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Analysis of the circular management model of information and communication technology resources of large enterprises in the European Union

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ABSTRACT

Objective: The aim of this article is to determine the level of differentiation of large enterprises operating in the European Union in terms of the sustainable use of information and communications technology tools and to reduce the dimension of variables describing the circular model of managing information and communications technology solutions.

Research Design & Methods: We used quantitative analysis, considering secondary data from the Eurostat database for 2022 from the information and communications technology (ICT) and the environment by the size class of the enterprise section. We conducted a pilot study using data from large enterprises from 27 European Union countries. We analysed data using the diagnostic-descriptive method, principal component analysis, MOORA method, and linearly ordered object grouping.

Findings: The research results indicate that large enterprises represent different levels of circularity in the use of green IT/ICT related to the selection, use, and disposal of devices. Most entities operating in 18 European Union countries achieve an average level of circularity of ICT devices. Thus far, they have not included the reuse of ICT devices in the procedure consistent with the 3R circularity principle. The process of selecting, recovering, and recycling ICT equipment is carried out unevenly and in stages. On the other hand, the indicator of pro-environmental involvement displays low intensity, and in such a situation, the surveyed entities did not achieve the strategic goals assumed by the European Union in the field of circular economy regarding the selection and use of ICT equipment.

Implications & Recommendations: The research results enable managers to develop circular business models by reducing the consumption of raw materials, waste, greenhouse gas emissions, and energy. They support strategic decisions on the transition from a linear model of ICT equipment management to a circular model. They also support European Union policymakers in developing legal regulations aimed at closing material and energy loops. Moreover, they provide guidance on the allocation of financial support to improve the level of circularity of large enterprises.

Contribution & Value Added: The article makes a significant contribution to the development of the circular economy theory by developing an original indicator of pro-environmental involvement in the process of selecting ICT equipment and conducting a comprehensive analysis of circularity in the management of ICT devices in large enterprises of the European Union. The conducted research reveals significant differences in the implementation of the principles of the circular economy in the countries studied, constituting a starting point for further actions to improve efficiency and transfer best practices in this area.

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INTRODUCTION

Contemporary changes in the business environment have a fundamental impact on its functioning. The environment is under the influence of many phenomena related mainly to the ongoing process of globalization of markets, increasing competition, rapid flow of information, and rapid and intensive development of new information and communication technologies (ICT). Together with the abolition of trade and political and economic barriers, the above circumstances oblige managers to implement immediate and effective actions related to the adaptation of entities to current market conditions. For this reason, it is necessary to introduce appropriate economic models together with action programs that will meet the requirements of the VUCA and BANI environment[1] (Kok, 2018; Ramakrishnan, 2021) and challenges conditioned by, among others, the climate crisis, energy crisis, global warming, improper exploitation and natural resources use.

Despite the increasing devastation of the natural environment, most economies in the world are based on the traditional linear model of business operations. In this type of economy, natural resources are reduced and the volume of waste produced increases. This type of material circulation pattern in the economy is subject to unfavourable assessment because it is impossible to subordinate it to the designated principles of sustainable development (SD). Therefore, it is necessary to transform economies in the scope of more efficient use of natural resources, reduction of pollutant and gas emissions, mitigation and adaptation to climate change in accordance with the SD concept using environmentally friendly information and communication techniques and technologies. An alternative solution to the linear method of resource use, which is replaced by a closed loop of material flow, is the concept of the circular economy (CE). Its main assumption is the use of reverse material flow with simultaneous negligible management of natural resources at minimal costs resulting from actions taken in the field of environmental protection and related to the impact on the environment (Agyapong *et al.*, 2024).

Nowadays, the key role of ICT technology is indicated in the process of minimizing the negative impact of enterprises on the natural environment. Nevertheless, according to the estimates, this sector generates several per cent of global greenhouse gas emissions. From the perspective of implementing the circular model in enterprises, it is important to use ecological solutions in the field of ICT (so-called green IT/ICT), which consist of the appropriate design, production, selection, use, and disposal of such equipment effectively and rationally, slowing down or limiting to zero the impact on the natural environment. Thus, the circular model of managing ICT devices allows reductions in the use of hazardous materials in the production of computer equipment, the selection and design of energy-saving, environmentally friendly devices, and improving energy efficiency during the production life cycle (Nath & Agrawal, 2020). Therefore, the key assumption of the conducted analyses is to find an answer to the research question:

RQ: To what extent do large enterprises in the European Union implement the principles of the circular economy during the life cycle of ICT equipment?

The main objective of the article is to determine the level of differentiation of large enterprises operating in the European Union in terms of the sustainable use of ICT tools and to reduce the dimension of variables describing the circular model of managing ICT solutions.

Due to the above objective, we conducted pilot studies, for which we obtained statistical data from the Statistical Office of The European Communities (Eurostat) database from the sections on ICT and environment by size class of enterprise, sustainable development indicators, and ICT usage in the enterprise by NACE Rev. 2 activity in enterprises employing 25 people or more for the year 2022.[2] We interpreted the results using the diagnostic-descriptive method with principal component analysis (PCA), the MOORA method, and the grouping of linearly ordered objects.

The article is divided into four parts. The first section presents the theoretical background along with a review of the literature on the circular economy, highlighting the importance of information and com-

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[1] VUCA is an acronym for Volatility, Uncertainty, Complexity, Ambiguity. BANI is an evolution of the 1980s concept of VUCA and means functioning in a Brittle, Anxious, Non-linear, Incomprehensible environment.

[2] The European Union (EU) has released such statistics for the first time for 2022.

munication technologies in achieving sustainable development goals. Additionally, it addresses the need to transform the linear economy model into a circular one and to implement pro-ecological solutions in the processes of manufacturing, using, and disposing of IT equipment to minimize their negative impact on the environment. The second section outlines the research methodology, detailing the methods used: principal component analysis, multi-objective optimization based on ratio analysis, linear ordering, the Gini coefficient, and the Lorenz curve. The third section describes the data collection process, presents the results of the analysis, and verifies the research hypotheses. The final section analyses the empirical findings to date and discusses the limitations of the research along with its future directions.

LITERATURE REVIEW AND HYPOTHESES DEVELOPMENT

The European Union's Assumptions for a Sustainable Circular Economy

The SD concept, popularized in the late 1980s by the United Nations (UN) Commission on Environment and Development, was created in connection with the need to counteract the degradation of the natural environment. In 2015, over 190 countries in the UN accepted the resolutions resulting from the '2030 Agenda' and thus decided to apply 17 Sustainable Development Goals (SDGs) in their national regulations, including 169 detailed tasks (Costa *et al.*, 2024).

Scholars consider SD as an integral approach to business aimed at strengthening competitive advantage and profitability through the sustainable creation of shared value and close cooperation with all stakeholders, as well as the integration of factors: E – environmental, S – social responsibility and G – corporate governance (ESG) in the decision-making process (Taticchi & Demartini, 2021). However, one of the first definitions indicates that it is development that meets current needs without depriving future generations of the possibility of meeting their needs. Thus, the essence of SD is to introduce such a process of change in which the exploitation of resources, directions of investment, the course of technological progress and institutional changes remain in harmony, maintaining the current and future possibility of satisfying human aspirations (Keeble, 1988).

The current inadequacy of the adopted SD development model results from the maintenance of a linear management model in line with the principle of 'take – produce – use – throw away,' which makes it impossible to reuse depleted resources. Thus, the availability of natural resources has significantly exceeded the prospects for their reconstruction. Conditions of this type indicate that the linear model of the economy is inappropriate, destabilizing, and takes on a character that does not engage in the SD idea. Therefore, changing the indicated circumstances is possible by using the CE model.

The CE concept recognises that the value of products, materials, and resources is maintained for as long as possible and that waste generation is minimized as an important contribution to the European Union's (EU) efforts to create a sustainable, low-emission, resource-efficient, and competitive economy (COM/2014/0398, 2014). To strengthen the circularity level, organizations should apply the 3R principle (reduce, reuse, recycle), at least in the area of waste handling. This approach concerns reducing (1R) or waste generation. It is considered the first stage in companies' efforts to implement the concept of sustainable development, which involves reducing the consumption of natural resources and energy. Another element of the 3R principle is reuse (2R), which involves extending the life cycle of products. It is based on the reuse of products, reducing the demand for new resources. The last component, recycling (3R), concerns the transformation of waste into secondary raw materials. As a result of this process, materials are transformed into new products that reduce the demand for natural resources and reduce the amount of waste. The above-mentioned 3R circular economy standards display close interdependence. The order in which they are implemented is also crucial. Therefore, products that are not subject to the reduction process should be reused so that they are recycled during the last stage. Implementation of such activities allows for the systematic use of secondary raw materials in production processes. Such a procedure contributes to the reduction of energy and natural resources use. In this way, it supports the implementation of the objectives of the circular economy by reducing the negative impact of companies on the environment (Appiah-Otoo *et al*., 2023). Based on this rule, the Canadian formula 4RV + ogeS was created, i.e., reduce, reuse, recycle, regenerate, valorize + zero greenhouse gas emissions. The next configuration concerns the Swiss 5R, consisting of reducing, repairing, reusing, recycling, and reinventing. The above-mentioned principles contributed to the creation of the 9R competitiveness level pyramid, in which the following activities were distinguished: refuse, reduce, re-reuse, repair, refurbish, remanufacture, re-purpose, recycle, and recover (Cramer, 2023).

The EU's strategic plans record the transformation of the economy following the procedures into a closed loop. At the end of 2015, the EU adopted the directive Closing the Loop: An EU Action Plan for the Circular Economy, the so-called CEAP1, which concerned the plan of action undertaken in connection with implementing the principles of a closed loop in each product life cycle. At the same time, next to CEAP1, the European Commission disseminated a set of legislative proposals (the so-called Circular Economy Package – CEP), which concerned the reform of the previously legally binding directives on waste, storage, packaging waste, and end-of-life vehicles, used batteries, accumulators, electrical and electronic equipment (Directive 2012/19/EU, 2012). The fundamental changes resulting from the directive concern included the following CE components:

- formulating common EU recycling targets and preparing the reuse of municipal waste by 2025 – with the recovery of 60%, and by 2030 – 65%;
- defining a common EU target for recycling packaging waste produced from plastics (by 2025 – 55%; 2030 – 65%), wood (by 2025 – 60%; 2030 – 75%), ferrous metals (by 2025 – 75%; 2030 – 85%), aluminium (by 2025 – 75%; 2030 – 85%), glass (by 2025 – 75%; 2030 – 85%), paper and cardboard (by 2025 – 75%; 2030 – 85%);
- a ban on storing selectively collected waste;
- promoting financial and economic instruments that discourage the waste storage process;
- organising an early warning system enabling monitoring and control of compliance with the implementation of recycling activities and targets;
- providing financial resources as an incentive for producers who plan to produce ecological products and support recycling programmes.

Moreover, the developed program indicated the requirement to intensify the use of many existing methods of measuring tasks conducted within the CE. These include procedures such as material flow analysis (MFA), life cycle assessment (LCA), diagnosis of mechanisms in the field of green public procurement (GPP), eco-management and audits (EMAS), environmental technology system control (ETV), extended producer responsibility (EPR), best available techniques (BREF), and eco-design (COM/2014/0398, 2014).

At the beginning of 2021, the EU adopted a new Circular Economy Action Plan for a Cleaner and More Competitive Europe (CEAP2), which is a continuation of CEAP1 and ESG. This program concerns an additional 35 actions influencing the process of transforming the economy into a circular one and defining a new level of the circularity indicator. According to the adopted directive, it should be doubled by 2030.

The program consists of five strategic directions of EU action, which refer to the scope of intervention. The first one sets out the procedures of sustainable product policy concerning their design, strengthening the position of consumers and public purchasers and closed circulation in production processes. The second direction refers to key product value chains and supporting selected sectors of the economy. The third part of the plan recommends reducing the amount of waste, drawing attention to the mandatory implementation of an effective policy in this area, which should support the prevention of waste generation. The fourth component of the program indicates the adaptation of the closed loop to the requirements of society, regions and cities. In turn, the final fifth element of the program includes cross-sectional activities carried out in the implementation of CE principles. Thus, the closed loop is presented from the perspective of a criterion influencing the achievement of climate neutrality. In this type of economic model, special attention is paid to profitability and support for its implementation through the development of research, innovation, and digital transformation. CEAP2 indicates the obligation to minimize the carbon and material footprint and the extension of the closed loop in the industrial sector to all its industries (COM/2020/102, 2020). Based on the above analysis of the literature on the subject, we put forward the following thesis:

T1: Large enterprises operating in the European Union are implementing selected principles that enhance the level of circularity, leading to a reduction in the negative impact of ICT equipment on the environment in the selection, operation, and disposal of such devices, resulting from the implementation of the sustainable development strategy.

ICT Technologies as a Key Component of the Circular Economy

Implementation of new ICT technologies in the management and development process of entities is a key condition for maintaining their competitive position. However, along with the expansive technological and industrial development, the economies of countries are constantly struggling with difficult tasks related to the devastation of nature, loss of biodiversity, anthropogenic climate changes and their negative consequences.

In connection with the threats indicated above, the EU has decided to draw attention to the interdependence between the implementation and use of ICT technologies and the protection of the natural environment. Consequently, the European Commission consistently analyses the connections between digitalization and the natural environment primarily from the perspective of sustainable development policy, the European Green Deal, the Digital Decade of Europe, the European Industrial Strategy, and the European Coalition for Green Digitalization.

Moreover, scholars consider ICT technologies tools that ensure the processing, collection, and transmission of information in electronic form (Arbeláez-Rendón *et al.*, 2023). They are based on seven main elements, consisting of software, computer hardware and peripherals (printers, scanners), cloud computing, transactions, ICT, data, and Internet access (Desruelle & Stančík, 2014). The rapid spread of ICT contributes to intensive energy consumption and excessive greenhouse gas emissions and, as a result, has a negative impact on the natural environment. Moreover, ICT equipment poses a serious environmental problem in the production and disposal phases. The indicated results are inconsistent with the SD goals adopted in the EU (Börjesson Rivera *et al*., 2014; Roussilhe *et al.*, 2023). Moreover, the popularization of information technology also contributes to the increase in the amount of electronic waste (Zahra, 2011; Laranja Ribeiro *et al.*, 2021).

The most important stage of implementing the SD and CE concepts resulting from cre for the environment is the implementation of the Green ICT/IT strategy, *i.e*., the use of ecological solutions in the area of information and communication technologies. Therefore, actions taken by large companies in this area should concern the design, production, planning, operation and recycling of computers, servers, subsystems, and devices such as monitors, printers, disks, communication, and network systems. In connection with the introduced directives, entities operating in the EU are obliged to implement the indicated stages considering an ecologically rational and efficient approach and limiting or completely reducing the negative impact on the natural environment (McNamee *et al.,* 2010).

Green IT/ITC concerns the sustainable use of resources, considering their increasing benefits for the environment and the economic system. Such circumstances are related to the need to reduce the negative impact of economic activity on the environment and in particular, to promote the SD strategy in all areas of the organization's functioning (Lautenschutz *et al.*, 2018; Awewomom *et al.*, 2024). For this reason, scholars consider such technologies an optional concept that allows for resolving environmental dilemmas in the field of resource-efficient production and environmental protection

The literature defines green information technology (IT)/ICT as an organization's ability to systematically adapt to the SD criteria of the environment (such as pollution prevention, equipment management, and use of clean technologies) in the design, production, acquisition, use and disposal of IT technology infrastructure, as well as the ability to adapt human and managerial elements of the IT infrastructure (Hernandez, 2018).

Scholars consider green IT/ICT to be the science and principle of designing, manufacturing, and disposing of computers, servers, and related components (*e.g*., monitors, printers, external drives, external memory media, software, network systems, communication systems, and data transmission) in an efficient and reliable manner with minimal impact on the environment. Taking the above actions enables an organization to achieve economic profitability and improve the efficiency of operating IT systems, taking into account the social, ethical, and environmental dimensions of SD (Unhelkar, 2011). Therefore, the Green IT/ICT concept considers the dimensions and levels of environmental sustainability, the energy efficiency system and the total cost of ownership of the technology, which includes disposal and recycling (Murugesan & Gangadharan, 2012). Green IT/ICT technologies should meet the following criteria: a) minimize environmental degradation, b) reduce greenhouse gas emissions to zero, contributing to a safe environment for the health of society and other forms of life, c) limit the consumption of natural resources and electricity, d) increase the use of renewable energy sources (Fawole *et al.*, 2023).

The implementation of Green IT/ICT is related to the implementation of two basic and mutually subordinate strategic goals. The first one supports companies in activities that reduce the direct contribution of IT technologies to carbon footprint emissions. The second one enables meeting the challenges related to overall greenhouse gas emissions by using green technologies that reduce the environmental footprint of the company (Butler & Hackney, 2021).

The fundamental goal of the Green IT/ICT strategy is to reduce energy consumption and operating costs while controlling the ever-increasing requirements related to efficiency and resource multiplication. We should consider the effect of IT/ICT devices on the environment from a two-category perspective. The first one concerns the first-order effects, which refer to the negative impact of the production, use, and disposal of IT/ICT equipment (Hilty & Aebischer, 2014; Kumar & Daman, 2023). Second-order consequences refer to the desired impact of information systems (IS) on improving the environmental sustainability of enterprises and society following the Green IS concept (Anthony Jr, 2019; Theis & Schreiber, 2020).

Moreover, apart from minimizing energy consumption, the strategic goal of Green IT is to reduce greenhouse gas emissions generated by computer systems and data centre infrastructure. The implementation of the above-mentioned goals is supported by the following strategic actions, which consist in reducing PCs' energy consumption, enabling energy management functions, turning off unused systems, using screen savers, using thin client computers, using ecological data centres, saving energy, eco-friendly design and virtualization (Murugesan & Gangadharan, 2012; Ojo & Fauzi, 2020).

The literature on the subject identifies four key principles that enable the use of environmentally friendly IT/ICT technologies, which are: a) the use of natural materials recovered in the process of sustainable consumption, b) rational management of IT/ICT devices at the end of their life cycle, c) reduction in greenhouse gas emissions and pollutants as a result of improved production processes, d) continuous improvement of environmentally friendly standards to protect the environment and secure human health (Anthony *et al.*, 2020). The above assumptions emphasize the versatility of using the green IT/ICT strategy as a program aimed at reducing carbon footprint emissions *(*Asadi *et al.*, 2017; Queirós *et al.*, 2020). Nowadays, the SD and CE concept in the field of green technologies is complemented by the following goals: a) energy efficiency resulting from storing and virtualizing data in the cloud, optimization, cooling and intelligent management of energy used by the computer, b) ecological office environment: intelligent and natural room lighting systems, paperless information processing, c) ecological transport, d) ecological industry, e) waste management: reuse, reduction, recycling of resources (Khadivar *et al.*, 2024).

The implementation of the above-mentioned strategic actions and programs allows companies to gain an advantage resulting from the use of energy-saving and environmentally friendly solutions. Strategies related to the improvement of processes aim at reducing energy consumption, proper processing and disposal of e-waste, enabling the extraction of raw materials from them, and the application of a recycling process that provides entities with significant savings as well as the implementation of CE principles together with SDG. Based on an analysis of the literature on the subject, the thesis is that:

T2: Despite uniform legal regulations of the European Union, large enterprises still differ in the level of use and circularity of ICT equipment and in their adaptation to sustainable development criteria in accordance with the principles of selection, repair, recycling, reuse, and management of green ICT resources, which affect the effectiveness of closing material loops in the circular economy model.

RESEARCH METHODOLOGY

Principal Component Analysis

Principal component analysis (PCA) is based on the correlation or covariance matrix resulting from the initial set. This method allows for the selection of primary variables that have a significant impact on the value of individual principal components (PC), *i.e.*, those that shape a homogeneous group. In such a case, PC is a representative of this group. On the other hand, the remaining components are orthogonal, and their number is smaller or equal to the number of primary variables (Tsoulfidis & Athanasiadis, 2022). Based on the applied PCA, the new model is created describing the structure of dependencies between the studied variables. Thus, the mathematical PCA model is shaped using the following system of linear equations (Drees & Sabourin, 2021):

$$\begin{gathered} X_1 = a_{11}Z_1 + a_{12}Z_2 + \cdots + a_{1p}Z_p \\ X_2 = a_{21}Z_1 + a_{22}Z_2 + \cdots + a_{2p}Z_p \\ \vdots \\ \boldsymbol{X_p = a_{p1}Z_1 + a_{p2}Z_2 + \cdots + a_{pp}Z_p} \end{gathered} \qquad (1)$$

in which:

X_p - *p*-th variable (*p=1,2,…,n*);
$Z_1 \ldots Z_n$ - main components;
$a_{p1} \ldots a_{pp}$ - principal component coefficients.

In the next stage of the analysis, we selected factor loadings to consider an appropriately large share in explaining the total variability of the output data. As a rule, we selected an appropriate number of dimensions (D), the variance of which cannot be less than 75% of the total variability (Morrison, 2004). We extracted the number of PCs using the scree criterion and Kaiser (Boudt *et al.*, 2022), which is based on including only dimensions with eigenvalues greater than 1 in further analysis. In connection with the study, we rotated the collected data according to the normalized varimax (maximum of the variance) method, which allowed the maximum differentiation of loadings in the dimension area.

The key assumption of the PCA method is the appropriate comparison of results and loadings of vectors corresponding to the maximum eigenvalues, which include the most important information regarding the analysed problem. Therefore, using PCA, we created a new set of orthogonally located descriptors called PC. They represent the majority of information included in the independent variables according to the minimizing values of variance (Hilbert & Bühner, 2020).

In connection with the identification of the activities of large enterprises related to the implementation of the circular economy when selecting, operating, and discontinuing the use of ICT devices, in the first stage of the research, we selected 15 diagnostic variables from the Eurostat database for 2022 from the ICT and environment section by enterprises' size class:

X1 – Enterprises applying some measures affecting the amount of paper used for printing and copying;

X2 – Enterprises applying no measures affecting the amount of paper used for printing and copying;

X3 – Enterprises applying some measures affecting the energy consumption of the ICT equipment;

X4 – Enterprises applying no measures affecting the energy consumption of the ICT equipment;

X5 – Enterprises applying some measures affecting the paper or energy consumption of the ICT equipment;

X6 – Enterprises with very high digital intensity index, which apply some measures affecting the paper or energy consumption of the ICT equipment;

X7 – The enterprises considered the environmental impact of ICT services, or ICT equipment before selecting them;

X8 – Enterprises with a very high digital intensity index, which considered the environmental impact of ICT services, or ICT equipment before selecting them;

X9 – The enterprises considered the environmental impact of ICT services, or ICT equipment before selecting them and applying some measures, affecting the paper or energy consumption of the ICT equipment;

X10 – Enterprises with a very high digital intensity index, which considered the environmental impact of ICT services, or ICT equipment before selecting them, and applying some measures, affecting the paper or energy consumption of the ICT equipment;

X11 – When the ICT equipment of the enterprise is no longer used, it is disposed of in electronic waste collection/recycling;

X12 – When the ICT equipment of the enterprise is no longer used, it is kept in the enterprise;

X13 – When the ICT equipment of the enterprise is no longer used, it is not kept in the enterprise;

X14 – When the ICT equipment of the enterprise is no longer used, it is sold, returned to a leasing enterprise, or donated;

X15 – When the enterprise's ICT equipment is no longer used, it is not sold, returned to a leasing enterprise, or donated.

Multi-attribute Optimization Method and Linear Ordering by Standard Deviations

The literature considers the multi-objective optimization method based on ratio analysis (MOORA) to be an objective, multi-criteria method used to solve problems related to the decision-making process (Karande & Chakraborty, 2012). It is based on ratio analysis and the concept of a reference point or proportion system. It also serves to solve complex problems that have several divergent attributes that are subject to constraints (Chakraborty *et al.*, 2023). MOORA effectively shows excellent correlation of priority order with the reference solution, which is not affected by additional attributes (Behzadian *et al.*, 2010; Singh *et al.*, 2024) and unspecified criteria weights (Sutarno *et al.*, 2019). Therefore, this method can simultaneously analyse multiple quantitative and qualitative choice attributes in the decision-making process (Pérez-Domínguez *et al.*, 2018).

However, in the situation of considering a decision problem, the criteria and their results must be measurable to enable measurement for all supposed alternatives. Among the opposing criteria, certain ones are considered favourable (reaching the maximum value), and others are considered unfavourable (for which the minimum values are preferred in each case). In the MOORA ratio method, both types of criteria are considered with the aim of organizing and isolating one or more alternatives from the set of available possibilities (Arshad *et al.*, 2024).

We initiated the research process using the discussed method with a decision matrix (*x*) (step 1):

$$\boldsymbol{x} = \begin{bmatrix} x_{11}, x_{12} & \cdot & x_{1n} \\ x_{21}, x_{22} & \cdot & x_{2n} \\ x_{m1}, x_{m2} & \cdot & x_{mn} \end{bmatrix} \tag{2}$$

in which:

x_{ij} - output quality characteristic of different attributes of *m* alternative values in criterion *n*, i=1,2,…, *n*;

n - number of attributes *j = 1,2,…, m*;

m - number of alternatives.

Then, we conducted the decision matrix data normalization, during which we transformed the values of each criterion from different alternatives into values that allow direct comparison (step 2) according to the formula:

$$\boldsymbol{x}^*_{ij} = \frac{\boldsymbol{x}_{ij}}{\sqrt{\sum_{i=1}^{m} \boldsymbol{x}_{ij}^2}} \tag{3}$$

in which:

x_{ij} - response of alternative *j* to attribute *i; j=1,2,…,m*;

m - number of alternatives; *i=1,2,…,n*;

n - number of attributes;

x^*_{ij} - dimensionless number in the interval [0,1] representing the normalized response of alternative *j* to criterion *i*.

In the case of normalized multi-objective optimization, we summed the results for favourable attributes (maximization) and limited when unfavourable attributes occur (minimization). Then the optimization problem proceeds according to the formula (step 3):

$$\boldsymbol{y_i = \sum_{j=1}^{g} x_{ij}^N - \sum_{j=g+1}^{n-g} x_{ij}^N} \quad (4)$$

in which:

g - number of attributes that should be maximized;

$(n-g)$ - number of attributes that should be minimized;

y_i - normalized value of the alternative with respect to all attributes.

Next, we multiplied the normalized criteria values by the appropriate criteria weight coefficients to obtain the following optimization relationship:

$$\boldsymbol{y_i = \sum_{j=1}^{g} w_j * x_{ij}^N - \sum_{j=g+1}^{n-g} w_j * x_{ij}^N} \quad (5)$$

in which:

w_j - the weight of the *j*-th attribute, which we can attribute using the analytic hierarchy process (AHP) method or the selected entropy method.

For this research, we used the Shannon entropy method.

According to the weighted values of the criteria, y_i can have a positive or negative scale in relation to the maximum (favourable attribute) and minimum (unfavourable attribute) number in the decision matrix. We indicated the preference based on the ranking of alternatives according to the obtained value y_i. The best alternative had the highest value of y_i, while the marginal alternative had the lowest level y_i (step 4). In the MOORA method, it is recommended to prepare a systematic ranking of y_i values for each alternative in order to make final decisions, enabling decision-makers to determine the optimal alternative (Brauers & Zavadskas, 2009).

Recently, the MOORA method has gained popularity in solving problems related to engineering designs, real estate performance assessment, robot selection, personnel selection, quality control, production scheduling, medical waste management, health care management, site selection, enterprise selection, and determining the recipients of intelligent applications (Thakkar, 2021; Ngemba *et al.*, 2021; Akmaludin *et al.*, 2021; Rizk-Allah *et al.*, 2020; Akkaya *et al.*, 2015; Arabsheybani *et al.*, 2018; Dinçer *et al.*, 2019).

In turn, the standard deviation method allows for the systematization of variants based on the study of the deviations of the aggregated variable value (in this study, the value of the y_i, indicator, which was obtained in stage 3 of the MOORA method) from the average value of this variable (Panek & Zwierzchowski, 2013). Therefore, it is possible to divide objects, considering the level of the studied phenomenon, and classify them into four typological groups. The basis for the process of generating classes of linearly ordered objects are the ranges of the y_i u indicator values formed using the arithmetic mean ($\bar{s}$) and the standard deviation *S*(*s*) (Rani *et al.*, 2023). The created set of objects is arranged into four groups containing objects with values of the synthetic variable from the following disjoint ranges (Şahin, 2021): group I: $y_i \geq \bar{s} + S(s)$; group II: $\bar{s} + S(s) > y_i \geq \bar{s}$; group III: $\bar{s} > y_i \geq \bar{s} - S(s)$; group IV: $y_i < \bar{s} - S(s)$.

Categories classified in group I displayed a very high level of the phenomenon being studied. Group II, on the other hand, included objects with a high level of this phenomenon. Group III, however, included variants with an average intensity of the analysed event. The final group IV consisted of objects representing a low level of the diagnosed phenomenon.

To diagnose the degree of diversity of large enterprises from the 27 EU countries from the perspective of the sustainable use of ICT tools, we considered a total of 18 variables, including the 15 indicated in the previous point used for the PCA analysis and three additional diagnostic variables from the Eurostat database for 2022 from the ICT and environment by size class of enterprise, sustainable development indicators, and ICT usage in enterprise sections.

In the process of creating the ranking using the MOORA method, we identified the variables that should be maximized and minimized. Table 1 presents them.

Table 1. Attributes subject to maximization and minimization

Variable name	Variable description	Optimization type
X1	Enterprises applying some measures affecting the amount of paper used for printing and copying	Maximization
X2	Enterprises applying no measures affecting the amount of paper used for printing and copying	Minimization
X3	Enterprises applying some measures affecting the energy consumption of the ICT equipment	Maximization
X4	Enterprises applying no measures affecting the energy consumption of the ICT equipment	Minimization
X5	Enterprises applying some measures affecting the paper or energy consumption of the ICT equipment	Maximization
X6	Enterprises with very high digital intensity index, which apply some measure affecting the paper or energy consumption of the ICT equipment	Maximization
X7	The enterprises considered the environmental impact of ICT services or ICT equipment before selecting them	Maximization
X8	Enterprises with very high digital intensity index, which considered the environmental impact of ICT services or ICT equipment before selecting them	Maximization
X9	The enterprises considered the environmental impact of ICT services, or ICT equipment, before selecting them and applying some measures affecting the paper or energy consumption of the ICT equipment	Maximization
X10	Enterprises with very high digital intensity index, which considered the environmental impact of ICT services or ICT equipment before selecting them, and apply some measures, affecting the paper or energy consumption of the ICT equipment	Maximization
X11	When the ICT equipment of the enterprise is no longer used, it is disposed of in electronic waste collection/recycling	Maximization
X12	When the ICT equipment of the enterprise is no longer used, it is kept in the enterprise	Minimization
X13	When the ICT equipment of the enterprise is no longer used, it is not kept in the enterprise	Minimization
X14	When the ICT equipment of the enterprise is no longer used, it is sold, returned to a leasing enterprise, or donated	Maximization
X15	When the ICT equipment of the enterprise is no longer used, it is not sold, returned to a leasing enterprise, or donated	Minimization
X16	Reducing electricity consumption by ICT equipment	Minimization
X17	Enterprises with very high digital intensity index	Maximization
X18	Circular material use rate	Maximization

Source: own study.

Gini coefficient and Lorenz Curve

The Gini concentration coefficient is a solution used to measure the unevenness of the distribution of a random variable. The Lorenz concentration curve is its graphical representation, based on which it is estimated. The Gini index reflects the proportion of the area located between the concentration curve and the line of uniform distribution to the area of the triangle placed under the line of uniform division (Göktaş & Akkuş, 2021). The concentration space is the area between the diagonal of a unit square and the Lorenz curve, with the probable maximum coinciding with the area below the diagonal (egalitarian line). The maximum area of the concentration surface is considered to be the area of a right-angled triangle, which was defined by the line $y = x$, as well as the segments with edges (0.0); (1.0) and (1.0); (1.1) (Blesch *et al.*, 2022). To determine the Gini coefficient, we may use the following formula (Kristensen, 2022):

$$\boldsymbol{G(y)} = \frac{\sum_{i=1}^{n}(2i - n - 1) * y_i}{n^2 * \bar{y}} \tag{6}$$

in which:

n - number of observations;
y_i - value of the i – th observation;
$\bar{y}$ - average value of all observations, *i.e.*, $\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i$.

In the above formula, the y_i values should be arranged in ascending order, and i symbolizes the unit number in the ascending sequence. The Gini coefficient occurs in the interval [0;1] (Marchetti & Tzavidis, 2021). It is created based on the Lorenz curve, which determines the degree of concentration of a one-dimensional distribution of a random variable. It is created by connecting points whose coordinates occur as cumulative relative frequencies of variables arranged according to increasing share and integrated parts of the studied feature of a specific entity and all its preceding units. The curve is located in a unit square with a side of 100 (100% = 1) units of measurement of the designated scale, within which points with coordinates defined by cumulative indicators are placed. Its boundaries are formed by the lower left and upper right vertices of the square. By connecting the obtained points with straight line segments, a concentration polygon is obtained. In turn, if they are connected with a curved line, a concentration curve (Lorenz) is generated (Sitthiyot & Holasut, 2021).

In the case of ranked observations $\mathrm{y_i}$, which have non-negative values $0 \le \mathrm{y_i} \le \mathrm{y_2} \le \cdots \le \mathrm{y_n}$, $\sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{y_i} > 0$, the Lorenz curve takes the form of a broken line whose vertices $(\mathrm{x_h}, \mathrm{z_h})$, for $\mathrm{h} = 0,1, \dots, \mathrm{n}$, with the following coordinates (Chang *et al.*, 2018):

$$\boldsymbol{x_0 = z_0 = 0, x_h = \frac{h}{n}, z_h = \frac{\sum_{i=1}^{h} y_i}{\sum_{i=1}^{n} y_i}} \tag{7}$$

in which:
n - number of observations;
y - the value of the i-th observation;
y_n - level of the phenomenon in a certain period.

The concentration curve is a straight line created as a result of combining points with the following coordinates (Schneider, 2021):

$$\boldsymbol{\left(N, \sum_{i=1}^{N} u_i\right)} \tag{8}$$

in which:
N - number of a given entity in the ordered set of entities according to the decreasing share in the total value of the feature, N – takes values from *1* to *n*;
u_i - an indicator of the share of a given feature.

The slope coefficient of a straight line

A linear function is a relationship defined as $f: R \to R$. On the other hand, we can determine a straight line in the coordinate system that is not parallel to the Y-axis by a functional formula determining the so-called directional equation (Glen & Zazkis, 2021):

$$\boldsymbol{y = ax + b} \tag{1}$$

in which:
$a, b \in R, a$ - slope;
b - free term of the linear function.

The slope *a* in the above linear function formula represents the increase in the function value as a result of increasing the argument by 1. And the intercept *b* determines the point where the graph of the function intersects the Y-axis (Wells, 2016).

Therefore, the slope coefficient determines the degree of the straight line slope, which is equal to the tangent of the angle of the tangent to the curve that the given straight line draws with the positive direction of the X-axis. To interpret the level of the slope of the tangent to the graph, one indicates the increase in the value plotted on the X-axis and the corresponding increase in the value on the Y axis (Stoer & Bulirsch, 2002). By estimating the dependence of the indicated increments, we obtained the value of the slope of the tangent, *i.e.*, $\Delta y / \Delta x$. In turn, its graph is a straight line intersecting the Y-axis at the point (0,b) and inclined to the positive semi-axis X at an angle α consistent with the relationship $tg\alpha = \mathrm{a}$ (Bewick *et al.*, 2003).

RESULTS AND DISCUSSION

Circular Activities of Large Enterprises in the Area of ICT Solution Management

In the first stage, we identified the actions of large enterprises undertaken in connection with implementing the concept of closed-loop ICT equipment and its selection, taking into account the impact on the environment following the SD strategy. To present the procedure related to the selection, recycling, and disposal of devices used for the digitalization of the studied entities, we used the PCA method.

The study made it possible to distinguish identical dimensions (course of action) that contribute to the correlation between the analysed variables (CE assumptions regarding the management of ICT resources). We indicated the degree of dependence between individual attributes by the correlation matrix (see Table 2). The absolute value of the correlation coefficient informs us of the strength of the dependence between the analysed variables. We obtained strong positive and negative correlations.

The symmetry of the matrix allowed us to omit information above the main diagonal to increase clarity. The values of the correlation coefficients obtained for the observed pairs of variables ranged from -0.9999 to 0.9847 and thus indicated a strong relationship between the variables. We initiated the process of extracting the dimensions of the factors by analyzing the significance of the correlation matrix. Therefore, we applied Bartlett's sphericity test and assessed the adequacy of the input variables selection for the PCA analysis using the Kaiser-Mayer-Olkin coefficient (KMO). The value of the KMO coefficient at the Overall MSA level was 0.707, with the simultaneous significance of Bartlett's test of sphericity $\chi^2 = 431.608$, df = 105.000, p <0.001 (see Table 3).

The obtained KMO measure (0.707) exceeded the acceptable threshold of 0.5 and thus confirmed the validity of using PCA analysis. On the other hand, Bartlett's test of sphericity enabled us to verify the null hypothesis (H0), assuming that the correlation matrix between variables used in the analysis was unique. Based on the obtained p-value (<0.001), we rejected H0 in favour of the alternative hypothesis (H1). This result indicates that the correlation matrix was not unique, and there were significant correlations between the analysed variables, indicating the occurrence of unobservable dimensions. Thus, the test values justified the use of PCA analysis.

The PCA data graphic projection technique made it possible to isolate the connections and disharmonies that occurred between the studied behaviours of large enterprises related to the transformation focused on SD through the implementation of CE principles regarding the use of ICT equipment in the combination of the first two PCs (see Figure 1).

Based on the obtained data, we prepared a PCA projection, in which orthogonal variables explained a total of 71.37% of the total variance, *i.e.*, the total multidimensional variability of the application of procedures for eliminating the potential impact of ICT technologies on the natural environment was transformed. The applied analysis showed that the type of activities undertaken by the surveyed organizations in the field of CE differentiated by features related to the first seven components D1-46.50%, D2-27.87%, D3-11.69%, D4-6.34%, D5-4.65%, D6-3.66%, and D7-1.99%. Together, the above-mentioned components explained 99.70% of the total variance, *i.e.*, the total multidimensional variability of the implemented standards. Therefore, the conducted study revealed that the adaptation of material loops to minimize the consumption of raw materials in large enterprises was characterized by differentiation due to the applied CE procedures.

The projection of the standardized D1 and D2 coefficients, found in linear combinations with the variables responsible for the type of procedure resulting from the management of ICT resources onto a circle with a unit radius and centre at the origin of the coordinate system, presents groups of correlated CE procedures used by entities (see Figure 1).

Table 2. Matrix of coefficients of correlation between variables

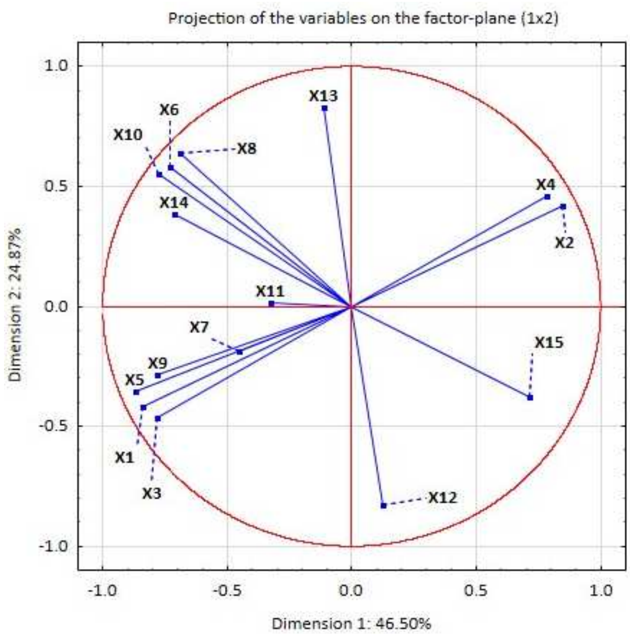
Variables	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12	X13	X14	X15
X1	1.0000														
X2	-0.9999	1.0000													
X3	0.7984	-0.7996	1.0000												
X4	-0.7969	0.7983	-0.9998	1.0000											
X5	0.9814	-0.9815	0.8002	-0.7989	1.0000										
X6	0.3748	-0.3747	0.3253	-0.3260	0.4422	1.0000									
X7	0.3344	-0.3339	0.4041	-0.4019	0.3045	0.0267	1.0000								
X8	0.2608	-0.2597	0.2358	-0.2354	0.3138	0.9199	0.3141	1.0000							
X9	0.7385	-0.7383	0.6808	-0.6787	0.7284	0.2662	0.8639	0.4064	1.0000						
X10	0.3845	-0.3837	0.3626	-0.3622	0.4367	0.9472	0.3057	0.9847	0.4602	1.0000					
X11	0.2534	-0.2538	0.1138	-0.1157	0.2684	0.3551	-0.1167	0.2635	0.0601	0.2763	1.0000				
X12	0.1582	-0.1580	0.2168	-0.2174	0.1152	-0.4711	-0.0240	-0.5434	0.0269	-0.4913	0.2084	1.0000			
X13	-0.1654	0.1655	-0.2260	0.2275	-0.1237	0.4633	0.0260	0.5382	-0.0293	0.4851	-0.2133	-0.9986	1.0000		
X14	0.3990	-0.4010	0.3194	-0.3233	0.4537	0.7281	0.0924	0.6453	0.3428	0.6823	0.3454	-0.2242	0.2096	1.0000	
X15	-0.4005	0.4028	-0.3248	0.3295	-0.4555	-0.7251	-0.0897	-0.6410	-0.3410	-0.6786	-0.3468	0.2182	-0.2015	-0.9991	1.0000

Source: own study.

Table 3. KMO measure and Bartlett's test of sphericity

KMO measure of sampling adequacy		0.707
Bartlett's test of sphericity	Approximate chi-square	431.608
	degrees of freedom	105.000
	p-value significance	< 0.001

Source: own study.



Variable	Dimension 1 of energy and paper usage of ICT equipment	Dimension 2 of unused ICT equipment
X1	-0.842820	-0.417227
X2	0.843337	0.417397
X3	-0.780474	-0.462084
X4	0.780499	0.460969
X5	-0.869534	-0.355662
X6	-0.732577	0.582495
X7	-0.452359	-0.187265
X8	-0.687906	0.639593
X9	-0.780416	-0.285914
X10	-0.776516	0.553312
X11	-0.323639	0.012419
X12	0.125051	-0.828178
X13	-0.114486	0.826869
X14	-0.713675	0.383368
X15	0.713874	-0.376790

Figure 1. Distribution of the main component loads in large enterprises implementing the principles of the circular economy for ICT equipment and secondary raw materials
Source: own elaboration in the Statistica package.

According to the determined loading vectors of the principal components, the activities undertaken by the surveyed companies with a very high digital intensity index were also characterized by a strong positive correlation. Their struggles led to the application of procedures affecting the consumption of paper or energy by ICT equipment (X6). They also considered the impact of ICT services or equipment on the environment before choosing them, and therefore, the entities introduced selected solutions regarding the consumption of paper or energy by ICT equipment (X10). In turn, D1 was characterized by a strong positive correlation, which concerns the procedures for unused ICT equipment. Therefore, the procedures of large enterprises focused on the disposal of such equipment as part of the collection or recycling of electronic waste (X11). Moreover, enterprises introduced solutions aimed at reducing the consumption of paper or electricity by ICT equipment (X5) and, before choosing ICT services and equipment, they consider their impact on the environment (X7).

The research also allowed us to distinguish activities related to reducing the adverse impact of ICT on the environment, which were distinguished by a strong negative correlation. This group included companies that store ICT equipment when it is no longer used (X12) or do not store used equipment (X13); unused devices are not sold, donated to charity, or returned to the lessor (X15), in companies with a very high digital intensity index, which take into account the impact of ICT services and equipment on the environment before choosing them (X8); large entities do not apply any procedures in the scope of activities aimed at reducing the consumption of paper for printing and copying (X2), but use solutions preventing excessive consumption of paper or energy by the used ICT equipment (X5); entities that do not initiate any activities in connection with minimizing the use of energy by ICT devices (X4) or use procedures that affect the amount of paper used for printing and copying (X1).

Furthermore, the applied PCA enabled the identification of actions taken by large enterprises as part of the elimination of the unfavourable impact of ICT technologies on the environment, which do not have correlations. These included entities that did not store unused devices of this type (X13) and those that considered the impact of ICT services or equipment on the environment, paper or energy consumption (X9) before choosing and using them; enterprises with a very high digital intensity index considered their impact on the natural environment before choosing information and communication services and technologies (X8) and used procedures that influenced the energy consumption of ICT equipment (X3); unused ICT devices were stored in enterprises (X12) that did not implement any procedures related to the use of the amount of paper for printing and copying (X2).

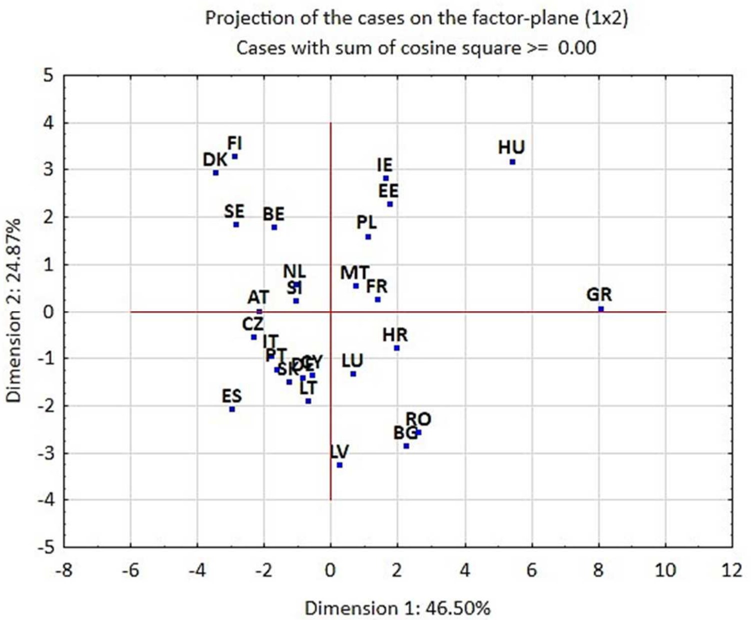


Figure 2. The degree of saturation in the implementation of the intentions to close the loop of ICT devices in large entities

Where: AT – Austria, BE – Belgium, BG – Bulgaria, HR – Croatia, CY – Cyprus, CZ – Czechia, DK – Denmark, EE – Estonia, FI – Finland, FR – France, DE – Germany, GR – Greece, HU – Hungary, IE – Ireland, IT – Italy, LV – Latvia, LT – Lithuania, LU –Luxembourg, MT – Malta, NL – Netherlands, PL – Poland, PT – Portugal, RO – Romania, SK – Slovakia, SI – Slovenia, ES – Spain, SE – Sweden.
Source: own elaboration in the Statistica package.

The final stage of the research, which was conducted using the PCA method, made it possible to obtain the result of projecting the location of enterprises in individual EU countries onto the dimensions of the planes (see Figure 2). It aimed to classify entities from the 27 EU countries based on identical actions taken to achieve circularity in the process of managing ICT equipment. The scatterplot showed four coherent groupings of countries that implemented CE principles regarding the methods of selecting, operating, and managing ICT equipment. The relatively homogeneous first group of countries, distinguished based on D1, consisted of CZ, IT, PT, SK, ES, CY, LT, and ES. The above-mentioned countries were characterized by the smallest negative factor loading values by being farthest to the left from dimension 1. This component informs about the methods of managing ICT equipment following CE principles. They consist of limiting the amount of waste and reducing pollution by closing the loop through the multiple uses of materials and recycling to extend their use by large enterprises. The second group of countries is formed by FI, DK, SE, BE, NL, SI, and AT, distinguished by positive factor loadings. The third group is formed by the countries located on the right in the graph closest to dimension 2 (D2), *i.e.*, LU, HR, RO, BG, and LV. The fourth cluster consisted of the countries IE, EE, PL, MT, and FR. Moreover, when analysing the distribution of points on the map, we should note that there are countries that differ from others in terms of the analysed variables. The first component has a fundamental impact on their differentiation. Thus, among the EU countries that differ from the studied group, we should distinguish two countries, namely GR and HU.

The conducted research shows that large enterprises operating in the 27 EU countries fragmentarily narrow the material loop resulting from the adaptation of ICT resources according to the 3xR hierarchy (reduce, reuse, recycle). It involves actions following the developed CE procedures aimed at rational management of raw materials and waste in the process of using ICT equipment and thus limiting its adverse impact on the natural environment. The surveyed enterprises use procedures X5, X6, X7, X8, and X10 as part of the first reduce principle. The subsequent standards of conduct result from the application of the X11 approach in the scope of the third recycle principle. However, the second reuse criterion is not currently included in the implemented CE concepts of large enterprises located in the EU.

On should consider the results of the PCA analysis should be consistent with the research conducted so far, which indicates differences in the implementation of CE principles depending on the region in which the enterprises operate (Geissdoerfer *et al.*, 2017; McMahon *et al.*, 2024). However, companies with a lower level of digitalization usually ignore the principle of reusing ICT equipment (Upadhyay *et al.*, 2021). Moreover, previous research results highlight the use of different CE models in companies, mainly depending on location and region, with highly specialized procedures and recycling strategies. They mostly concern countries with higher digital intensity FI, SE, and NL (Korhonen *et al.*, 2018). Thus, the conducted research confirms that the analysed entities implement the principles of the circular economy at the basic level of 3R, in a fragmented manner. They mainly focus on reduction (1R) and recycling (3R), while the reuse of equipment remains at the initial implementation stage.

In connection with the conducted research, it is necessary to verify the thesis that large enterprises implement selected principles, strengthening their level of circularity and leading to a reduction in the negative impact of ICT equipment on the environment in the scope of selection, operation, and disposal of such devices, resulting from the implementation of the SD strategy.

Sustainable Use of ICT Equipment in EU Countries

The circular economy uses a production and consumption model whose main goal is sustainable development resulting from the maximum extension of the life cycle of products. It results from the process of sharing, borrowing, repairing, certain use, reselling, refurbishing, and recycling previously used materials and products. Consequently, the essence of using this type of model of conduct is the possibility of achieving a positive impact on the natural environment. During the next stage of the research process, we presented the level of differentiation of large enterprises operating in the EU in terms of sustainable use of ICT tools using the MOORA method, which enabled the generation of a non-subjective ranking (see Table 4).

The ranking of large enterprises and grouping of objects using the standard deviation method indicated the differentiation of the level of sustainability and resource efficiency in the circulation of ICT devices, affecting their market competitiveness. The range for the analysed data between the maximum value for DE (20.647) and the situation of GR (-0.019) equalled 20.666.

The dominant position in the ranking was occupied by entities from DE (1st place), FR (2nd place), and ES (3rd place), which were characterized by significant values of diagnostic features. Large enterprises located in these countries are characterized by the highest degree of closed circulation in the management of ICT equipment. Therefore, when devices of this type are not used, they undertake activities consisting of their processing in the scope of selective collection or recycling of electronic waste (X11, DE – 92.1%; FR – 85.4%; ES – 92.1%). Moreover, they also reduce the consumption of energy (X5, DE – 84.3%, FR – 80.8%; ES – 91.5%) and paper for printing and copying (X1, DE – 80.3%; FR – 77.9%; ES – 90.5%) by ICT equipment. They also pay attention to the impact of ICT services and equipment on the environment before choosing them (X7, DE – 65.4%; FR – 66.6%; ES – 83.6%) and applying measures to reduce the consumption of paper and energy by this type of equipment (X9, DE – 61.0%; FR – 60%; ES – 81.3%; X16, DE – 44.7%; FR – 67.2%; ES – 52.8%). However, if such devices are not used, they are disposed of through sale, donation, or transfer to a leasing company (X14, DE – 60.2%; FR – 38.2%; ES – 53.9%).

Table 4. Circularity ranking of ICT tools of large enterprises

EU country	Y_i	MOORA Ranking	Typological Class
BE	3.09112	8	II
BG	0.87673	15	III
CZ	3.88717	7	II
DK	1.34806	14	III
DE	20.64743	1	I
EE	0.51175	19	III
IE	0.80918	16	III
GR	-0.01978	27	IV
ES	8.62807	3	I
FR	9.01042	2	I
HR	0.31916	22	III
IT	8.52856	4	I
CY	0.06388	26	III
LV	0.27424	23	III
LT	0.51665	18	III
LU	0.23444	25	III
HU	0.79527	17	III
MT	0.46766	20	III
NL	5.33632	6	II
AT	2.82469	9	III
PL	5.74425	5	II
PT	1.74168	11	III
RO	1.71924	12	III
SI	0.23732	24	III
SK	1.35658	13	III
FI	0.35797	21	III
SE	2.68905	10	III

Source: own study in MATLAB&Simulink.

The last places in the ranking belonged to large enterprises located in GR (27th place), CY (26th place), and LU (25th place). This type of entity was characterized by the lowest level of circular management of their ICT devices in terms of unused computer equipment that was not sold, returned to the leasing entity, or transferred free of charge (X15, GR – 81.9%; CY – 51.4%; LU – 52.2%) but stored in the enterprise (X12, GR – 61%; CY – 63.9%; LU – 59.2%). Furthermore, the surveyed entities did not take any actions to reduce the consumption of energy (X4, GR – 56%; CY – 39.5%; LU – 42.6%) and paper used for printing and copying documents (X2, GR – 52.3%; CY – 18.5%; LU – 20.7%) by such devices. They applied only some measures influencing the paper and energy consumption of ICT equipment to a small extent (X6, GR – 6.8%; CY – 20.5%; LU – 16.1%). Moreover, large entities with a very high digital intensity index did not consider the impact of ICT equipment on the natural environment before deciding to purchase it (X8, GR – 4.4%; CY – 23.9%; LU – 13.4%).

According to the determined measures (Yi) for large enterprises operating in the 27 EU countries, we conducted their linear ordering using the MOORA method, considering the value of the aggregate variable. Consequently, typological classes were indicated, presenting the division of large entities due to their involvement in the process of sustainable and effective management of ICT resources, which contributed to the implementation of environmental goals following the CE concept. Table 5 presents the analysis results.

Based on the conducted research, we may conclude that solutions enabling the retention of the added value of ICT tools for as long as possible and the prevention of waste generation or reduction in the amount of waste generation in large enterprises are being introduced gradually. Therefore, the management of ICT equipment aimed at closing their life cycle, consisting of the use of waste generated in the process of functioning of devices and materials, reducing the consumption of raw materials, reducing waste, and multiplying the stream of waste used in recovery and recycling among the surveyed enterprises, is characterized by different intensity and slow action (see Figure 3).

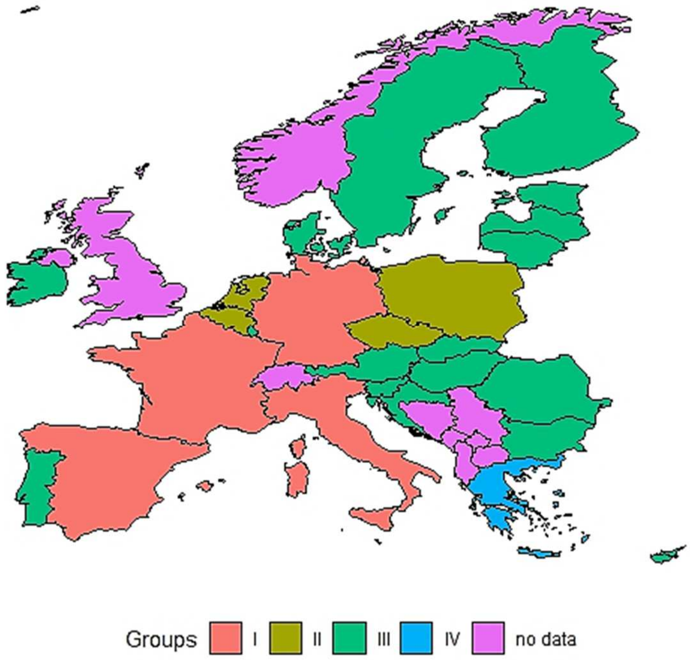


Figure 3. Classification of large enterprises according to the level of circularity of ICT equipment
Source: own elaboration in the RStudio software.

According to the conducted research, large entities located in the 'Old EU' (EU15) in DE, FR, ES, and IT were classified in typological class I and were simultaneously characterized by a very high level of sustainable management of ICT equipment (synthetic measure at the level of ≥7.509). Such enterprises in the above-mentioned countries displayed a very high digital intensity indicator (X17, DE – 18.6%; FR – 7.6%; ES – 18.9%; IT – 19.9%) and a significant indicator of circular use of materials (X18, DE – 13%; FR – 19.3%; ES – 7.1%; IT – 18.7%).

On the other hand, a high level of repair, recycling, and reuse, as well as effective management of waste resulting from the abandonment of ICT equipment use, was recorded by large enterprises operating in Central Europe (PL, CZ) and Western Europe (NL, BE) classified in typological class II. This type of community displayed a high index of the analysed variables, due to the value of the synthetic measure, which was within the range of 7.509-3.037. Large entities grouped in class II were characterized by a high degree of ICT equipment utilization within the collection/recycling of electronic waste (X11, PL – 85.5%; NL – 81.4%; CZ – 95.9%; BE – 90.4%), a significant indicator of circular use of materials (X18, NL – 27.5%; CZ – 11.9%; BE – 22.2%; PL – 8.4%) and a very high digital intensity indicator (X17, PL – 15.7%; NL – 12.7%; CZ – 17.4%; BE – 19%).

The most numerous class III was characterized by an average level of actions taken in connection with maintaining the value of ICT resources for as long as possible and minimizing waste in the process of closing material loops in the surveyed enterprises. Entities operating in 18 EU countries were classified in this grouping. According to the value of the synthetic measure, which was at the level of 3.037-(-1.435), large enterprises displayed an average degree of actions influencing the consumption of paper or energy by ICT equipment (X6). Moreover, used devices of this type are not sold, donated, or returned to the leasing company by the surveyed entities.

The extreme IV typological class includes large enterprises operating in the GR area representing Mediterranean Europe, which has achieved the lowest possible level of ICT resource utilization through the process of sharing, reusing, refurbishing, and recycling. This type of situation is indicated by the negative value of the synthetic measure (-1.435). The entities studied were characterized by one of the lowest values of the digital intensity measure (X17 – 7%) and the circular use of materials indicator (X18 – 3.1%).

According to the research results, we may conclude that large enterprises located in the EU do not particularly undertake activities related to the effective management of ICT devices. Their conduct in the field of the circularity of ICT equipment is characterized by an average pace. This type of circumstance is confirmed by the conducted MOORA ranking, in which large enterprises from 67% of EU countries represent an average level of sustainable management of ICT devices. In addition, unused ICT equipment is stored (X12) in 58.4% of large enterprises or is not subject to sale, donation, or return to the lessor (X15) in the case of 46.9% of entities. On the other hand, following the purpose of the directive used electronic equipment should have been returned, disposed of, and recycled at a level of 65% already in 2019, and in 2030 it should be completely at 100% (Directive 2012/19/EU, 2012). In response to this unrealized intention, the European Commission has committed to presenting an 'initiative on closed-cycle electronic devices' in line with its sustainable products policy (COM/2020/98, 2020).

In the next research stage, the uneven distribution of large enterprises located in the EU that considered their impact on the environment before choosing ICT services and equipment was also determined. The Gini coefficient value was 0.6168. Therefore, we may conclude that there was significant inequality and great diversity among large entities in the selection of ICT devices from the perspective of their impact on the environment. Moreover, the Lorenz concentration curve illustrates the high level of differentiation (see Figure 4).

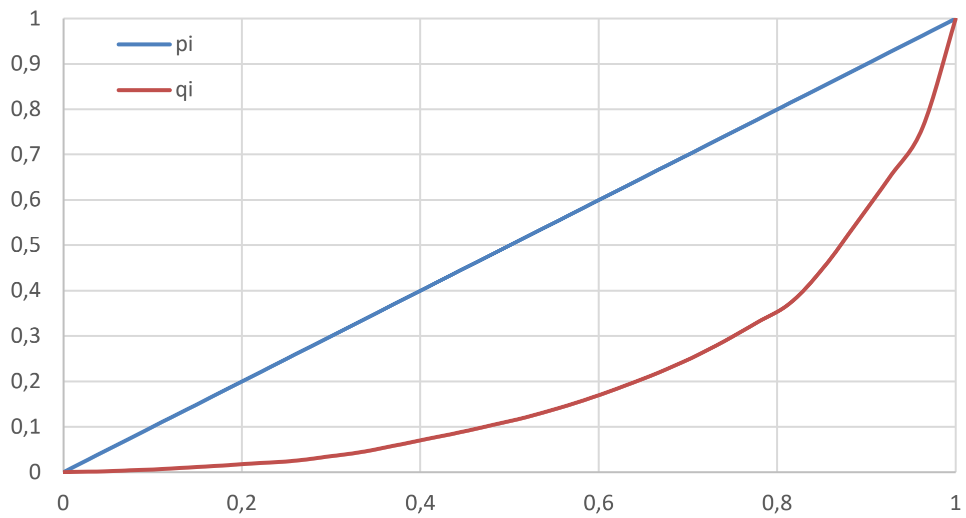


Figure 4. Lorenz curve
Source: own elaboration in the RStudio software.

The Lorenz curve shows the percentage distribution of large enterprises in relation to their cumulative share in the process of fully respecting the impact of ICT devices on the natural environment before their use. Thus, it shows the disproportions between the highest and the lowest level of involvement of entities in the selection of appropriate equipment from the perspective of environmental sustainability in the 27 EU countries. According to the calculated Gini index, we may divide large enterprises located in the EU into three groups according to the level of differentiation of the examined variable.

The first group with a high level of differentiation in the selection of ICT devices due to their environmental impact includes large enterprises operating in DE, FR, IT, and ES. These entities achieved high values on the Lorenz curve and low values of the pi and qi indices, suggesting that they are significantly involved in the selection of pro-environmental ICT tools.

The second group consisted of the surveyed companies with an average level of variable differentiation located in AT, SE, CZ, NL, RO, PL, HU, BE, PT, IE, SK, BG, FI, LT, GR. They occupy a central position on the Lorenz curve and have an average value of the pi and qi indices. Therefore, they are distinguished by a moderate involvement in the appropriate selection of ICT devices from the perspective of reducing their negative impact on the environment compared to the previous group of companies.

The third class included large enterprises with a low level of differentiation in the choice of ICT equipment in terms of its impact on the environment. Entities of this type are located in MT, CY, EE, LU, HR, LV, SI, DK and are located close to the beginning of the Lorenz curve. In addition, they have low values of the pi and qi indices. This type of situation means that large entities in the indicated countries consider the impact of the environment when choosing ICT equipment but to a lesser extent than enterprises from the high and medium differentiation group.

The last stage of the research concerned the analysis of the degree of involvement of large enterprises in activities related to the application of pro-ecological solutions necessary for creating a circular model of selecting ICT equipment in accordance with the implementation of the SD concept. We initiated the diagnosis was initiated by plotting points on the plane for variables characterizing the digital intensity level indicator (DII – X) of large enterprises, which, before selecting ICT equipment, took into account its impact on the environment and took actions related to reducing energy and paper consumption (sICT – Y). Then, we fitted a straight line (trend line) to the obtained data in accordance with the formula Y=aX+b, where (aX) denoted the slope of the line, (b) reflected the slope of the line.

To assess the strength and direction of the relationship between variables X and Y, we used the R2 coefficient (Pearson's linear correlation coefficient squared), which takes values from the range [-1;1]. We compared the obtained results with the classification proposed by J. Guilford, according to which (Chicco & Jurman, 2020):

$|r| = 0$ – no correlation
$0.0 < |r| \leq 0.1$ – correlation is weak
$0.1 < |r| \leq 0.3$ – weak correlation
$0.3 < |r| \leq 0.5$ – average correlation
$0.5 < |r| \leq 0.7$ – high correlation
$0.7 < |r| \leq 0.9$ – very high correlation
$0.9 < |r| < 1.0$ – almost complete correlation
$|r| = 1$ – full correlation
in which: r – correlation coefficient between variables.

The correlation coefficient between the procedure for selecting ICT equipment, considering its savings, efficiency, and environmental impact, and the level of application of digital technologies for the surveyed enterprises with very high analysed indicators was 0.943. According to J. Guilford's division, we should conclude that the variables were closely dependent on each other because the correlation was almost complete. Entities with high intensity for the sICT and DII parameters had a correlation coefficient of 0.420. Thus, there was an average linear relationship between the surveyed variables. The R2 coefficient of enterprises characterized by low intensity was 0.904. Therefore, the level of dependence between random variables was very high. On the other hand, among entities with very low intensity of the surveyed features, the correlation was 0.930. Therefore, we should consider that there was a statistically significant, almost complete relationship. Such connections mean that with the increase in digital intensity, the degree of pro-ecological awareness of entities regarding the selection and application of ICT devices increases. Such activities contribute to the implementation of SDGs and the creation of a circular model for managing ICT equipment.

According to the research conducted, the slope coefficient (a) assumed variable values, which were at the level of 0.697 for a very high variable (x) to 0.315, indicating large enterprises with very low digital intensity. The slope coefficient determined for the analysed variables, which assumes the value of 0.697, characterizes enterprises distinguished by a very high digital intensity index, which, before choosing ICT equipment, considered its impact on the environment, including paper and energy consumption. Thus, if the level of very high digital intensity of large entities is increased by 10%, it will contribute by 69.7% to the intensification of activities aimed at a more favourable selection of ICT devices considering the assumptions of the CE concept.

Enterprises with a high (0.559) and low (0.533) digital intensity index also stood out with a high coefficient due to their adherence to a pro-ecological approach when choosing ICT equipment. If such enterprises strive to increase the DII index by 10%, there will be an intensification of ecological activities related to the choice of ICT equipment and the optimization of energy and paper consumption of 55.9% and 53.3%, respectively.

In turn, for large enterprises with very low digital intensity, the slope of the straight line reached the value of 0.315. Therefore, if the level of digital intensity increases by 10%, the pro-ecological awareness of the surveyed entities in terms of the appropriate choice of ICT equipment will increase by 31.5%.

Based on the conducted research, we determined ranges for individual categories of the digital intensity indicator due to the level of pro-ecological awareness of large enterprises when choosing ICT equipment, taking into account paper and energy consumption. Thus, the analysed X and Y indicators provided information on the level of activities undertaken by entities as part of the implementation of the SD concept and the creation of the CE model. To determine the ranges, we built an interval distribution series, in which we grouped the data according to specific value classes. We used this type of method due to the significant amount of data, for which analysis without taking into account the previous ordering was problematic. In accordance with the procedure for creating an interval distribution series, we assigned partial numbers to variants of features grouped into ranges, which are adequate to the variants classified into class ranges (Chattamvelli & Shanmugam, 2023). Based on the conducted analysis, we established the ranges of pro-environmental involvement in the process of selecting ICT equipment (PESE) for variables x and y with unnoticeable indicators at the level of 0.0 to 0.19, poor from 0.20 to 0.39, average from 0.40 to 0.59, high from 0.60-0.79 and very high from 0.80 to 1 (see Figure 5).

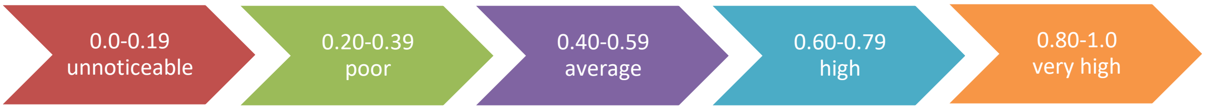


Figure 5. Distribution of pro-environmental commitment in the ICT equipment selection process
Source: own elaboration.

According to the CE assumptions, large enterprises should similarly strive to increase the level of digital intensity and the degree of selection of ICT equipment, considering its impact on the natural environment, so that the slope of the straight line reaches a value close to 1. Then, such entities will be fully engaged in the process of creating circular management of ICT devices and thus applying a closed cycle for this type of equipment.

However, if the coefficient (a) takes a value within the range of 0, it should be concluded that the level of digital intensity will not affect the selection of energy-efficient and environmentally friendly ICT devices. This indicates that large enterprises did not undertake pro-ecological actions related to the selection of ICT equipment in accordance with the SD concept consisting in the transition from a linear to a circular business model.

The conducted research shows that 70% of large enterprises with a very high digital intensity index have considered the impact of ICT equipment on the environment and have reduced the energy and paper consumption of these devices. Thus, such entities have a high PESE index. 56% of the surveyed entities with a high degree of digital intensity, when choosing ICT devices, drew attention to its pro-ecological significance in implementing the principles of the circular economy. Therefore, they have achieved an average level of the PESE index. Noteworthy, over half of large enterprises (53%) with a low digital intensity index have taken action to implement a closed loop in the selection of ICT devices. Despite this, they have achieved an average range of the PESE index, just like the entities from the previous group. In turn, 32% of organizations with a very low digital intensity index consider the impact of ICT equipment on the environment from the perspective of reducing energy and paper consumption. Their PESE index is at a low level.

Based on the EU CE action plans announced so far and recommendations on recycling devices, the pro-environmental involvement indicator in the selection process of ICT equipment should be between

0.75 and 0.85. The conducted research shows that most large enterprises currently have a low/unsatisfactory level of the analysed indicator and thus have not achieved the assumed strategic goals in the field of CE concerning the sustainable and pro-environmental selection of ICT equipment.

The results of the study show significant differences in the advancement level in the circular management of ICT equipment. This case also confirms previous analyses regarding the differences in the implementation of circular economy principles depending on the country of location of large enterprises. In DE, FR, and ES, organizations are distinguished by their significant involvement in taking pro-ecological actions. Such behaviour results from the immediate adaptation and implementation of EU policies supporting sustainable development (Diaz & Baumgartner, 2024; Drofenik *et al.*, 2025). In turn, entities operating in GR and CY, which occupy lower positions in the MOORA ranking, experience difficulties in implementing circular solutions due to the slower pace of development of the circular economy model, which is also confirmed by research by other authors (Govindan, 2023). However, the growing interest in the pro-ecological use of ICT equipment is noticeable in organizations with a higher digitalization level (including DE). For this reason, the key factors in the development of circular economy activities concerning ICT equipment are legal regulations and awareness-raising initiatives (Santarius *et al.*, 2023; Charfeddine & Umlai, 2023). Studies also indicate significant inequalities in the level of advancement of activities related to closed circulation. Therefore, the authors of previous studies propose the unification of legal regulations in the EU (Baran, 2019). Moreover, some of them point to the high costs of transforming enterprises towards a circular economy model (Bocken *et al.*, 2016). They also expose the insufficient resources of enterprises, which prevent the implementation of technological innovations (Geissdoerfer *et al.*, 2017).

The conducted research allowed us to verify the thesis, which indicates that, despite the adoption of uniform EU legal regulations, large enterprises still experience differences in the level of use and circularity of ICT equipment and their adaptation to SD criteria under the principles of selection, repair, recycling, reuse, and management of green ICT resources. This affects the effectiveness of closing material loops in the circular economy model.

CONCLUSIONS

The research presented in this article on large enterprises operating in the 27 EU countries allowed us to determine the level, degree, and pace of circularity in the process of selecting, using, repairing, recycling and reusing ICT devices. Based on this research, we can conclude that large entities partially narrow the material loop, which results from the rational management of ICT equipment. They currently use technological resources in accordance with the 3R principle, in connection with which they only implement the first and last assumption, *i.e.*, reduce and recycle.

To reduce waste resulting from the use of ICT devices, they use certain measures that affect the paper or energy consumption of ICT equipment (X5 and X6) or select equipment before purchase, considering its impact on the natural environment (X7 and X8). Furthermore, companies with a very high digital intensity factor consider both of the above criteria (X10). In terms of implementing the last principle, large companies dispose of unused ICT equipment based on the collection or recycling of electronic waste. Thus far, entities operating in the EU have not included the reuse of ICT devices under the second principle of reuse.

Studies have also shown that large enterprises display a varied degree of circularity and resource efficiency in the adopted model of managing ICT equipment. The highest intensity in the process of closing material loops is distinguished by entities located in the old EU, *i.e.*, in DE, FR, and ES. On the other hand, the lowest scope of minimizing the use of raw materials and waste generation is distinguished by enterprises also located in the old EU (GR, LU) and CY, located in the eastern part of the Mediterranean Sea.

Based on the constructed synthetic measure, we prepared a ranking presenting the level of circularity of ICT equipment in the surveyed enterprises. A very high level of circulation of raw materials and materials is characteristic of entities operating in the old EU (4 countries). An identically high scope is also distinguished by large enterprises from Western Europe (2 countries) and Eastern Europe (2 countries). The average level is represented by entities operating in 18 EU countries. On the other hand, a low level of closing material loops is characteristic of the surveyed enterprises from one country in Southern Europe.

The Gini coefficient, with a value of almost 62%, also confirmed the significant diversification in the implementation of principles influencing the creation of a circular model of ICT equipment management in large enterprises. Thus, the conducted research indicates a non-identical state of involvement and awareness of entities in activities related to the implementation of the new circular economy model. Moreover, the developed indicator of pro-environmental involvement in the process of selecting ICT equipment is low. Therefore, we should recognize that, for large enterprises, activities related to minimizing the consumption of raw materials, waste generation, reduction of greenhouse gas emissions, and reduction of the level of energy use, which are related to closing the process loop, do not constitute their strategic goals. Currently, contrary to the legal regulations in force in the EU, the CE model is not a key direction of action included in the business strategies of the entities studied. Nevertheless, we should consider the use of procedures aimed at rationalizing the consumption of paper and electricity and recycling ICT devices as positive behaviours of selected enterprises.

Based on the conducted research, we recommend intensifying activities for the circular economy in EU countries, especially in the area of closing the material cycle, recycling, and reusing ICT equipment. Countries with a high level of circularity (Germany, France, Spain) should develop technological innovations and transfer knowledge to countries with a lower level of advancement.

In Central and Western European countries (including Poland and Belgium), it is necessary to increase the share of reusing materials and to educate and support the adaptation of national laws and regulations to EU guidelines and standards regarding the circular economy. On the other hand, countries with an average level, representing the majority in the EU, should invest in the waste management system and infrastructure necessary for waste processing and introduce economic support mechanisms for enterprises.

Countries with the lowest level of circularity (Greece, Cyprus) require the modernization of waste management systems and the adaptation of national laws and regulations to EU requirements. It is also necessary to take appropriate actions within the EU structures, such as harmonizing regulations, increasing activity in the implementation of the principles of the circular economy, and exchanging good practices to achieve the objectives of the directives by 2030.

The conducted research has limitations resulting, in particular, from the short time horizon and data availability. Thus far, such research has not been conducted. Eurostat collected data on ICT and the environment for the first time in 2022. Therefore, we recommend continuing the research in the future in a longer time horizon to compare the effectiveness of the CE model implementation from the perspective of the effectiveness of ICT equipment management in all groups of enterprises.

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Use of Artificial Intelligence

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