, it is essential to examine the digital drivers behind business model transformation, as they shape both the pace and direction of the transition to the new economic paradigm. Moreover, it is important to assess the practical implications of these changes – specifically, the adaptability of business models to circular economy principles across operational, innovative, and strategic dimensions.

Amid growing pressure from consumers, governments, and civil society, businesses are increasingly required to embrace new value creation models characterized by resource efficiency, renewability, and circularity. Digital technologies are critical enablers of this transformation, essential for ensuring the sustainability and competitiveness of contemporary business models.

In this context, developing an integrated indicator capable of quantitatively assessing the level of digital – circular integration becomes especially important.

To address this need, the author proposes the Index of Digital Circular Economy Integration (IDCEI), a composite measure designed to evaluate the degree of transformation in business environments toward a digitally oriented circular economy. The methodological foundations for constructing the IDCEI are detailed in Paragraph 2.2.

Current academic literature demonstrates a growing interest in digitalization within the context of circular transformation. For instance, D. Chiaroni, P. D. Vecchio, D. Peck, A. Urbinati, D. Vrontis identify digitalization as a key enabler of circularity, capable of reshaping enterprise operations, product design, and consumer behavior [3]. Similarly, G. Bressanelli, N. Saccani, and M. Perona examine the sustainability of digitally servitized business models through a "what-if" systemic approach, highlighting potential risks associated with load redistribution and unintended consequences [2].

A. Pagoropoulos, D. Pigosso, and T. McAloone underscore the capacity of digital technologies to enhance resource efficiency and generate new business model opportunities [4]. In a related vein, M. Antikainen, T. Uusitalo, and P. Kivikytö-Reponen emphasize the role of digital solutions, particularly Big Data and analytics in optimizing resource flows and improving product traceability [5].

A systematic review by C. Chauhan, V. Parida, and A. Dhir maps out technologies that support circularity, drawing attention to the gap between theoretical contributions and practical implementation challenges [6]. P. Rosa, C. Sassanelli, and S. Terzi propose archetypes and classification frameworks for circular business models in digitally enabled contexts [7]. In parallel, V. Ranta, L. Aarikka-Stenroos, and J.-M. Väisänen explore how digital technologies can help overcome transition barriers and foster innovation [8], while F. Lüdeke-Freund, S. Gold, and N. Bocken develop a typology of circular economy business models, with a particular focus on the enabling role of digital tools [9].

In the context of digital transformation of business models, particularly under conditions of instability and post-crisis recovery, agent-based modeling and intelligent optimization algorithms play a critical role. T. Cherniavska, N. Tanklevska, B. Cherniavskiy present several approaches that highlight the potential of digital technologies for optimizing vital systems in wartime and post-war scenarios. Their studies include the development of an agent-based decision-making system for managing water resource remediation in the Kherson region [10], an architecture-oriented agent-based model for optimizing transport evacuation and emergency medical assistance during the war in Ukraine [11], and the application of bee colony algorithms for medical logistics optimization in emergency and post-conflict settings [12]. These works demonstrate how AI-driven and agent-based solutions can support the adaptation and resilience of complex systems in the face of disruption. Such approaches offer valuable insights for circular economy strategies, which require flexible, sustainable, and digitally enabled business models to respond

effectively to environmental and systemic challenges. Y. Kyrlov, V. Hranovska, V. Savchenko, L. Kononenko, O. Gai, S. Kononenko explore sustainable rural development through the application of digital and nanotechnologies in education and business, highlighting their potential to foster innovation and support circular business model adaptation in rural areas [13]. Similarly, L. Kononenko, O. Atamas, H. Nazarova, Y. Selishcheva, S. Kononenko examine tax optimization for small agricultural producers via innovative-integrated structures, contributing to the development of more efficient and sustainable business models [14]. A. Karnaushenko, N. Tanklevska, T. Povod, L. Kononenko, V. Savchenko highlight the role of blockchain technology in transforming agricultural business models toward circularity, emphasizing its potential to support transparency and traceability in supply chains [15].

Despite the increasing relevance of this topic, the specific impacts of digital technologies on the integration of circular economy principles – both at the firm level and across industry sectors – remain underexplored. In particular, limited scholarly attention has been paid to how digital technologies restructure business models, redefine value creation logic, and transform customer engagement. Moreover, it remains unclear to what extent firms can effectively embed circularity into both existing and newly developed business models.

Consequently, conducting empirical research aimed at identifying the digital drivers of business model transformation within the circular economy paradigm while analyzing sector-specific dynamics, exploring implementation barriers, and assessing the potential for achieving sustainable competitive advantage appears both timely and relevant.

The aim of this study is to quantitatively evaluate the digital drivers influencing business model transformation within the circular economy paradigm, drawing on evidence from European Union countries. To this end, the research develops a composite indicator – the Index of Digital Circular Economy Integration (IDCEI) – analyses its structural components, conducts cross-national comparisons, and identifies institutional and sector-specific characteristics that underpin the transition towards digital circularity.

Achieving this objective requires the verification of several scientific assumptions that clarify the causal relationships between levels of digitalization, investment activity, and the degree of circular business model implementation. Accordingly, the following hypotheses have been formulated to reflect the anticipated structural interdependencies among key factors driving digital – circular transformation, and to facilitate empirical validation of the study's conceptual framework:

H1: there is statistically significant variability among EU countries regarding the level of digital-circular transformation of business models, attributable to differences in institutional, economic, and technological readiness.

H2: a higher degree of digitalization particularly through the adoption of ERP systems and artificial intelligence (AI) is positively correlated with the extent to which circular practices are embedded within business models.

H3: the volume of investments directed towards the circular economy constitutes a critical factor in accelerating digital-circular transformation; however, investment alone does not ensure a high level of integration in the absence of well-developed digital infrastructure.

H4: the digital – circular transformation of business models within EU countries is uneven, owing to varying degrees of technological maturity, economic capacity, and alignment with sustainable development policies.

2.2 Research methodology

2.2.1 Methodological framework

The methodological framework of this study is grounded in an interdisciplinary approach that integrates the concepts of digital transformation, business model innovation, and circular economy principles. To address the research objectives, a comprehensive methodological toolkit was employed, incorporating both qualitative and quantitative analytical techniques.

A systematic review of recent scientific literature was conducted using databases such as ScienceDirect, the OECD iLibrary, and Google Scholar. The aim was to identify key digital drivers of circular transformation and to establish a robust theoretical and analytical foundation. Sources were selected using relevant keywords, including "circular economy business models", "digital transformation", "servitization", and "resource efficiency".

The empirical analysis draws on official statistical data from Eurostat, the OECD, and the World Bank, encompassing a range of digital and circular economy indicators for European Union member states. These data were used to construct the Integrated Digital Circular Economy Index (IDCEI), a composite measure designed to capture the extent of digital-circular transformation.

To enable a more in-depth analysis, the following methods were applied:

1. Correlation analysis was carried out to examine the interrelationships among key variables.
2. A multiple linear regression model was estimated using the ordinary least squares (OLS) method to assess the relative impact of each factor on the IDCEI score.

3. K-means clustering was employed to identify homogeneous groups of countries based on their levels of digital – circular maturity.

4. Principal Component Analysis (PCA) was utilized to visualize the spatial distribution of countries within a multidimensional analytical framework.

5. Scenario analysis was incorporated to simulate potential transformation trajectories of business models, accounting for institutional and sector-specific contexts.

This integrated methodological approach enabled empirical testing of the research hypotheses (H1–H4) and facilitated a comprehensive characterization of the digital-circular transformation process in contemporary business models.

2.2.2 Conceptual foundations of the Integrated Digital Circular Economy Index (IDCEI)

The Integrated Digital Circular Economy Index (IDCEI) is a composite indicator designed to quantitatively assess the extent to which digital technologies are integrated with circular economy principles within national economies. The index captures the degree to which countries are adapting their business models to align with contemporary sustainability imperatives, viewing digitalization not as an end in itself, but as a strategic enabler of resource efficiency, renewability, and circularity.

Employing a composite index methodology, the IDCEI enables cross-national comparisons of digital – circular maturity, thereby identifying leading performers, laggards, and structural disparities in integrated transformation processes. In addition, the index supports policy benchmarking, strategic monitoring of progress on key indicators, and the identification of areas requiring enhanced institutional capacity or targeted investment. As such, the IDCEI serves both diagnostic and prognostic functions, reframing digital transformation from a purely technological endeavor to a foundational pillar of sustainable economic development within the circular economy paradigm.

The IDCEI comprises the following five indicators:

- digital intensity of enterprises (%) – representing the overall level of digitalization across businesses;
- share of enterprises using ERP systems (%) – reflecting the depth of digital integration in internal operational processes;
- investment in the circular economy as a share of GDP (%) – indicating governmental financial commitment to the circular transition;
- circular Material Use Rate (CMU, %) – measuring the proportion of secondary materials reused in production cycles;

– waste generated per unit of GDP (inverse indicator) – serving as a proxy for eco-efficiency.

To ensure cross-country comparability, all component indicators were normalized using the Min-Max normalization method, a linear rescaling technique that transforms data into a [0,1] range

$$x_{norm} = \frac{X - X_{min}}{X_{max} - X_{min}}. \quad (2.1)$$

For the indicator "Generation of waste excluding major mineral wastes per unit of GDP", inverse normalization was applied, as lower values signify higher levels of resource efficiency. This transformation ensures that all indicators follow the same directional logic, where higher scores reflect more advanced digital-circular integration (formula (2.2))

$$x_{inv.norm} = 1 - \frac{X - X_{min}}{X_{max} - X_{min}}. \quad (2.2)$$

The calculation of the Integrated Digital Circular Economy Index (IDCEI) is expressed as a weighted sum of the normalized component indicators, thereby capturing the composite nature of the index

$$IDCEI = 0.2 \cdot ERP_{norm} + 0.2 \cdot Digital_{norm} + 0.2 \cdot Invest_{norm} + 0.25 \cdot CMU_{norm} + 0.15 \cdot (1 - Waste_{norm}). \quad (2.3)$$

The resulting index values range from 0 (indicating the lowest level of transformation) to 1 (representing the highest level), thereby enabling meaningful comparisons and benchmarking across countries.

Weighting coefficients for constructing the IDCEI were determined through analytical weighting, taking into account strategic priorities defined by the European Union under the European Green Deal and the Circular Economy Action Plan. The adopted weighting structure reflects both the functional importance of each indicator in business model transformation and their representativeness in cross-country comparisons.

Specifically, the digital component, accounting for a combined 40%, comprises two indicators: the share of enterprises using ERP systems (weighted at 20%) and the Digital Intensity Index of enterprises (also weighted at 20%). ERP systems play a pivotal role in the digital integration of internal processes, particularly resource and logistics management – essential aspects for implementing circularity principles. Meanwhile, the Digital Intensity Index captures the overall readiness of the business

environment to adopt advanced technological solutions such as artificial intelligence, cloud computing, and analytics.

The overall circular component constitutes 45% of the total weighting. Within this component, the Circular Material Use Rate (CMU) – considered a key indicator of circularity in European statistical frameworks – holds a 25% weighting. A further 20% is allocated to investments in the circular economy as a share of GDP, reflecting national financial commitments to sustainable development and the innovative transformation of production processes.

The eco-efficiency indicator – generation of waste excluding major mineral wastes per unit of GDP – is included using inverse normalization, with a weighting of 15%. Although this indicator primarily reflects the outcomes of resource use rather than directly driving transformation, it signifies progress in reducing waste generation and pollution, thereby justifying its moderate weight in the index structure.

Therefore, the proposed weighting scheme effectively balances the technological and environmental dimensions of transformation, capturing both potential capacity and actual performance in realizing a digitally driven circular development model.

2.3 Results

2.3.1 Investments in the circular economy

European Union investments in digital technologies are crucial for accelerating the transition to a circular economy. Under the EU's Multiannual Financial Framework for 2021–2027, significant resources are allocated to digital transformation and the development of Industry 4.0, including support for research in artificial intelligence, cybersecurity, and advanced digital skills. Such investments create the necessary conditions for implementing circular business models by promoting the broader adoption of digital solutions across both economic activities and societal practices [16]. Specifically, the EU plans to mobilize over 100 billion EUR to support regions that require substantial adaptation to the green economy, including the decarbonization of the energy sector and the integration of circular economy practices [17, 18] (**Fig. 2.1**).

To evaluate the impact of investments on the development of the circular economy across EU countries, generalized data on private investments in circular economy sectors for the period 2019–2023 are presented below (**Table 2.1**). Countries were selected based on their total investment volumes in 2023 and categorized into three distinct groups: leaders (Germany, France, the Netherlands, Italy), moderate performers (e.g. Czech Republic, Spain, Finland), and countries with the lowest

investment levels (Cyprus, Latvia, Malta, Bulgaria, Greece). This classification facilitates the identification of structural differences between countries and supports a more detailed analysis of the factors underlying uneven investment distribution within the EU's circular economy landscape.

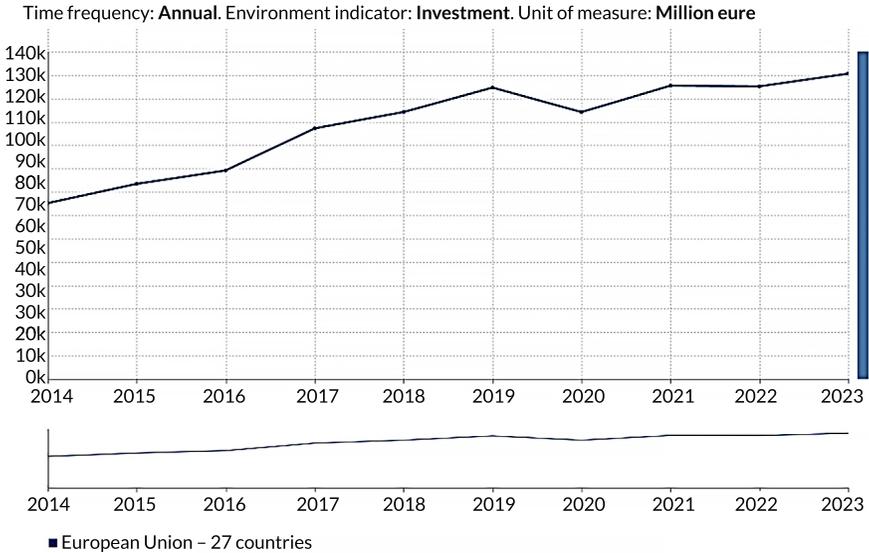


Fig. 2.1 Private investment to circular economy sectors
Source: [17, 18]

Between 2019 and 2023, investment dynamics in circular economy sectors across EU countries were mixed. An analysis of the 15 selected countries reveals sustained investment growth in certain states, alongside notable fluctuations or declines in others. **Table 2.1** illustrates trends in private investment in circular economy sectors across EU countries during the 2019–2023 period. The data highlight a general upward trend in investment, while also revealing significant heterogeneity among member states. The highest growth rates were recorded in Finland (+29.6%), Luxembourg (+23.5%), and the Czech Republic (+10.0%), reflecting the successful implementation of sustainability policies, government support for innovation, and strong private sector readiness to adopt circular practices. Moderate investment growth was observed in France (+8.1%), Romania (+6.3%), and Germany (+13.4%), indicating steady development within their respective circular economy sectors.

Table 2.1 Dynamics of investments in the circular economy by EU country (2019–2023)

Country	2019	2020	2021	2022	2023	Change 2023 vs 2019 (%)
Germany	34831	35255	37147	37342	39500	13.40
France	20832	21993	23523	21961	22515	8.08
Netherlands	11346	8666	10360	10740	11229	-1.03
Italy	13118	8142	9734	9861	10173	-22.45
Czech Republic	1618	1557	1816	1732	1780	10.01
Romania	1098	940	1329	1135	1167	6.28
Hungary	1120	1009	1040	1095	1145	2.23
Luxembourg	858	721	1033	1016	1060	23.54
Finland	759	773	1389	957	984	29.64
Cyprus	75	68	129	66	68	-9.33
Malta	93	76	68	80	83	-10.75
Slovenia	146	133	169	126	127	-13.01
Greece	370	327	527	203	174	-52.97
Latvia	349	215	205	229	234	-32.95
Other countries	33864	30669	33156	34225	35365	4.40

Source: [17, 18]

Conversely, several countries experienced a reduction in investment levels. The sharpest declines were recorded in Greece (-52.9%) and Latvia (-32.9%), alongside negative trends in Italy (-22.5%), Slovenia (-13.0%), Malta (-10.8%), and Cyprus (-9.3%), necessitating further analysis of national strategies and priorities related to the green transition.

Thus, the results indicate growing investment activity in selected EU member states within the circular economy, while simultaneously underscoring persistent structural disparities. These findings highlight the need for targeted support policies to address negative investment trends and promote deeper integration of circular principles into economic planning at both national and supranational levels.

Governmental support plays a critical role in fostering investments in the circular economy. For example, France launched the Eco-responsible Digital Acceleration programme under the France 2030 plan, providing financing for projects focused on eco-design and digital product lifecycle extension [19]. In 2023, Germany adopted the National Circular Economy Strategy (NCES), prioritizing digital solutions such as resource tracking and introducing a Digital Product Passport for industry [20, 21]. Such state-level initiatives incentivize the private sector to invest in relevant technologies and infrastructure.

Overall, these findings demonstrate not only the structural disparities among EU countries in adopting circular economy models but also emphasize the need for adaptive support and stimulation policies tailored to each member state's economic, regional, and technological specificities.

Regarding Ukraine, the State Statistics Service of Ukraine does not report this indicator in the Eurostat format [21], and investments in circular solutions remain relatively low.

2.3.2 Calculation of the Integrated Digital Circular Economy Index (IDCEI) based on statistical indicators

The Integrated Digital Circular Economy Index (IDCEI), developed by the author, was applied to analyze the current state of digital-circular maturity of business models in selected EU countries. The index is constructed from the following five indicators:

- digital intensity level of enterprises (Digital);
- proportion of enterprises using ERP systems (ERP);
- investment in the circular economy as a share of GDP (Invest);
- circular material use rate (CMU);
- generation of waste excluding major mineral wastes per unit of GDP (Waste).

Within the research, Min-Max normalization was employed to standardize the primary indicators. Notably, the indicator "Generation of waste excluding major mineral wastes per unit of GDP" was inversely normalized due to its negative correlation with resource efficiency. The weighting of each indicator was determined analytically, taking into account the strategic priorities outlined in EU policy frameworks related to the circular economy and digital transformation.

Table 2.2 presents the input data and the final IDCEI calculations for the countries included in the sample described in Paragraph 2.3.1.

The top performers in terms of digital-circular integration are the Netherlands, Luxembourg, and Malta, which demonstrate high levels of both digital maturity and circularity. At the lower end of the ranking are Romania, Latvia, and Hungary, reflecting structural constraints in circular economy investments and slow progress in digitalization. The corresponding ranking is visualized in **Fig. 2.2**.

The results obtained enable a comparative assessment of countries based on their readiness to develop digitally enabled circular business models. Moreover, the IDCEI can serve as a foundational tool for the ongoing monitoring of transformation dynamics towards digital circularity.

Table 2.2 Input data and results of the Integrated Digital Circular Economy Index for 2023

Country	Digital intensity level of enterprises (Digital), %	Proportion of enterprises using ERP systems (ERP), %	Investment in Circular Economy as a Share of GDP (Invest), %	Circular material use rate (CMU), %	Generation of waste excluding major mineral wastes per GDP unit (Waste)	IDCEI
Germany	62	43.7	0.92	13.9	48	0.599
France	53	47.3	0.77	17.6	43	0.602
Netherlands	79	49.9	0.99	30.6	56	0.834
Italy	61	42.2	0.46	20.8	66	0.526
Czech Republic	51	29.0	0.56	12.8	81	0.336
Romania	28	22.6	0.33	1.3	110	0.024
Hungary	54	35.2	0.56	5.9	110	0.305
Luxembourg	59	43.8	1.23	10.2	31	0.656
Finland	86	56.9	0.36	2.4	46	0.561
Cyprus	68	41.6	0.2	5.4	71	0.358
Malta	77	46.5	0.37	19.8	44	0.623
Slovenia	52	37.0	0.19	8.8	57	0.378
Greece	44	45.3	0.07	5.2	70	0.41
Latvia	49	34.0	0.58	5.0	85	0.288
EU Average	59	43.3	0.34	11.8	60	-

Source: [17, 18, 22, 23]

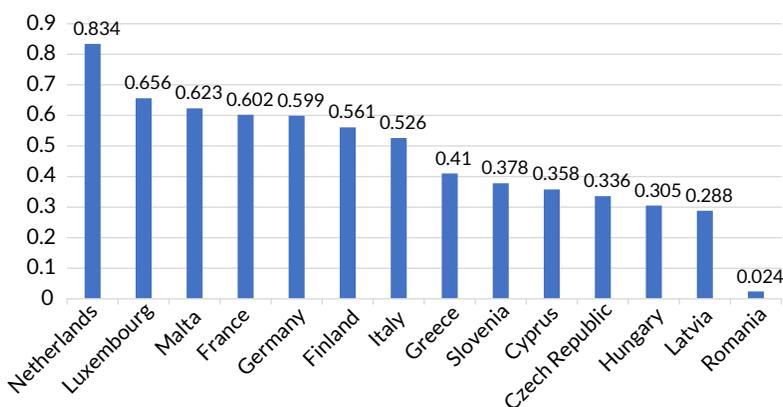


Fig. 2.2 Ranking results of the Integrated Digital Circular Economy Index for 2023
Source: visualized by the author of this study

Simultaneously, the quantitative assessment of digital-circular integration through the IDCEI provides a basis for conducting a qualitative analysis of potential scenarios for further business model transformation. Given the high degree of variability across countries, sectors, and institutional contexts, the application of a scenario-based approach is deemed appropriate as an analytical tool for forecasting possible development trajectories of a digitally oriented circular economy in both the medium- and long-term perspectives.

2.3.3 Empirical verification of the Integrated Digital Circular Economy Index (IDCEI) structure

To validate the methodological soundness of the constructed Integrated Digital Circular Economy Index (IDCEI), a correlation and regression analysis [24] of its constituent indicators was conducted. Given that the IDCEI is a composite indicator aggregating five variables, it is essential to empirically test which components contribute most to inter-country variability and to assess the extent to which the empirical structure aligns with the theoretically assigned weighting scheme.

This approach does not aim to predict IDCEI values per se since they are derived from a linear combination of normalized indicators – but rather to evaluate the actual statistical significance of each component in shaping the index. In doing so, the robustness and validity of the index's construction are empirically verified.

The Ordinary Least Squares (OLS) method was employed to estimate the contribution of each indicator to the overall variance in IDCEI scores across countries. The dependent variable was the IDCEI score, while the independent variables were the five components included in the index. The results are presented in **Table 2.3**.

The results presented in **Table 2.3** suggest that the most substantial contributions to the variance in the IDCEI are made by the following predictors:

- CMU (Circular Material Use Rate) is the most influential variable ($p < 0.001$), highlighting the centrality of resource recirculation in digital-circular integration;
- ERP systems play a critical role in operational digitalization ($p = 0.001$), underscoring the importance of internal process integration;
- Invest (investment in the circular economy) also demonstrates strong statistical significance ($p = 0.002$), reflecting the level of resource commitment to structural transition;
- Waste is negatively associated with the IDCEI ($p = 0.032$), emphasizing the inverse relationship between inefficiencies in value creation chains and digital-circular maturity.

Table 2.3 Results of the OLS regression model for IDCEI

Variable	Coefficient	Std. error	t-statistic	p-value	95% confidence interval
Const	-0.0907	0.104	-0.875	0.407	[-0.330; 0.148]
Digital	+0.0008	0.001	0.844	0.423	[-0.001; 0.003]
ERP	+0.0106	0.002	5.005	0.001	[0.006; 0.015]
Invest	+0.1406	0.031	4.539	0.002	[0.069; 0.212]
CMU	+0.0087	0.001	6.787	0.000	[0.006; 0.012]
Waste	-0.0016	0.001	-2.591	0.032	[-0.003; -0.000]

Source: developed by the author of this study

Note: Model diagnostics indicate a high level of explanatory power: $R^2 = 0.986$, adjusted $R^2 = 0.977$, suggesting that the model explains 98.6% of the variance in the IDCEI. The F-statistic = 110.3 with a p-value < 0.001 confirms the overall statistical significance of the regression model

Conversely, the digital variable is not statistically significant ($p = 0.423$), indicating relatively weak explanatory power when decoupled from more advanced digital integration mechanisms, such as ERP.

To further explore the interrelationships among variables, a correlation matrix was developed and is presented in **Table 2.4**.

Table 2.4 Correlation matrix between the IDCEI and its component indicators

	Digital	ERP	Invest	CMU	Waste	IDCEI
Digital	1.00	0.83	0.26	0.50	-0.61	0.58
ERP	0.83	1.00	0.48	0.73	-0.73	0.85
Invest	0.26	0.48	1.00	0.67	-0.58	0.84
CMU	0.50	0.73	0.67	1.00	-0.77	0.93
Waste	-0.61	-0.73	-0.58	-0.77	1.00	-0.84
IDCEI	0.58	0.85	0.84	0.93	-0.84	1.00

Source: calculated by the author of this study

The analysis revealed a strong positive correlation between the IDCEI and the indicators CMU, ERP, and Invest, as well as a significant inverse correlation with Waste. These results confirm that the index structure effectively reflects cross-country differences in the integration of digital and circular approaches. In contrast, the moderate correlation between Digital and the IDCEI (0.58) indicates the need for further refinement of the digital component – particularly through the incorporation of specific technologies such as artificial intelligence (AI), the Internet of Things (IoT), or Digital Product Passports (DPP).

The correlation and regression analysis provided robust empirical support for the proposed structure of the Integrated Digital Circular Economy Index. The most influential variables in explaining IDCEI variance are those assigned the highest weights in the index methodology (CMU, ERP, Invest), thereby validating both the theoretical assumptions and the applied weighting scheme. These findings suggest that the IDCEI serves as a reliable tool for assessing the structural foundations of digital-circular business model transformation across EU member states.

Furthermore, the observed variability in IDCEI scores among countries points to significant structural asymmetries in their transformation trajectories. To identify these patterns and classify countries according to their level of digital-circular maturity, a cluster analysis was conducted. This approach not only enables the identification of countries with similar transition profiles but also provides a quantitative basis for topologizing transformation models at the supranational level.

2.3.4 Cluster analysis of the digital-circular transformation of business models

To identify typical groups of countries based on their level of digital-circular transformation, the *K*-means clustering method was applied. This technique enables the automatic grouping of countries according to the similarity of their digital and circular characteristics and is particularly suitable for detecting latent structures in multidimensional datasets.

The analysis incorporated the five key indicators that constitute the IDCEI: Digital, ERP, Invest, CMU, and Waste. All variables were pre-processed using normalization techniques to ensure equal contribution to the clustering process.

To determine the optimal number of clusters, the elbow method was employed. This approach involves evaluating the dynamics of inertia (i.e. within-cluster variance) across different values of *k* (number of clusters), ranging from 1 to 10. The resulting elbow point – where the rate of inertia reduction begins to plateau – indicates the most appropriate cluster count. The outcomes of this procedure are visualized in **Fig. 2.3, 2.4**.

Fig. 2.4 illustrates a distinct inflection point at $k = 3$, indicating that the optimal number of clusters is three. Beyond this point, the reduction in within-cluster inertia becomes marginal, suggesting limited benefits from further segmentation. Based on this result, the countries were grouped into three clusters reflecting typical trajectories of digital-circular transformation:

Cluster 0 – leaders in digital-circular transformation: these countries demonstrate high levels of digital maturity, extensive adoption of ERP systems, substantial

investment in circular economy initiatives, high Circular Material Use (CMU) rates, and low levels of waste generation. Collectively, these features reflect an advanced stage of twin transition implementation.

Cluster 1 – structurally lagging countries: this group is characterized by low levels of digitalization, limited ERP adoption, high waste intensity, and the lowest IDCEI values. Such a profile indicates systemic underperformance in both digital and circular domains.

Cluster 2 – digitally active but circularly underdeveloped countries: despite relatively high digital intensity, these countries report low CMU rates and limited circular economy investment. This imbalance constrains the overall depth of their business model transformation.

Step-by-step K-means clustering visualization ($k = 1$ to 10)

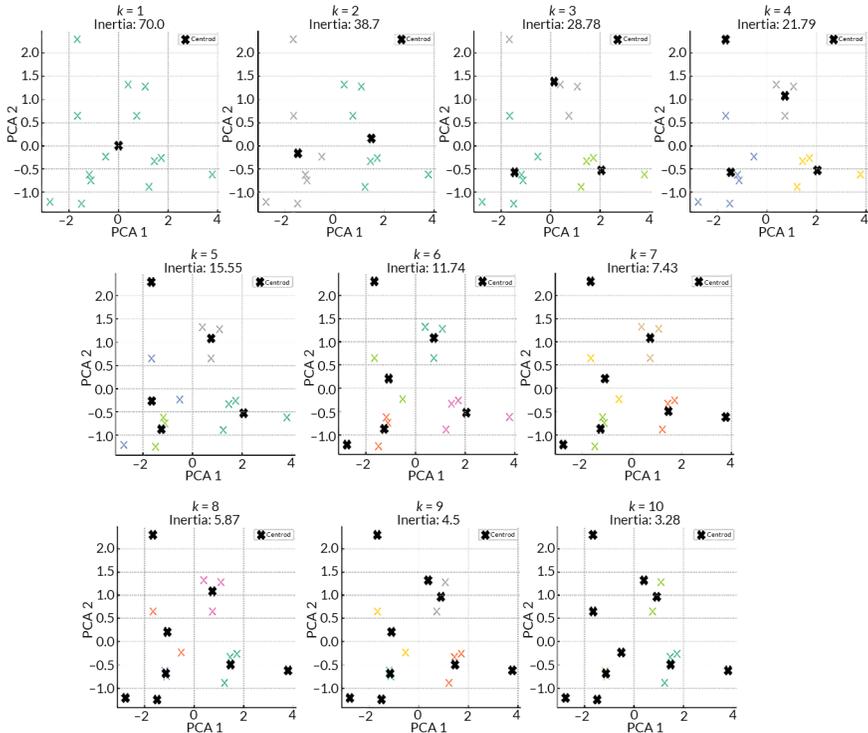


Fig. 2.3 Visualization of country clustering using the K-means method ($k = 1-10$)
 Source: visualized and calculated by the author of this study

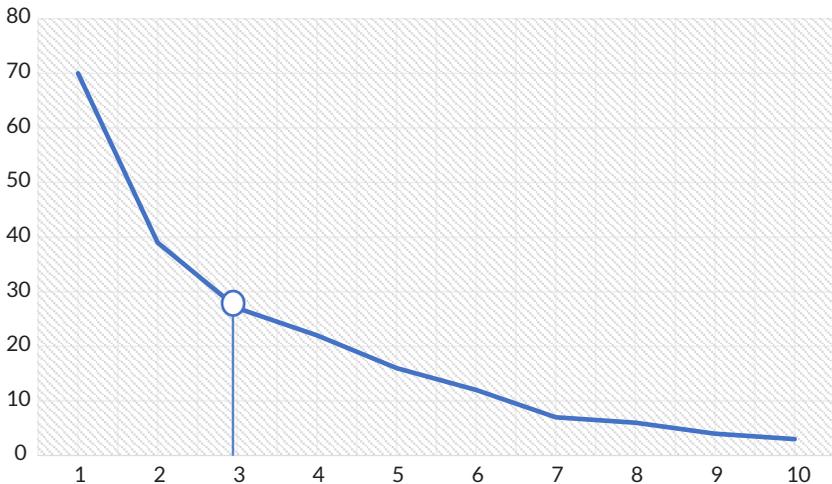


Fig. 2.4 Elbow method for determining the optimal number of clusters

Source: visualized by the author of this study

The average values of the key indicators for each cluster are summarized in **Table 2.5**.

Table 2.5 Average values of digital and circular indicators across identified clusters

Cluster	Digital	ERP	Invest	CMU	Waste	IDCEI	Number of countries
0	65.2	45.6	0.79	18.8	48.0	0.64	5
1	45.5	30.2	0.51	6.25	96.5	0.24	5
2	71.2	45.1	0.20	5.45	53.3	0.43	4

Source: calculated by the author of this study

For improved interpretability of the results, dimensionality reduction was performed using Principal Component Analysis (PCA). **Fig. 2.5** presents the spatial distribution of each country along the PCA1 and PCA2 axes, according to their respective cluster membership.

The cluster analysis confirmed the existence of significant cross-country disparities in the level of digital-circular transformation. The classification of countries into three distinct clusters enables the formalization of typical adaptation scenarios to the emerging economic paradigm and supports the development of differentiated strategies for fostering digital-circular progress.

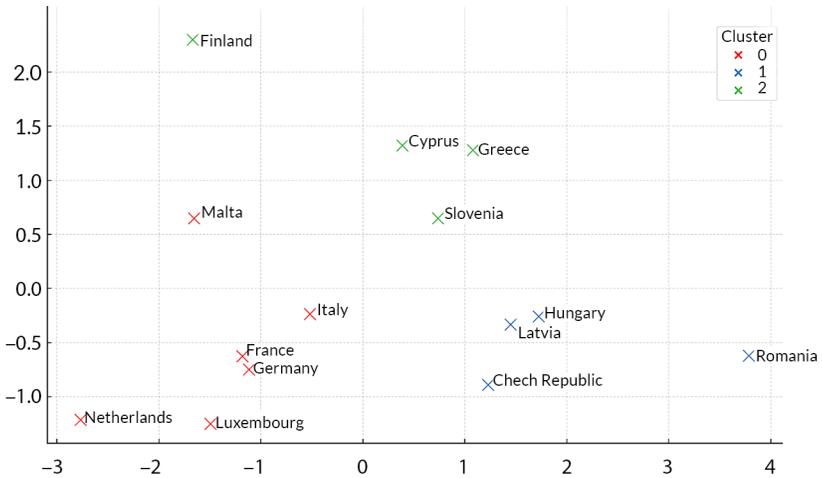


Fig. 2.5 Visualization of country clusters in the principal component space (PCA1-PCA2)
Source: visualized by the author of this study

At the same time, the quantitative assessment of digital-circular integration through the IDCEI provides a solid foundation for a qualitative exploration of potential future transformation pathways in business models. Given the high degree of variation across countries, sectors, and institutional contexts, the application of a scenario-based approach is justified as an analytical tool for forecasting possible trajectories in the evolution of a digitally enabled circular economy, both in the medium- and long-term perspective.

2.3.5 Scenario analysis of business model transformation within the digital-circular paradigm

In the context of digital transformation, analyzing the potential trajectories of business model development under the influence of digital technologies aligned with circularity principles is of critical importance. Based on the quantitative assessment provided by the IDCEI, a scenario-based approach is employed to model possible adaptation pathways of business models in response to the twin transition – digital and environmental.

The scenario analysis includes three variants – Optimistic: intensive digital integration, Moderate: fragmented implementation, and Pessimistic: Digital stagnation –

each reflecting different levels of institutional support, digital maturity, and capacity for integrating circular practices:

Scenario 1: Optimistic – intensive digital integration.

This scenario envisions the comprehensive implementation of key digital technologies, such as ERP systems for internal integration, artificial intelligence (AI) for data optimization, the Internet of Things (IoT) for resource monitoring, and Digital Product Passports (DPPs) for lifecycle transparency and management. These are supported by targeted governmental initiatives and robust institutional frameworks.

Business models evolve towards service-oriented structures, enabling flexibility, enhanced resource efficiency, and systemic circularity, in which reuse and recovery become central elements. This trajectory closely aligns with the strategic priorities of the European Green Deal [25], Digital Europe [26], and Horizon Europe [27].

Under this scenario, national performance converges with that of leading countries in 2023, such as the Netherlands and Germany, which exemplify advanced integration of digital technologies and circular practices. Industry demonstrates high ERP coverage (up to 80%), broad DPP adoption, and Circular Material Use Rates exceeding 30% [28]. In the construction sector, Building Information Modelling (BIM 5D) is widely adopted, along with digital material reuse platforms such as France's Circular Building Hub [29]. Agriculture becomes "smart", leveraging IoT, sensors, and AgTech platforms, resulting in waste reduction exceeding 17% [30].

Scenario 2: Moderate – fragmented implementation.

This scenario reflects the selective adoption of digital solutions, primarily by large enterprises, while small and medium-sized enterprises (SMEs) remain largely outside the scope of transformation. Governmental policies promoting circularity are limited in scope and often temporary.

Industrial ERP coverage ranges between 40–50% [31]. Logistics systems are partially automated but lack standardized digital frameworks for circularity. In construction, BIM is used without circular modules, and there is no system for material tracking. Agricultural digitalization is limited to large agribusinesses, with minimal support for SMEs, which continue to face barriers to financing and infrastructure access [32].

Scenario 3: Pessimistic – digital stagnation.

In the absence of political will and adequate technological infrastructure, digitalization and circularity principles fail to integrate into business models, and linear production systems persist. Circular practices are sporadic and confined to niche initiatives.

Industry lacks DPPs, ERP implementation remains below 30%, and waste per unit of GDP continues to rise. The construction sector relies heavily on primary

materials, with no digital tools or lifecycle monitoring in place. Agriculture remains traditional, with minimal or no digital integration, resource-intensive methods, and heightened ecological risks.

2.4 Conclusion

The objective of this study was successfully achieved: the digital drivers of business model transformation within the circular economy paradigm were quantitatively assessed using the proposed Integrated Digital Circular Economy Index (IDCEI). The methodology involved the construction of the composite index, its empirical verification, country-level clustering, and the development of transformation scenarios.

The IDCEI enabled a comprehensive assessment of the extent to which digital and circular attributes are integrated within national economies. The results of the correlation – regression analysis confirmed the analytical validity of the index structure. The most influential factors were identified as the Circular Material Use Rate (CMU), ERP system integration, investment in the circular economy, and eco-efficiency performance. By contrast, general digital intensity appeared less significant in the absence of deep operational integration of digital technologies.

Accordingly, all four research hypotheses (H1–H4) were empirically validated. The findings revealed statistically significant cross-country differences in digital-circular maturity, highlighted the crucial role of digitalization (particularly ERP integration) in supporting circular practices, and emphasized the importance of aligning digital infrastructure with investment capacity to ensure successful transformation.

The cluster analysis revealed three distinct development trajectories:

- Cluster 0 includes countries with high digital-circular maturity;
- Cluster 1 comprises structurally lagging economies with limited integration of digital and circular solutions;
- Cluster 2 represents digitally advanced countries with unrealized circular potential, calling for investment reorientation towards resource sustainability.

Scenario analysis demonstrated that the future trajectory of digital-circular transformation depends on institutional readiness, strategic commitment, and the capacity to embed digital innovation into sustainable business models. The optimistic scenario envisions the integration of ERP, IoT, AI, and Digital Product Passports (DPPs); the pessimistic scenario illustrates the risk of stagnation associated with continued reliance on linear production models.

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