

Research article

SUSTAINABLE DIGITAL PERFORMANCES OF EU COUNTRIES: A CRITIC-ARAS AND CLUSTERING APPROACH

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Abstract: The growing application of technology in industrial activities poses global ecological challenges in the form of resource depletion and raises awareness about the material reuse practice. Therefore the research focuses on prioritizing 25 EU nations according to their integration of digital technology (DT) in industry and the development of the circular economy (CE) as two important strategies towards sustainable development (SD). The author compared the ranking results from the CRITIC-ARAS multi-criteria model to assess the consistency between DT application in the industrial sector and CE practice in promoting SD. The sensitivity analysis of the proposed methodological scope was validated by MEREC and EDAS. Several hierarchical clusters of countries were generated according to SD scores. The research findings indicate a positive correlation between the application of DT and the current practice of CE. The top performers in achieving sustainable industrial development are the Netherlands, Germany, Belgium, Sweden and Italy. Romania, Bulgaria, Hungary and Greece achieve the weakest results. The paper proposes guidelines for enhancing SD which are important for future decision-making.

Keywords: Digital technology, circular economy, sustainability, MCDM, clustering.

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1. INTRODUCTION

Modern business entities that base their progress on technological growth and development face the pressure of Industry 4.0 on the use of natural resources. Traditional production systems based on the principle of production, use and disposal of products after their lifetime do not achieve sustainability and face the problem of limited capacities of natural raw materials [1,2,3]. An initiative that has proven to be effective in solving this problem is the recycling of already existing materials [4]. It is based on the reuse of available resources which mitigates the intensity of consumption and represents the essence of CE [5].

The application of software solutions and tools follows the development of Industry 4.0, impacting the sustainability of an economy [6]. Some of the innovative DT that find wide application in the industrial sector are the Internet of Things (IoT), cloud computing (CC), big data (BD), artificial intelligence (AI), robotics and 3D printing [2,7,8,9]. In addition to the fact that the implementation of DT in industry increases the economic profit of organizations it leads to the introduction of ecological practices such as energy saving, waste reduction and material recycling [9]. AI algorithms are used in practice to achieve the sustainability of production processes by reducing costs, production time and improving quality control [10]. They can be used to supervise manufacturing processes while CC and IoT sensors find their application to control production activities [10,11]. DT solutions reduce the number of failures by early detection of irregularities in operation, which optimizes the functionality of systems [12,13]. For example, IoT sensors can be used to monitor the condition of machines and equipment through signals, thus reducing the amount of waste [4]. By applying CC and AI, a large amount of data on the flows of discarded products can be collected and stored thus synchronizing the waste management process [14]. The adoption of DT is related to the higher production of digital devices and their quick depreciation which results in high rates of e-waste [15]. E-waste is deposited by discarding these products, but in that process a significant amount of valuable materials are captured that can be used through circular processes. In addition, a growing number of companies recognize the importance of using management systems, with attention shifting to managing resources and managing contacts with partners and customers [16].

A large number of studies employ multicriteria decision making (MCDM) methods in solving sustainability problems of DT and CE [17,18,19]. Authors frequently apply the CRITIC [20,21], Entropy [22,23,24] and SWARA [25] methods to objectively calculate the importance weights of criteria. An interesting rise in the application of recently developed MCDM methods for prioritization, including ARAS [18], EDAS [19], CODAS [20] and WASPAS [21], as well as traditional methods such as TOPSIS [22] [26] and VIKOR [27] has been observed. Study [28] propose using a hybrid CRITIC-TOPSIS model to form a sustainability index of 24 cities in China that rely on fossil fuel while [20] employs the CRITIC-SWARA-CODAS hybrid model to evaluate operational sustainability of energy systems. In the scope of sustainable waste management [29] use the fuzzy CRITIC-WASPAS model to identify the most appropriate waste management alternative in the healthcare sector while [19] introduce a novel CRITIC-EDAS method to rank the alternatives. In the energy sector authors [27] employ CRITIC-VIKOR to evaluate the risk of oil and gas production hazards, while [30] propose implementing CRITIC-VIKOR methodology to solve decision-making problems about adopting renewable energy technology.

The application of the ARAS method is becoming more widespread in recent research. Some researchers [23] implement the Entropy-ARAS methodology for material selection while others [24] use the Entropy-ARAS hybrid model for geothermal greenhouse site selection. Given that the ARAS methodology is relatively new in MCDM the studies under evaluation are part of the current research in SD. The ARAS methodology is employed for sustainable material selection in [17]. Authors [18] engaged in green supplier prioritization and discussed CE indicators while [31] extended the topic of on a fuzzy environment. Other researchers [25] performed extended SWARA-ARAS methodology to prioritize solar, wind and fuel cell alternatives for selecting the renewable energy system. In the field of sustainable policy [32] implemented this method for ranking SD policies.

The hybrid CRITIC-ARAS model which is central to this research is used in the existing literature to solve problems from different areas. An example of this methodological scope in the field of corporate sustainability is provided in [33]. The authors employed the objective CRITIC method to calculate global and local importance weight coefficients and the ARAS method for obtaining final ranks. The use of the entropy method to evaluate the importance coefficients and the ARAS-TOPSIS-GRA methodology to compare prioritization results of coal selection as a fuel alternative for thermal power plants is presented by [22]. Other researchers [26] engaged the CRITIC method to obtain weight values of the alternatives while final prioritization was performed using several MCDMs including COPRAS, ARAS, COCOSO and TOPSIS. The study focused on optimizing process parameters in order to increase energy efficiency. A more advanced version of the CRITIC-ARAS method was used to choose a logistics provider using fuzzy ARAS and distance CRITIC [34]. The use of a q-Rung Orthopair Fuzzy Sets CRITIC-ARAS is explained on an example from the food industry by [21] to select the most suitable business process. The authors use TOPSIS, COPRAS and WASPAS techniques to compare the results. The same authors [35] later employed T-spherical fuzzy CRITIC to determine the criteria importance weights and ARAS to prioritize sustainable green strategies for a logistics company. Moreover [36] examined mobile network operators using the CRITIC-ARAS methodology while [37] examined digital readiness through the case study of 38 OECD countries.

The existing approach in the academic literature that studies the progress of SD through Industry 4.0 and CE indicates the prevalence of fragmented research. In practice, there are scientific works that study the influence of DT on SD [10,11], the influence of CE on SD [18,19,29,38] as well as the influence of DT on CE [4,12]. However, the aforementioned observation indicates a deficiency in demonstrating the simultaneous impact of DT and CE on the SD concept on a national level, which could enhance our theoretical understanding. There is a lack of literature that deals with comparing the ranks of countries according to the application of DT within the framework of Industry 4.0 and the development of the CE simultaneously that generates an SD rank. Another scientific contribution is found in lack of CRITIC-ARAS methodological framework in solving this specific research problem. The main goal of this research is to evaluate the simultaneous impact of the development of the application of DT in industry and the development of CE on the achievement of SD in EU countries.

The main goal will be fulfilled through the following subgoals:

1. Forming the first MCDM prioritizing model for the application of DT in industry;
2. Forming a second MCDM prioritizing model for CE development;
3. Forming a third MCDM prioritizing model for the SD;

4. Conducting a sensitivity analysis;
5. Comparing DT with CE ranks, SD with SDG ranks using correlation analysis
6. Forming hierarchical clusters.

The idea of the paper is to sample those countries with high scores in both DT application and CE and differentiate them as sustainability leaders of Industry 4.0. The investigation will determine how well the DT and CE principles align in their development through SD ranking. The research paper covers five sections that include an introduction to the concept of sustainability and the importance of DT and CE within the theoretical and practical framework of SD. Section 3 provides a concise description of the secondary data collected for the study as well as the methodology used. Section 4 presents research results together with their discussion. In the last section 5, guidelines are proposed for the further development of the concept of sustainability through the application of DT and CE.

2. LITERATURE REVIEW

Sustainability is a concept that means meeting the needs of the current population in such a way that meeting the needs of future generations is not jeopardized. As such, it penetrates across all social and economic activities. It is defined by the 17 sustainability goals of United Nations (UN) that most countries strive to meet. The concept of sustainability is related not only to the digital development of countries but also to the practice of a CE, through which smart systems are used to monitor and control the consumption, reuse and recycle of resources [6,9,39]. The implementation of DT in CE can profoundly influence the development of sustainability by aligning with the set goals of SDG 9 (industry, innovation, and infrastructure), SDG 11 (sustainable cities and communities), SDG 12 (responsible production and consumption) and SDG 13 (climate actions) [39]. [40] identify three clusters of digitalized EU countries according to their connection with sustainable development. The first cluster consists of Bulgaria, Croatia, Cyprus, Greece, Hungary, Latvia, Lithuania, Poland, Portugal, Romania, Slovakia, Slovenia and Spain, which are characterized by a low level of digitalization accompanied by a low level of sustainable development. The second cluster consists of Austria, Belgium, Czechia, Estonia, France, Germany, Italy and Malta with medium values of digitalization and sustainable development. While the third cluster consists of the most advanced economies such as Denmark, Finland, the Netherlands, Norway and Sweden, which are digitally and sustainably the most developed EU members.

In the field of energy transition and energy system digitalization, which is the basis of the development of DT and CE, companies are increasingly applying the concept of open innovation. This type of innovation is carried out through the cooperation of a large number of external actors such as universities, the economy, public institutions, individuals, business partners and others. The exchange of information and ideas is done through online channels. Proposals from the external environment are often adopted through start-up ideas by individuals or even through the formation of online laboratories for research exchange [41,42]. Accordingly, countries such as Denmark, Portugal, Greece, Ireland, Germany, Finland and Estonia accelerated the energy transition in the previous two decades by increasing the share of renewable energy sources in their energy mix and reducing carbon dioxide production by up to 50% [43]. Cyprus, Poland, Slovenia, Luxembourg, Croatia, Lithuania, Belgium and the Netherlands recorded a positive change in the consumption of renewable energy, but with an increase in the share of carbon dioxide [43]. When looking at the regional energy transition of the EU countries of Eastern Europe, three clusters

appear. The first cluster includes Poland and Bulgaria, whose energy mix consists of fossil fuels; the second cluster comprises the Czech Republic and Slovakia, with dominant fossil and renewable energy alternatives, while the final group of Croatia and Slovenia tends to use renewable energy sources in their energy balance [44]. Such findings are influenced by the level of technological progress that determines the technology for electricity production, energy system digitalization or even its obsolescence.

There are large differences between the levels of technological progress and digitalization within the borders of the EU. Among them, the prerequisites for the innovations, such as human capital, research and development, infrastructure, institutions and market and economy regulation, are of general importance [45]. Research has shown that countries such as Austria, Denmark, Finland, Germany, the Netherlands and Sweden, which emphasize the intensity of digitalization, the organization of the market and the economy, as well as the presence of adequate infrastructure, achieve a high level of innovation. In these cases, human capital, along with institutions, is not as crucial for innovation output as the other mentioned factors. Bulgaria, Croatia, Greece, Latvia, Poland, Romania and Slovakia achieve a low level of innovation, which is associated with a lack of digital intensity, insufficient regulation of the market and economy, as well as infrastructure, which is a typical problem for this part of the EU. One of the reasons for the lack of importance of human capital is reflected in the insufficiently developed digital skills of the population, which is characteristic of countries such as Romania and Bulgaria but also Latvia and Malta [45,46]. Approximate results were also achieved in the field of digital connectivity, the presence of digital services and the adoption of DT by economic entities, in which a division between the developed North and West of Europe and the stagnant South and East can be observed [46]. The research reports evidence that follows and supports the same pattern of energy transition as the leading countries of Ireland, Luxembourg and Denmark. [47] proposed a more detailed division into clusters of EU countries in the adoption of DT. Their division into 4 categories of countries confirms that the leaders in digital business maturity are countries like Belgium, Ireland, Malta and the Netherlands belonging to cluster 1 and the countries Denmark, Estonia, Italy, Slovenia, Finland and Sweden that make up cluster 4. These countries are characterized by the use of advanced and sophisticated DT. The medium level of digital maturity includes Greece, Spain, France, Croatia, Austria and other countries. A lower level of digital maturity is achieved by companies in countries like Germany, the Czech Republic, Bulgaria, Cyprus, Latvia, Slovakia, Poland and others that rely on traditional DTs. In such cases, the authors [47] advise the application of the open innovation concept, where companies cooperate with each other as business partners in transferring knowledge and technology among themselves. When looking at the digitalization and robotization of EU members in small, medium and large companies, the division is as follows according to [48]. The best results are achieved by Finland, Denmark, the Netherlands, Belgium and Sweden. The next are Ireland and Portugal. After that, Estonia, Luxembourg and Italy are grouped together. While the worst results are achieved by companies from Romania and Greece. It must be noted that there are slight deviations when looking at the results according to the size of the company. Such research contributes to the creation of strategies aimed at a certain category of companies. The same division can be reduced to more advanced members of the old union (EU-14) and members of the new union (EU-13) that are late in the application and development of innovation and digitalization [49]. The main reasons for such empirical findings are different levels of investment in research and development and

application of DT. [50] points to the problem of unequal access to EU funds, according to which the majority of funds are retained in countries with developed DT such as Western and Northern Europe, while a smaller number of users belong to Eastern or Southern Europe. At the same time, it is emphasized that in developing countries, these funds are spent irrationally and do not achieve the intended effects. The result is a similar level of inequality in the adoption and application of digital technologies when comparing regions.

From the presented literature, it can be concluded that the adoption of DT, innovation and energy transition are coordinated in their progress and interconnected towards achieving sustainability. The EU countries that make overall progress in these fields are the developed economies of the Western, Northern and Central EU that rely on institutional support, lifelong learning and human capital in the field of innovation and digitalization. Most challenges occur in the countries of Eastern and Southern Europe. EU members from the southern and eastern parts should take over the innovative patterns of the more successful examples of the western and northern parts [51].

2.1. Digital technology for SD

The development of the Industry 4.0 concept acknowledges DT as a crucial component for achieving SD [6,39]. Industry 4.0 automates business operations and optimizes consumption and production, thus minimizing the harmful industrial impact [2,52]. In that process, a large amount of data is collected, which is used for management by artificial intelligence-assisted processing [10]. Real-time information access reduces decision-making time and promotes the rational use of natural resources [2]. With its application, DT improves the efficiency of the process, reducing the need for consumption of certain resources and saving time, energy and physical space.

CC is a system designed for collecting and storing an extensive amount of data without involving large physical space [53]. Computer resources known as cloud servers store data from smart devices and other data gathered in business operations [11]. CC enables efficient storage of data by providing remote access capabilities [54]. One of its advantages is to provide the ability to address resource overconsumption in traditional data management [9]. The application of CC is demonstrated by the example of [11] who examine its integration in project realization. The results indicate that its use is valuable in time resource management through efficient monitoring and easy information sharing. Moreover, the use in the energy sector is proven by examining the impact on increasing the operational efficiency of smart energy grids [55]. Integrated implementation with IoT creates a cloud of things (CoT) and enables the collection and storage of a large amount of information obtained from systems. Thus the analysis enables efficient utilization of resources, fosters intelligent network design and applies predictive analysis [55]. The same application is recognized in intelligent transportation systems. These systems commonly use IoT sensors to collect data and send it to the cloud for storage and further processing [54].

IoT is based on the exchange of data between sensors and devices, allowing real-time parameter exchange as well as the collection of necessary information for process management and timely decision-making [39,56]. [57] use an IoT device in the form of a smart industrial camera in the automotive industry to improve process efficiency and reduce resource consumption by minimizing material waste. The impact of installing IoT sensors to monitor a set of specified parameters on the regular maintenance of power generators is examined by [13]. The mobile network transmits the collected data to CC and

the graphical user interface (GUI) sends message alerts to users. Authors [4] demonstrate that the use of IoT sensors for waste management in urban containers, which would monitor waste levels, improves the sustainability of cities. This technological solution would lower the CO₂ emissions through optimized logistics and recycling centers managing their activities. In environmental management, [58] propose the use of such sensors for real-time monitoring of meteorological indicators in order to quickly respond to natural changes and develop a more efficient environmental management system.

Various industries extensively employ AI to tackle higher-level challenges. This involves utilizing knowledge bases and generating artificial algorithms through the application of machine learning (ML) techniques [10]. AI provides contemporary solutions for challenges that arise in corporate operations. By utilizing algorithms, the patterns of behavior in data could be analysed through testing, enabling the prediction of specific events or resource consumption. This capability greatly simplifies managerial tasks [59]. Applying AI to robot control plays a crucial role in reducing the time required for tasks and achieving more energy-efficient outcomes [12]. The authors suggest establishing smart factories that interconnect all operations and facilitate information flow among decision-makers. Other researchers [14] conducted a study examining the correlation between the implementation of AI through robotization and pollution generation within enterprises. An analysis of heterogeneity demonstrated that the use of robots in established and expansive organizations, particularly in urban areas, has a beneficial impact on pollution emissions mitigation [14]. [60] confirm that the implementation of robots in business processes results in a decrease in energy usage. [61] use patent data to illustrate the influence of AI on sustainable economic expansion by constructing a non-linear model. The results suggest that technological advancement aligns with sustainable economic growth through effectively managing natural resources.

In the context of customer relationship management (CRM) Industry 4.0 is primarily characterized by the prevalence of software bearing the same name. Implementing this technology enables more efficient tracking of client requirements and market demand, facilitates production process customization, and minimizes avoidable losses and excess inventory [16]. CRM serves as the foundation for managing customer relationships and has the ability to influence customers' preferences for adopting products and services [62]. It also helps in keeping customers aware of sustainability challenges because together with DT it influences the generation of environmentally friendly technologies [63]. Research study [64] identified various technologies present in that context, including virtual assistants, chatbots, virtual recognition and product recommendation systems.

An extensively utilized enterprise resource planning (ERP) system is implemented to enhance the efficiency of corporate operations, with its core functionality relying on data integration and interchange [65,66]. These systems offer managers information regarding operating and environmental costs thus supporting them in making decisions that align with strategic objectives [67]. They enhance inventory management, leading to waste reduction and a favorable effect on the environmental footprint of business operations [68]. In their study [69] showed the significance of incorporating product life cycle impact assessment with ERP to achieve the sustainability objectives of enterprises. [70] conducted a study using a structural model and found that connecting an ERP to the cloud in companies results in less information loss, faster information processing and a reduction in resource management errors. Organizations have the option to purchase pre-built ERP systems or develop their own system. It is crucial to consider the expenses and additional

resources involved in this undertaking [71]. In practice, organizations use these systems to incorporate the social, economic and environmental aspects of sustainability into their supply chain operations [72]. Author [66] proposes a novel ERP system built on the customers preferences that utilizes cloud services to facilitate the sustainable growth of medium and small businesses. Going one step further into digitalization [73] suggest the concurrent use of such systems and blockchain technology as a means to enhance the sustainability performance of enterprises.

2.2. Circular economy for SD

Named as a driving force of the SD, the CE concept is based on the circular material flow from production to consumption and vice versa within a closed loop [74]. The concept evolved from the 3R - reduce, reuse and recycle to even 9R - refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle or recover [1]. A multitude of indicators can be integrated into empirical research on CE distributed into energy and environment, material, efficiency, temporal or monetary groups as proposed by [27].

[75] conducted research on the SD and practice of CE in Europe based on a couple of indicators, among which the authors ranked the rate of deposition and recycling of urban waste and three indicators of the social progress index. The concept behind adding waste generation indicators comes from the idea that some countries have policies that aim to reduce waste production. Comparing these countries only by the rate of recycling would give false results in those cases. The results of the study showed that the difference between the Western and Eastern countries of the EU has narrowed, but that the gap between the North and the South is still hard to solve. Researchers in [38] used an MCDM gray relational analysis to prioritize 23 EU countries based on their CE practice aligned with SD. The data on CE indicators were collected for the period 2010-2016 and distributed into four groups: consumption and production, waste management, competitiveness and innovation and secondary raw materials. The author identified western and northern countries such as Germany, France, the Netherlands, Denmark and Italy as pioneers in CE while several central and southern countries such as Slovakia, Romania, Bulgaria, Greece and Cyprus were found as followers. When comparing to SDGs, the waste reduction goal from SDG 12 is highly prioritized as a strategy for reaching SD. [76] use the Pythagorean fuzzy AHP-CODAS model to evaluate CE and SDG practices to prioritize developing nations. The authors investigate the feasibility of implementing a circular supply chain in countries that produce a high amount of waste. The underlying force behind this initiative is related to management activities and the government's initiatives. Authors [77] prioritized 28 EU member states according to their CE performances in the 2006-2016 period. They used indicators of the production of municipal waste, food waste, municipal waste recycling rate, domestic material consumption, material reuse rate, share of reused material trade and patents related to CE. The study explored the relationship between the size of an economy measured by GDP and mentioned indicators. The results reveal that countries with high GDPs, such as France, Belgium, Italy and others have low material consumption due to the rise in using recycled raw material. Germany, France, Luxembourg and other high-income countries have a higher share of recycling waste and trading with recycled material. Low-income countries such as Croatia, Bulgaria, Greece, Romania, Malta, Hungary, Estonia and others are struggling with the inefficient EU CE policy application and low level of waste reduction. [78] explored the relationship between DT and CE in Europe by considering nine DT proxies and six CE proxies that incorporate

generation of municipal waste, amount of patents in CE, circular material use, recycling rate of all waste, of bio-waste and e-waste. Statistical analysis showed a non-linear relationship between these two concepts, which indicates that in the initial phase of adoption of DT, its impact on CE is smaller because the basis of digitalization development and the necessary infrastructure are being formed, but that in the later stages of DT development, its impact on CE becomes noticeable. Authors [3] investigated the relationship between CE and GDP in 28 EU countries using a panel econometric model. The proxies of the circularity rate included several macroeconomic measures and trade in secondary raw material. The study indicates that in the short run the high GDP countries achieve a high consumption rate and low circularity; however by looking at the long run this relationship tends to have the opposite trend. Trade of used material and environmental taxes can improve CE practice in reducing waste generation and saving additional raw material usage.

The prioritization of CE practice is present among different industrial sectors. Authors [79] used AHP and MAVT to rank the possible bottlenecks of CE value chains while [74] used the fuzzy AHP method to prioritize overall indicators of CE in the industrial sector. [80] broadened the scope of the same issue by engaging the best-to-worst DEMATEL methodology to prioritize indicators in the manufacturing sector. The study revealed that the managerial approach along with information and technology (IT) has a dominant impact on this problem especially the engagement of powerful information systems such as IoT. Research study presented in [81] confirmed the opportunity for IoT to improve CE and digitalize the sector.

While the share of renewable energy consumption in gross final energy consumption is primarily aligned with the broader SD agenda rather than being an inherent component of the CE, it has been incorporated into this study as a relevant metric for CE practices. The REC represents a strategic intersection between the increased use of DT that should be powered by a large renewable energy supply [82] and the objective to mitigate raw materials exploitation [74]. According to the UN the idea of renewable energy is to use sources that are available in our environment while conserving natural energy resources and protecting the earth [71]. This notion closely aligns with the CE principles and REC remains a valuable CE proxy. The perspective promoted by the Ellen MacArthur Foundation is similar to this mechanism and is manifested through three CE principles [83, 84]. The first refers to the management of natural resources and their preservation, the second to the circular flow of materials and components and the third to the optimization of design. [27] discuss that renewable energy indicators are valuable in evaluating the energy and environmental dimension of CE.

3. RESEARCH DATA AND METHODOLOGY

The study was conducted on a sample of 25 member states of the European Union, excluding Malta and Cyprus due to incomplete data. The data were gathered for the year 2021, which acts as a reference year for the prioritization process and comparative analysis. The research incorporates indicators that are presented in Table 1 and Table 2 and categorized depending on whether they represent indicators of DT usage in companies that contribute to digital development or indicators of CE development. These values were sourced from publicly accessible databases, including Eurostat [85] and the OECD [86]. The majority of the indicators are available as percentages, eliminating the need for data standardization. Only data concerning the trade of recyclable raw materials, exclusively

expressed in metric tons, were subject to linear scaling. The methodological scope integrates four multi-criteria decision-making (MCDM) methods. The authors use the Criteria Importance Through Intercriteria Correlation (CRITIC) approach to calculate the weight coefficients of the observed criteria in order to express objective preferences among them. The method was primarily employed due to its ability to reduce uncertainty and eliminate the risk of subjective preferences as noted by [20]. Also, this method is useful when prioritizing a large number of alternatives because it is simple to implement and discuss the outcome [19]. Given its objective nature, the CRITIC method relies on the information it receives from the initial decision matrix [87]. According to [87] a criterion with a smaller variance obtains a lower weight coefficient due to lower prediction power. Over the years, the CRITIC method was subject to modifications, so [88] proposed a modification taking into account distance correlation instead of Pearson's correlation. The original CRITIC method is based on the following steps [87]:

1. Establish a decision matrix with criteria and alternatives.
2. Standardize the decision matrix.
3. Calculate each criterion's variance to determine the amount of criteria information.
4. Calculate the correlation of each individual pair in the decision matrix.
5. Calculate the weights coefficients using the values obtained from previous steps 3 and 4.
6. Normalize the obtained weights coefficients within a given range of $0 < w_j < 1$.

Table 1: Digital technology indicators

Name	Abbreviation	Unit	Source
Enterprises use Internet of Things	IoT		
Enterprises buy cloud computing services used over the internet	CC	Percentage (%)	[85]
Businesses using Artificial Intelligence	AI		
Businesses using Customer Relationship Management software	CRM		
Businesses using Enterprise Resource Planning software	ERP		[86]

Table 2: Circular economy indicators

Name	Abbreviation	Unit	Source
Circular material use rate	CM		
Recycling rate of municipal waste	MW		
Recycling rate of waste of electrical and electronic equipment	WEEE	Percentage (%)	
Share of renewable energy consumption in gross final energy consumption	REC		
Trade in recyclable raw materials import	RMI		[85]
Trade in recyclable raw materials export	RME	Tone	

The authors used an alternative weighting method to perform sensitivity analysis when criteria importance is questioned. The MEmethod based on the Removal Effects of Criteria (MEREC) was employed as its computation algorithm provides a different approach to obtain criteria importance weights. The method was developed by [89] in 2021 and requires several steps:

1. Construct a decision matrix including criteria and alternatives.
2. Normalize the decision matrix using a linear approach.
3. Compute the total alternatives performances.
4. Compute the performances after eliminating each criterion individually.
5. Compute the absolute difference between the steps 3 and 4.
6. Calculate the final weights by dividing the individual difference of each criterion with the summarized absolute difference from the step 5.

The Additive Ratio ASsessment (ARAS) methodology was applied for performing final rankings. The developers of this MCDM method are authors [90]. The ARAS is an effective method for ranking a large number of alternatives and finding the optimal solution [24]. By comparing the optimal function of the alternative with the optimal function, the degree of utility is obtained, which serves as the final ranking of the alternatives and enables maintaining objectivity [33]. The application of the ARAS method consists of the following steps [90]:

1. Create a decision matrix by defining criteria and alternatives.
2. Normalize the decision matrix.
3. Assign weight coefficients that have already been calculated using one of the methods for calculating weighting values.
4. Calculate the optimality function as the sum of the normalized weighted value of the alternative.
5. Calculate the degree of utility by dividing the value obtained from step 4 with the value of the optimality function of the best alternative.
6. Rank the obtained values from step 4 from highest to lowest value.

Evaluation Based on Distance from Average Solution (EDAS) is another contemporary MCDM that is used in this study to test the stability of the proposed methodological framework. As expressed in the title, the method is based on calculating positive and negative distance from the average solution [91]. The practical steps of EDAS are follows [92]:

1. Create a decision matrix by defining criteria and alternatives.
2. Calculate the mean values.
3. Normalize the decision matrix.
4. Calculate the positive and negative distance from the average value.
5. Calculate the weighted positive and negative distances.
6. Normalize both, positive and negative distances.
7. Derive the ranking scores from the values obtained in the previous step 6.

Subsequently in this paper a Spearman's correlation rank and hierarchical analytical clustering were utilized to uncover the connection between the DT and CE ranks and SD and SDG ranks. Several studies such as [22,26,34] used Spearman's correlation rank to correlate the prioritization results of different MCDM's. Hierarchical cluster analysis is often used to create clusters by sequentially comparing the largest average correlations values of each pair of variables or clusters in the trial clusters until all clusters variables are grouped into one cluster [93].

4. RESEARCH RESULTS AND DISCUSSION

The Table 3 provides a concise overview of the key findings obtained through the CRITIC and MEREC approaches. All criteria that were considered were marked as

beneficial that means higher values are desirable and report better performances in DT and CE.

When evaluating DT criteria through CRITIC the weight coefficients for each technology showed minimal deviation except the use of ERP software that has slight advantage ($w_{ERP} = 30.6\%$). The weight coefficients for CE allocates a higher priority to renewable energy consumption ($w_{REC} = 23\%$), while the lowest relevance is assigned to the recycling rate of municipal waste ($w_{MW} = 13.9\%$). The reported dominant effect of REC on CE supports the author's intention to incorporate this metric as a criterion in the decision-making process. This finding matches the theoretical view from [27], who argue that the energy and environmental dimension is dominant when assessing the CE contribution to SD, and it also lines up with the CE principles supported by Ellen MacArthur Foundation [84], mainly the optimization of natural resource use via renewable energy systems.

MEREC reported greater importance differences between the criteria, reducing the value of ERP software ($w_{ERP} = 17\%$) and customer management software ($w_{CRM} = 14.1\%$), compared to other DT criteria. Regarding the CE criteria, the differences are even greater and are noted in the significance of the WEEE ($w_{WEEE} = 1.2\%$) and RME ($w_{RME} = 1.7\%$) criteria.

The weight coefficient values showed sensitivity when using diverse MCDM and therefore they were further used in the prioritization process by applying the selected MCDMs.

Table 3: Results of CRITIC and MEREC methods for calculating objective criteria weights

		CRITIC	MEREC
Criterion		Objective weight	Objective weight
DT	IoT	0.192	0.215
	CC	0.206	0.260
	AI	0.192	0.214
	CRM	0.204	0.141
	ERP	0.205	0.170
CE	CM	0.148	0.042
	MW	0.139	0.034
	WEEE	0.180	0.012
	REC	0.230	0.448
	RMI	0.169	0.448
	RME	0.135	0.017

The ARAS method for multi-criteria decision making was employed to prioritize EU nations based on their utilization of DT in enterprises and the advancement of CE. The Table 4 provides the ranking positions when considering CRITIC and MEREC weight values. The scores of both ranking DT and CE were used to create a singular ranking defined as SD. As criteria authors used DT and CE rankings, with equal weights coefficients were allocated to them ($w_{DT} = 0.5$; $w_{CE} = 0.5$). The sensitivity analysis of the prioritization methodology was carried out by additional EDAS method. Statistically significant Spearman's ranking of the correlation coefficient between positions for DT according to CRITIC-ARAS and CRITIC-EDAS methods is $\rho=1$; for CE it is $\rho=0.966$, while for SD it is $\rho=0.972$, which confirms the stability of the ranking when applying alternative prioritization method. However, major inequalities are observed when the

weight values of the criteria change significantly as in the case of CE indicators, which means that they are subject to scenario changes. The CRITIC method is based on the correlation value between the criteria, while the MEREC method relies on the impact of the elimination of individual criteria on the result. This knowledge reports a research gap for further studies of the complex relationships between the criteria. As well as the possibility of introducing additional parameters that would potentially clarify the obtained relationships.

Table 4: Prioritization results by ARAS and EDAS

Method Nation	DT				CE				SD			
	C-A	M-A	C-E	M-E	C-A	M-A	C-E	M-E	C-A	M-A	C-E	M-E
Belgium	4	5	4	5	4	4	5	7	3	4	3	4
Bulgaria	24	24	24	24	23	15	20	19	24	24	24	24
Czech Republic	13	12	13	12	19	24	18	25	17	18	16	21
Denmark	8	10	8	10	7	8	7	6	8	8	5	7
Germany	6	6	6	6	2	3	2	3	2	2	2	2
Estonia	19	19	19	19	12	21	15	21	16	21	17	19
Ireland	10	9	10	9	17	9	12	12	12	10	13	10
Greece	22	22	22	22	18	12	16	10	22	15	18	15
Spain	11	11	11	11	5	2	6	2	6	3	6	5
France	16	17	16	17	6	6	4	5	10	6	8	9
Croatia	21	20	21	20	16	16	17	17	20	19	19	18
Italy	9	8	9	8	3	5	3	4	5	5	4	6
Latvia	18	18	18	18	13	17	14	15	15	16	15	16
Lithuania	12	13	12	13	15	13	13	13	14	14	14	14
Luxembourg	14	15	14	15	20	25	23	22	18	23	21	22
Hungary	23	23	23	23	25	22	24	23	23	25	23	25
Netherlands	7	7	7	7	1	1	1	1	1	1	1	1
Austria	2	2	2	2	10	20	11	20	7	13	9	11
Poland	20	21	20	21	9	7	8	9	13	9	12	13
Portugal	15	14	15	14	24	19	25	18	19	17	22	17
Romania	25	25	25	25	21	10	21	11	25	20	25	20
Slovenia	5	4	5	4	11	14	10	14	11	12	10	12
Slovakia	17	16	17	16	22	23	22	24	21	22	20	23
Finland	1	1	1	1	14	18	19	16	9	11	11	8
Sweden	3	3	3	3	8	11	9	8	4	7	7	3

C-CRITIC; M-MEREC; A-ARAS; E-EDAS.

Findings from the main CRITIC-ARAS model demonstrate that there are differences in the rankings of EU nations. EU member states like the Netherlands, Germany, Belgium, Sweden and Italy achieved high rankings across all categories of DT, CE and SD. Their rankings indicate a successful adoption of digital transformation in Industry 4.0 and attempt to develop CE with the support of innovative technology. The results are supported in the literature by studies [40], [45] and [46] where the same cluster of countries is recognized as forthrunner in DT and SD. These nations serve as model representatives of

the western and northern parts of EU in achieving SD. Among them only Belgium has harmonious development in both categories. The results are also in line with [75] who confirmed that Belgium is the leader in SD and CE in Europe. When analyzing the perspective of DT adoption it can be concluded that this trend is not consistent across all nations. This is evidenced by the lower rankings of Finland, Austria, Slovenia and Ireland in terms of their compliance with CE specifications. Average DT performers come from the central and eastern EU territories such as the Czech Republic, Lithuania, Latvia and Slovakia. The findings are empirically supported in [45] where authors conclude poorer DT development due to bigger problems such as low innovation outputs and lack of DT infrastructure. On the other side southern EU nations Hungary, Bulgaria, Romania and Greece achieve the lowest ranks. The authors confirmed SD ranks using several studies by [94,95,96] who evaluated progression in attaining SDGs in EU countries. Among the observed EU members the special cases are Finland and Poland. In particular, these two nations demonstrate a significant disparity in rankings. Finland outperforms in the field of DT while achieving poorer performance in CE practice. Three out of four companies in Finland use CC services, while the performance of other DT indicators is over 40%. CE indicators show weaker results. The rate of use of recycled material is less than 2%; the value of foreign trade in these materials is at a low level, and about 40% of electricity comes from renewable sources, which indicates the possibility of further development of the CE strategy. The problem of low material recycle in Finland was observed by [75]. Poland, on the other hand, reports the opposite trend. This nation outperforms in CE while slowing down in the DT transition. The CE indicators show a higher level of international trade, which is reflected in the highest value of imported used materials and the rate of their use. Poland reports poor results in the domain of IoT and AI use in business, while other indicators show that approximately every third company uses CC, CRM and ERP systems. The positive outcome in CE domain is reflected in [75] research who identifies Poland as nation with promising future. Obtained result lines up with the theoretical discussion set out in Section 2.1, where it is said that using IoT, CC and AI allows real-time resource management and process optimization [2,10,12], which becomes the base for the higher SD output we see in these countries.

The diversity of the results of the development of DT and CE across EU emphasized the necessity for additional analysis. Therefore a Spearman's correlation rank was computed to demonstrate the relationship between DT and CE concepts in CRITIC-ARAS hybrid model. The Table 5 presents the findings. The rank comparison revealed a positive correlation between DT and CE. Additionally, it was demonstrated that the development of DT in a certain way drives the development of CE ($\rho=0.611$, $p=0.000$), and the strength and direction of this relationship are statistically significant at the level of 0.01.

Table 5: Spearman's rank correlation coefficients of DT and CE

	Rank DT	Rank CE
Rank DT	1	0.611*
Rank CE	0.611*	1

*Correlation is significant at the 0.01 level (2-tailed).

In order to validate SD prioritization, the results were questioned using the SDG's ranking list for the 2021 [97]. The correlation analysis in the Table 6 suggests high positive and statistically significant relationship among the two rankings ($\rho=0.712$, $p=0.000$). The prioritization using SD complies with SDG prioritization suggesting the validity of the

proposed SD concept. This result empirically confirms the theoretical premise set in Section 2, where the literature points out that DT, especially IoT based waste monitoring [4], AI assisted production optimization [10] and the management of e waste flows [15] acts like a driver for CE practices. Also, the non linear relationship between DT adoption and CE improvement reported by [66] puts this into a wider frame, because it implies that the positive correlation we see here actually mirrors a more mature stage of digitalization across EU economies.

Table 6: Spearman's rank correlation coefficients of SD and SDG

	Rank SD	Rank SDG
Rank SD	1	0.712*
Rank SDG	0.712*	1

*Correlation is significant at the 0.01 level (2-tailed).

Further investigation implies the need to implement a technique for classifying nations based on their prioritizing ratings, using hierarchical cluster analysis in order to detect heterogeneity. The findings are displayed in the following Table 7. The relationship between the two concepts of DT and CE, which impact on SD was examined. All three analyses were performed iteratively in two stages to identify the optimal number of clusters and subsequently assign the nations to the appropriate clusters. The chosen clustering method in the hierarchical cluster algorithm is Ward, with the squared Euclidean distance metric as in [38]. The analysis indicates that two clusters emerge in each concept. The first clusters in DT and CE, which are numerically smaller in terms of elements, are comprised of nations that are ranked higher, whereas the second clusters are comprised of nations that have attained a lower ranking. All nations that attain high level of DT and CE are classified as nations with achieved progress in SD of Industry 4.0.

Table 7: Hierarchical Cluster Analysis

	Cluster 1	Cluster 2
DT	Belgium, Denmark, Germany, Netherlands, Austria, Slovenia, Finland, Sweden	Bulgaria, Czech Republic, Estonia, Ireland, Greece, Spain, France, Croatia, Italy, Latvia, Lithuania, Luxembourg, Hungary, Poland, Portugal, Romania, Slovakia
CE	Belgium, Denmark, Germany, Spain, France, Italy, Netherlands, Austria, Poland, Sweden	Bulgaria, Czech Republic, Estonia, Ireland, Greece, Croatia, Latvia, Lithuania, Luxembourg, Hungary, Portugal, Romania, Slovenia, Slovakia, Finland
SD	Belgium, Denmark, Germany, Spain, Italy, Netherlands, Ireland, Austria, Slovenia, France, Finland, Sweden	Bulgaria, Czech Republic, Estonia, Greece, Croatia, Latvia, Lithuania, Luxembourg, Hungary, Poland, Portugal, Romania, Slovakia

The illustrative representation of the two concepts is provided in the Figure 1 by a tree diagram or a dendrogram [93], which is the result of a cluster analysis that combines the rankings of the nations according to the DT and CE. The graphic display suggests the presence of a much complex division among nations and categorizes them based on their shared values.

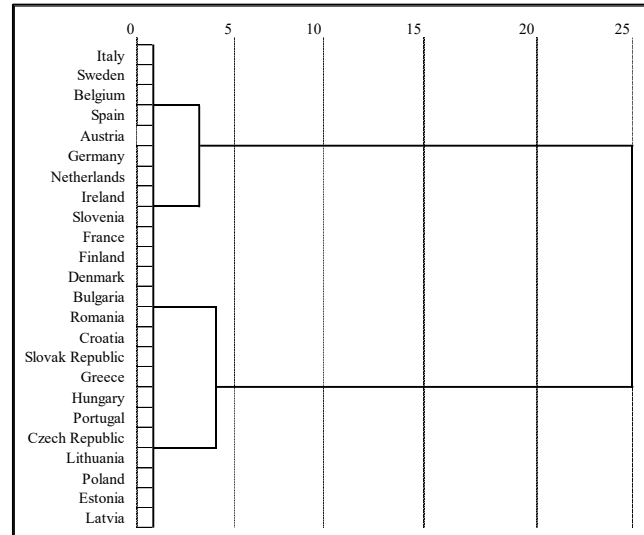


Figure 1: Dendrogram of SD hierarchical clusters

DT Cluster 1. The DT concept suggests that Belgium, Denmark, Germany, the Netherlands, Austria, Slovenia, Finland and Sweden classified as cluster 1 are the EU member states with the highest use of DT in the business sector. Austria and Slovenia stand out by the share of enterprises that use IoT and AI, which is roughly 50%. According to the number of businesses buying cloud computing services used over the internet, the best results are achieved by the Scandinavian countries of Finland and Sweden with over 75%. Denmark is a complete leader when it comes to the introduction of software solutions in business. In terms of software utilization, according to the rate of introduction of the CRM system, the leaders are Belgium and the Netherlands (more than 52%), while Belgium and Denmark have the leading position in ERP. The results of cluster 1 could be improved in specific cases. In countries like Denmark and the Netherlands every fifth enterprise uses IoT and AI in their work. Less than 50% of companies in Austria, Germany and the Netherlands use CC services. Slovenia and Sweden have average results in the introduction of ERP and CRM systems (less than 40%). Harmonized development in all DT categories is achieved by Finland, while large differences within the categories exist in Slovenia, Denmark and Germany. The results are in line with [47] study on EU digitalization which identified Denmark, Estonia, Italy, Slovenia, Finland and Sweden as countries with the highest application rates of AI, CC ERP and CRM in their enterprises. These cluster level findings operationalize the theoretical arguments from Section 2.1, like the high IoT and AI adoption rates in Austria and Slovenia align with the documented ability of these technologies to cut down material waste, and to optimize energy usage in manufacturing [10,12]. Meanwhile the CC leadership shown by Finland and Sweden, basically mirrors the expected part of cloud infrastructure, in terms of making data driven and resource efficient operations possible [9,53].

DT Cluster 2. Nations from central and eastern Europe often occupy lower ranks in this classification and form cluster 2. Ireland, Italy and the Czech Republic dominate this group according to the use of IoT and AI. Italy, Ireland and Estonia are the leaders in the frequency of CC use (more than 50%). ERP software is used frequently in this cluster and

most often in Spain, Portugal, France and Lithuania. Data indicate that CRM lags behind in use but is most often used in Luxembourg and Greece (between 30% and 40%). Weak indicators of the use of DT in all categories were recorded in Romania, but the results of Bulgaria are not promising either. In addition, Estonia has a low rate of IoT and AI usage (less than 20%), while CRM is weakly used in Latvia and the Czech Republic. Literature in the section 2 confirms that those countries typically rely on conventional DT without employing cutting edge technology since they lack of financial but also human resources [47]. Again, as confirmed by [47] and [49] and described as the cluster of new Union or countries that were last to receive EU membership. Authors [50] argue that this result is a direct consequence of unequal financial allocations from the EU, where the majority of funding is derived to West and North EU member states. Different findings were presented in [98] study who described Belgium, Denmark, Germany, Ireland, Malta, the Netherlands, Finland and Sweden as leaders in DT access however countries like Portugal, Poland, Romania and Bulgaria perform outstanding in employing DT in enterprises. Besides DT in enterprises [98] includes elements of innovation in their ranking scores that could lead to opposite results than the current study.

CE Cluster 1. Belgium, Denmark, Germany, Spain, France, Italy, the Netherlands, Austria, Poland, and Sweden are at the forefront of CE development and have been allocated to Cluster 1. The Netherlands is a leader in terms of the use of circular materials (approximately 30%) and also in terms of foreign trade of used materials. In terms of the recycling rate of municipal waste, Germany and Austria are in the lead (more than 60%), while Italy, Germany, Poland and Austria dominate e-waste recycling with rates of 80%. In terms of the share of REC, Sweden achieves the best results. Sweden, Spain, Denmark and Poland have the lowest percentage of recycled material use with less than 10%. The lowest recycling rates for municipal waste are in Sweden and Poland, at almost 40%, while the WEEE rate in the Netherlands, Belgium and Spain is around 70%. Austria has the lowest value of trade in recycled materials by a significant margin. REC is below 15% in Belgium, the Netherlands and Poland. The results are confirmed in [77] who clustered EU countries in four clusters. The cluster 1 in the current research approximately corresponds to clusters 1 and 2 in their research. The slight difference in clustering can be attributed to the integration of GDP related to CE. Also, [38] revealed the same countries as leaders in CE in a study of 23 EU member states with the exception of Poland, Finland and Spain as they were clustered into second group.

CE Cluster 2. The majority of eastern and southern EU nations are experiencing a slow pace of CE development and are allocated to cluster 2. Estonia has the largest share of used material, but it is only slightly more than 15%. Slovenia and Luxembourg recycle more than 50% of urban waste, while the results for e-waste recycling are far more positive and the Czech Republic, Croatia and Slovakia can be singled out with over 90% recycling rates. By far the highest value of imports of used materials is in Ireland, and this country also records high exports. Romania realizes the highest value of RME. According to REC, the largest share is owned by Finland and Latvia. Romania, Finland, Ireland and Portugal record less than 2% use of circular material. The municipal waste recycling rate is less than 20% in Romania and Greece, while the e-waste recycling rate is at an enviable level in all countries over 75% except in Portugal where it is 51.7%. Limited trade in used materials is achieved by Luxembourg, Slovakia and the Czech Republic. Ireland and Hungary have the smallest share of RECs (less than 15%). The findings are in line with [3] and [77] who find southern parts of EU as less CE developed compared to northern countries.

SD Cluster 1. Netherlands, Germany, Belgium, Sweden and Italy as the top 5 performers on the SD ranking list experience harmonious development in the areas of DT and CE. What drives the development of these countries is the greater application of all categories of DT in practice. The ranking of these countries according to CE gives priority to the recycling rate of urban waste, but in other CE categories these countries have room for improvement. This particularly applies to the recycling of e-waste and use of the recycled material.

SD Cluster 2. Nations in eastern and southern EU, including Bulgaria, Romania, Hungary and Greece, are at the bottom of the ranking estimated by SD. Countries belonging to this cluster can achieve better results if they focus on the introduction of software solutions for process management and greater use of CC and CRM services. CE practices contribute to good e-waste management results where these countries score better than cluster 1 countries. However their international trade activities could be improved.

The regional heterogeneity we identified through the prioritization, and clustering outcomes can be viewed a little like the lens used in the theoretical framework presented in Section 2. In the literature it's typically noted that the ability to adopt DT and carry out CE strategies is not just a matter of will, but it is shaped by wider structural pressures, such as economic endowment, institutional quality and the way policy coherence is actually maintained [98,99,100]. Significant differences between regions appear from several key reasons. The countries of western and northern Europe have significantly greater economic resources for investment in development and innovation, so the data on the use of DT are far more favorable than for the countries of southern and eastern Europe [99]. On the same territorial basis, there is a difference in the adoption of policies that define the legal framework of CE development. While western and northern countries are leading in implementation and innovation in this area, southern and eastern countries are struggling to adopt and implement the proposed policies [100]. The previous challenges affect the development of unfavorable conditions for southern and eastern countries, where the results of innovation and knowledge transfer are weaker precisely because of the lack of resources and institutional support for these activities, so they lag behind in development [101]. Another important reason is the cultural difference between the populations, according to which the population of western and northern Europe shows a higher level of awareness about environmental protection and the need to recycle than the rest of the EU, so they practice these activities more intensively [102].

4. CONCLUSION

The role of Industry 4.0 in economic and social development is critical for achieving SD. This paper presents an analysis of the application of advanced DT such as IoT, cloud computing, AI and software solutions such as ERP and CRM in organizations. After that an evaluation of the impact of the application of DT in Industry 4.0 on the sustainability was carried out. For this purpose, a comparative analysis of the application of DT and the development trend of CE was carried out. Research has revealed a positive relationship between DT and CE. The results showed that mostly western EU nations are leading the way in achieving SD through the intensive application of DT and progress in the field of CE. In this process, the nations in the eastern and southern parts of the EU often lag behind. The central regions of the EU attain average outcomes compared to the nations under observation. Belgium attains compatibility in developing both concepts. However, the

analysis also reveals special cases, like Finland and Poland, where the development of these two concepts lacks harmonization.

The research's practical contribution manifests in the development of three models that facilitate multi-criteria decision-making and comparative analysis. These models serve as the foundation for the recommendations that follow, aimed at achieving SD through DT and CE. The economic policy guidelines for countries with low DT development results that support CE and sustainable development are as follows:

- Formation of special public and private funds with the purpose of investing in the implementation of advanced technological solutions for the modernization of activities and processes and increasing efficiency. This economic policy measure would be implemented through financial incentives for the introduction of automation and optimization of processes based on the use of artificial algorithmic solutions.
- Launching government's action plans aimed at providing fiscal incentives through tax reductions to establish a larger number of smart factories within Industry 4.0 to optimize production, maintenance, consumption and waste management. Such plans would have the primary goal of adopting integrated systems for managing processes, resources, people and supply chains with the aim of reducing errors, deficiencies and the environmental footprint.
- Increasing the budget of the research and development sector for the development of technological solutions based on artificial intelligence that predict failures, maintenance activities, production and consumption levels, as well as foreign supply and demand; This also includes the installation of intelligent sensors that serve to connect the operation of devices and machines, collecting analytical data in real time in order to increase process efficiency and reduce production costs.
- Establishing a science-business cooperation program to provide courses and programs for the training and retraining of personnel in the field of information technologies who could be the carriers of the introduction and application of new technologies.
- Opening regional centers for digital development and innovation to support small and medium-sized enterprises on the path of digital transition.
- Creating government development strategies and policies aimed at introducing and developing digital infrastructure in the form of data centers and cloud computing capacities that could support the implementation and expansion of DT.

The following are some recommendations for countries with low CE scores to achieve DT and SD development:

- Formation of public and private investment funds for financing and co-financing the construction of smart recycling centers, which will raise the level of recycled material, enable proper waste management and solve the problem of low-efficiency recycling processes.
- Coordination of the development strategy of the energy sector with the aim of developing a smart network for the generation of renewable energy sources to meet the needs of the energy-demanding DT and create strategies for converting waste into energy.
- Adoption of fiscal policy measures to provide financial incentives or tax breaks for internal and external trade in recycled materials as an incentive for smart use of natural resources.
- Strengthening of institutional mechanisms for controlling the implementation of signed agreements on the introduction and development of CE by competent

institutions. This measure would regulate the monitoring of the producer's responsibility for the sustainable disposal of the product after its useful life.

- Regulating the market of secondary raw materials to ensure sustainable supply chains in order to exchange secondary raw materials that in other activities may be primary raw materials. This measure could include the management of supply chains through digital platforms, which would accelerate the flow of information and increase the transparency of domestic and international cooperation.
- Raising public awareness of the importance of proper waste disposal, recycling and reuse of products through public forums and promotional activities.

In order to achieve sustainability, we must coordinate the development of DT and CE concepts through the creation and implementation of harmonized policies and strategies. We can infer this conclusion from the suggested practical applications that engage with SD. Therefore, for future balanced development towards SD, it is necessary to form business models that integrate DT and CE practices into their activities. This strategy with people in its core is a practical guide for Industry 5.0 that is established on DT, sustainability and human resources.

The author acknowledges the different limitations of the research. The primary constraint refers to the variety of criteria used to assess DT, as well as the limited number of nations included in the study. An additional limitation refers to the analysis of one reference year, which makes it impossible to study the dynamics of the research problem. The available databases for 2022 and 2023 are incomplete, which would reduce the number of involved economies and compromise the consistency of the prioritization. Future research might consist of a broader scope of criteria and longer time span to analyze the digital advancements in Industry 4.0.

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