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CIRCULAR MANUFACTURING AND INDUSTRY 5.0. ASSESSING MATERIAL FLOWS IN THE MANUFACTURING PROCESS IN RELATION TO E-WASTE STREAMS

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ABSTRACT

The article aims (1) to evaluate material flows in the manufacturing process reflecting the level of circular manufacturing of European Union countries and (2) to estimate the relationship between the level of circular manufacturing and the volume of e-waste put on the market, illustrating the implementation effect of Industry 5.0 technologies. A systematic country classification was created according to development conditions for environmentally sustainable enterprises and trends in e-waste volumes. Multidimensional data analysis and the linear ordering method were used to achieve the research objectives. The dynamics of changes in the identified variables were analysed using dynamics indexes and the average annual rate of change. Relationships were estimated using Pearson's linear correlation coefficient. The main research result is the estimated synthetic development measure illustrating the level of circular manufacturing in the context of material flows. Significant differences were observed between the synthetic development measure values representing the level of circular manufacturing in European Union countries. This means countries' circular manufacturing levels are significantly higher than others. Moreover, the values of correlation coefficients were estimated between the level of circular manufacturing and the volume of e-waste put on the market and between the average annual rate of change of the synthetic development measure and the average annual rate of change of the e-waste volume. The coefficient values do not confirm a statistically significant relationship between the indicated variables. Most countries have average conditions for developing environmentally sustainable businesses, but at the same time, they show negative trends in the volume of e-waste generated.

KEY WORDS

circular economy, environmentally sustainable enterprises, Industry 4.0, Industry 5.0, circular manufacturing, sustainability

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INTRODUCTION

Sustainability of the production system and elimination of waste are at the centre of circular manufacturing. Circular manufacturing is a new production approach that helps to create environmentally sustainable enterprises (Le et al., 2023; Gupta et al., 2021). In today's world, circular manufacturing can be regarded as an important aspect of corporate social responsibility. Moreover, this aspect elevates corporate social responsibility to a truly meaningful level beyond a marketing concept.

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Environmental management has been traditionally part of responsible corporate behaviour. The circular manufacturing approach triggers significant change in manufacturing by minimising waste through reducing, reusing/refurbishing, recycling, and recovering (Acerbi et al., 2021a; Acerbi et al., 2021b). This approach helps to reduce the overall environmental impact and revolutionarily transform the production system (Kumar et al., 2019).

Customer expectations are becoming more individualised and complex, driving change in company operations aiming to ensure better availability of products and resulting in increased consumption of company resources, mainly raw materials and energy (Ogiemwonyi et al., 2023). Circular manufacturing is complex and multifaceted; thus, it is difficult to grasp its systemic and dynamic nature (Roci et al., 2022). In a company, the implementation of the R-strategy (refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover) is seen as its dynamic capability (Mora-Contreras et al., 2023). Digital technologies facilitate the implementation of circular manufacturing systems. Previous research in the context of the impact of Industry 5.0 on the creation of circular economic cycles focused on issues related to the following three areas:

- supporting the circular economy by using Big Data to implement industrial symbioses in cities (Song et al., 2017; Song et al., 2015),
- avoiding wastage of products and materials by optimising flows in supply chains and production systems using Big Data Analytics (Ciccullo et al., 2022; Li et al., 2022) and the Internet of Things (Martikkala et al., 2023; Ramya et al., 2023; Seker, 2022),
- minimising wastage of resources and increasing the level of processing using new technologies such as the Internet of Things, artificial intelligence and machine learning (Said et al., 2023; Andeobu et al., 2022).

The research focus on prioritising the green economy and efficient use of scarce resources is consistent with Huang et al.'s (2022) approach to Industry 5.0. However, Masoomi et al. (2023) pointed out that an important research gap is the lack of a comprehensive framework addressing sustainability challenges, particularly resource efficiency, circular manufacturing, and social and environmental impacts in the context of Industry 5.0. Concerning circular manufacturing, Industry 5.0 technologies support companies in creating circular, smart products (Ghobakhloo et al., 2022), enabling smart and sustainable manufacturing (Sami et al., 2023), enabling circular life cycle (Fraga-Lamas et al., 2021), and sustainable resource management (Paschek et al., 2022). The development and application of advanced information technologies of Industry 5.0 is expected to improve business operations' efficiency and productivity while reducing waste and resource consumption (Psarommatis et al., 2023).

Liu et al. (2023) showed that Industry 4.0 technologies enable the implementation of circular manufacturing, but further rigorous verification of empirical results is needed. The publication explores the environmental context of Industry 5.0/4.0, the goals of circular manufacturing, and the Industry 5.0/4.0 technologies supporting enterprises towards circular activities. The purposes of the article are to evaluate material flows in the manufacturing process reflecting the level of circular manufacturing of European Union countries and to estimate the relationship between the level of circular manufacturing and the volume of e-waste put on the market, which illustrate the effect of the implementation of Industry 5.0 technologies. The adopted goals are based on the assumption that, unlike Industry 4.0, Industry 5.0 technologies are more focused on human needs in the context of sustainable development. Thus, they should support activities with the least possible negative environmental impact. One effect of their implementation should, therefore, be the reduced amount of waste generated through sustainable material flows in terms of the created environmental burden. The publication presents an analysis of the effects of circular manufacturing in the context of the e-waste streams in the European Union countries.

1. Literature review

1.1. Circular manufacturing goals

Today's economy forces manufacturers to change their management model due to three trends: vertical integration, digitisation and cost leadership (Krings et al., 2016). Additionally, extended producer responsibility imposes liability for products on companies in the post-consumer phase (Dan et al., 2023). The drive to be competitive forces manufacturing companies to increase the availability of high-value-added products. As a result, they are implementing new business models allowing them to offer high-quality products to meet demand and, at the same time, promote a new perspective on the role of resources in the economy, thus enabling them to achieve the goals of the circular economy (Wu & Pi, 2023).

The goal of the circular economy is to reduce waste and maximise resource use by extending the life cycle of products. Three characteristics of the circular economy can be distinguished (Ren et al., 2023):

- elimination of waste and pollution in the context of sustainability and renewal rather than in the context of efficiency and waste in terms of products and processes,
- restoration of the value of products and materials (instead of discarding them) through repair, reuse and recycling,
- restoration and regeneration of natural systems to ensure they are available for future generations.

The goals of circular manufacturing, such as extending product life cycles, reducing waste and thereby improving sustainability, can also be achieved through infrastructure for sharing information among ecosystem players (Barata et al., 2022). Actions taken on governmental levels of individual European Union member states or regions to implement the circular economy influence the level of goal achievement connected with, among other things, resource scarcity, climate change, the creation of global value chains and the implementation of UN sustainable development policies (Kulczycka, 2018). Therefore, the activities implemented at the level of the national economy set the course of action for companies with respect to circular production. Active sectoral cooperation with economic players is essential for designing effective strategies and policies that will motivate and eliminate barriers to introducing circular economy programmes in enterprises and support the implementation of new technologies and innovative processes in this regard (Skare et al., 2023).

When measuring circular manufacturing, it is important to consider material flows used in the economy and discharged into the environment or reintroduced into economic processing. Circular manufacturing, which is a characteristic of environmentally sustainable enterprises, is reflected in the country's circular economy. Therefore, circular economy assumptions adopted at the state level set the course for enterprises in this area, creating the right conditions for their operation and decision-making in the context of shaping material flows in closed production loops. For this reason, the following research question was formulated:

Q1: How should circular manufacturing be measured considering material flows used in the economy and discharged into the environment or reintroduced into economic processing?

1.2. Environmental context of Industry 5.0

The Industry 4.0 paradigm is essentially technological and harmonious with the business models' optimisation and economic thinking. However, it is not suitable for environmental and social aspects according to an independent expert report of the European Commission (2021b). The Industry 5.0 paradigm places the Industry 4.0 paradigm in a broader context, widening the strategic focus and going beyond value extraction to shareholders. The Industry 5.0 paradigm recognises the power of industry to achieve societal goals beyond jobs and growth to become a resilient provider of prosperity by making production respect the boundaries of our planet and placing the well-being of the industry worker at the centre of the production process. References to the environment in the context of sustainable development can already be found in the concept of Industry 4.0. Ejsmont et al. (2020) identified seven main areas for supporting sustainability with Industry 4.0 technologies, specifically: management of sustainable product life cycle, achievement of sustainability, implementation of smart manufacturing, achievement of circular economy, achievement of compliance with triple bottom line, achievement of sustainable supply chain, development of new business models and organisational structures. In contrast, Tavares-Lehmann and Varum (2021) indicated that "circular economy" mentioned in the keywords of articles linking Industry 4.0 issues to sustainability ranks only fourth (behind "Industry 4.0", "Sustainability", and "Sustainable development" and ahead of "Manufacturing", "Internet of Things" and "Supply Chain Management"). Industry 5.0 complements the existing Industry 4.0 approach by specifically putting research and innovation at the service of the transition to a sustainable, human-centric and resilient European industry according to the definition of the European Commission (2021a). This concept is accompanied by the evolution of circular economy thinking. The circular economy is meant to overcome the difficulties of the current model focused on continuous growth and efficient resource utilisation (Adlin et al., 2023). Over recent years, sustainability has become an important aspect of corporate management philosophy and has become dominant in business strategy, processes and products (Morea et al., 2021; Formentini & Taticchi, 2016; Varriale et al., 2023). The European Commission adopted the new circular economy action plan in 2020 for a cleaner and more competitive Europe (European Commission, 2020).

The adoption of Industry 5.0 impacts people, the planet and profit that can be measured by the triple bottom line concept, which considers economic impact (e.g., efficiency improvement, increase in productivity, cost reduction, etc.), social impact (e.g., the potential to create new leadership jobs and allow the workforce to develop new skills, improve worker safety and well-being by automating dangerous or repetitive tasks) and environmental impact (e.g., reducing waste, improving energy efficiency, promoting sustainable manufacturing practices. For example, 3D printing can reduce waste by producing parts on demand) (Up-Skill Project, 2023). Each of the three Industry 5.0 pillars is generally present in Industry 4.0. However, Industry 5.0 allows for a broader consideration of social and environmental priorities by shifting from a primarily technology-focused to a more systemic approach.

The paradox of Industry 5.0 lies in its definition that this paradigm puts the human at the centre to realise its revolutionary approach to the Fifth Industrial Revolution. With reference to automation projects, proper and thoughtful risk management is found critical for project success. Risk management should cover the relevant change management activities including the management of the human-factor related risks. The Industry 4.0 paradigm focused on the technological drive rather than human aspects (Jafari et al., 2022). This makes the Industry 4.0 concept suitable for cases where full automation is possible. The Industry 5.0 concept goes further as it is capable of managing unique cases effectively and this is where human skills become valued. Human interaction plays an important role when it comes to customisation and this is well covered by the Industry 5.0 paradigm. The manufacturing industry serves to meet customer requirements where innovation and resilient reactions are mostly in demand.

Studies show that companies using digital tools increase the efficiency of reusing products, create relationships with customers, enable data collection and analysis, and provide an assessment of post-use phase product handling options that can potentially extend product life and improve recycling efficiency (Wu & Pi, 2023). The use of Industry 5.0 solutions to create circular manufacturing is all the more desirable as this manufacturing model is considered one of the engineering solutions for fostering sustainability (Ghimouz et al., 2023). For example, machine learning, which in the context of circular manufacturing can be used in controlling production, maintenance, recycling and remanufacturing processes, allows an increase in the profitability of production systems and their resistance to emerging failures (Paraschos et al., 2022). Another solution using new information technologies is additive manufacturing (AM), which supports waste reduction and extends the life of materials (Valera et al., 2023). Research conducted by Tavares et al. (2023) demonstrates 15 potential benefits of AM leading to the circular economy associated with each of the six ReSOLVE principles:

- Regenerate: promoting biodegradable materials use and energy from renewable sources, promoting the recovery, retention and restoration of ecosystem health;
- Share: promoting asset sharing, promoting reuse and second-hand use, promoting life extension through design for durability and upgradeability;
- Optimise: allowing growth in production performance and efficiency, promoting the removal of waste in production and supply chains, leveraging the use of big data and automation;
- Loop: encouraging the remanufacturing of products or components, encouraging the recycling of materials, expanding the scale of waste recovery and resource reuse;
- Virtualise: encouraging indirect dematerialisation;
- Exchange: promoting the replacement of old materials with advanced materials, promoting the application of new technologies, and promoting the choice of new products and services (capacity for innovation).

1.3. TECHNOLOGIES THAT SUPPORT THE CIRCULARITY OF ACTIVITIES BASED ON INDUSTRY 5.0/4.0 TOOLS

While the Industry 4.0 paradigm focused on the inclusion of digital production equipment into the manufacturing process, Industry 5.0 emphasises the human factor to provide decision-making or physical actions at decision nodes in the otherwise automated process flow (Turner et al., 2022). Industry 5.0 emphasises the aspects of environmental awareness and sustainability (Trstenjak et al., 2023). This also suggests the value-driven aspect of Industry 5.0 compared to the technology-driven Industry 4.0, which is meant to be the main difference between Industries 4.0 and 5.0 (Xu et al., 2021; Kemendi et al., 2022). Industry 5.0 is characterised by sustainability, human-centricity and resilience (European Commission, 2021a). This goes beyond the Industry 4.0 approach, which was about improving efficiency and productivity due to emerging technologies.

Digital technologies have an enabling role in operationalising the circular economy (CE) transition. A circular economy embodies the shift from a linear to a circular economy and focuses on decreasing the environmental pressure, e.g., material extraction and waste disposal (Cagno et al., 2021). Unfortunately, despite the supportive role of digitalisation in the development of the circular economy, it negatively impacts the environment through increased energy consumption (Islam et al., 2023; Avom et al., 2020) and an increase in the amount of e-waste generated (Shahabuddin et al., 2023; Vishwakarma et al., 2022). Thus, ICT is not only an important but also a problematic tool in the pursuit of sustainable development (Charfeddine & Umlai, 2023). The approach of circular manufacturing fundamentally reshapes the consumption of resources. Therefore,

Tab. 1. Main characteristics of enabling technologies

Enabling technology	Main characteristics
Cyber-Physical Systems (CPSs) and Cyber-Physical Production systems (CPPS)	Real-time data processing and information feedback, computational capability, decision-making capability; the concept that the virtual world and the physical world can be merged by CPS; Industry 4.0 uses CPS technology to build a CPPS platform to enable equipment in a smart factory to be more intelligent and create better production conditions enabling smart production
Internet of Things (IoT)	Data sharing enhances supply chain transparency; aims to solve communication problems between all objects and systems in a factory; IoT includes radio frequency identification (RFID) devices, infrared sensors, global positioning systems, laser scanners and other information sensing devices which can be connected to internet to an agreed protocol
Big Data Analysis (BDA)	Analytics based on large data set in a short period; facilitate and support the decision-making process (data-driven insights), e.g., in manufacturing, microprocessors may be installed on machines to collect production data, and sensors and microprocessors generate a huge source of data with a size beyond the traditional scale
Cybersecurity and Blockchain (CYB)	Ability to assure transparency and the protection of the cyber environment, e.g., secure and reliable communications, identity and access management of machines and users; can support circular purchasing and design, etc.
Additive Manufacturing (AM), esp. 3D printing	Enables direct production of 3D models, used for small batches with a high degree of customisation, shorter time-to-market and high production flexibility; ability to build parts with geometrical and material complexity not feasible with traditional manufacturing helps to reduce waste (e.g., by producing parts on demand) and favour the use of recovered materials instead of virgin raw materials
Artificial Intelligence (AI)	Cognitive science and research areas such as robotics, machine learning, natural language processing, image processing, artificial vision, etc., can support circular design, procurement, resource efficiency, waste management, and reverse logistics
Simulation (SIM)	Decision-making support; the only practical way to test models; reproduction of a system in an experimental model; potential for tracing and predicting the material flow along the supply chain, crucial for disassembly activities
Robotics (RB)	Help with the automation of the production process; robots are developing (more autonomous, flexible and cooperative; embedded intelligence can allow them to learn from human activities; collaborative robots (cobots) and human–robot interaction make work with humans possible)
Virtual Reality (VR) and Augmented Reality (AR)	Support the virtualisation strategy; VR provides a simulation tool for the recreation of a real-life environment; AR has progressed in applications to combine digital elements with real-world actions. VAR allows for simulating real situations, e.g., to train workers, avoid dangerous situations, and improve decision-making
Horizontal and vertical system integration	The realisation of truly automated and integrated value chains; can facilitate access to data, in particular allow collaboration among different stakeholders, offers opportunities for recycling activities and the redesign of products and processes
Cloud computing (CLOUD) technology	Allows the storage and sharing of data between stakeholders along the supply chain, the potential to promote collaboration; allows access from different devices; the model provides services to the user including software, hardware, platforms and other IT infrastructure resources

Source: (Neri et al., 2023; Sun & Wang, 2022; Laskurain-Iturbe et al., 2021; Yang & Gu, 2021; Rüssmann et al., 2015; García & García, 2019; Zhong et al., 2017; Zhou et al., 2015).

the implementation of circular manufacturing requires an integrated approach to manage the resources to realise the reduce, reuse, recycle, and recover principles. All this can be enforced through sound technological background. Following Laskurain-Iturbe et al. (2021), it was assumed that the outline of Industry 4.0 technologies looks as follows: Additive Manufacturing (AM), Artificial Intelligence (AI), Artificial Vision (AV), Big Data and Advanced Analyses (BDAA), Cybersecurity (CS), Internet of Things (IoT), Robotics (RB) and Virtual and Augmented Reality (VAR).

When it was first launched in 2011, there were nine pillars of Industry 4.0, i.e., cyber-physical systems (CPSs, the core of Industry 4.0), Internet of Things (IoT), Big data, 3D printing (otherwise known as additive manufacturing), robotics, simulation, augmented reality, cloud computing and cyber security (Yang & Gu, 2021). These pillars are capable of fully transforming the production flow. For example, Industry 4.0, industrial IoT, cloud computing, Big Data analytics and customer profiling, and cyber security can be considered as the most relevant enabling technologies for Supply Chain Management-Marketing (SCM-M) integration (Ardito et al., 2019). The circular economy practices can be enabled by adopting Industry 4.0 technologies. This issue is more challenging for small and medium-sized enterprises than for larger firms due to more limited resources and different characteristics (Neri et al., 2023). Table 1 shows the main characteristics of enabling technologies.

The Industry 4.0 era can be described as the era of intelligent manufacturing systems where manufacturing technologies are transformed by cyber-physical systems, the IoT and cloud computing (Zhong et al., 2017). Jafari et al. (2022) highlighted two major concepts: IoT and CPS. Cyber-physical systems are described as "a new generation of systems with integrated computational and physical capabilities that can interact with humans through many new modalities" (Baheti & Gill, 2011). Industry 4.0 technologies support companies in better circularity. In particular, most evidence shows the positive impact of additive manufacturing and robotics (Laskurain-Iturbe et al., 2021). The most important Industry 4.0 enablers for a cleaner production and circular economy within the context of business ethics are "Technical Capability", "Security and Safety", "Policy and Regulation", "System Flexibility", "Education and Participation", and "Support and Maintenance" (Shayganmehr et al., 2021).

Industry 5.0 puts the human-centric approach at the centre of the production process (Atif, 2023). An independent expert report about the results of a workshop with Europe's technology leaders pointed out that the enabling technologies for Industry 5.0 are a set of complex systems that combine technologies and can only unfold with others as part of systems and technological frameworks. The corresponding categories are:

- Individualised human-machine-interaction: technologies that interconnect and combine the strengths of humans and machines (technologies that support humans in physical and cognitive tasks, e.g., augmented, virtual or mixed reality technologies, collaborative robots ("cobots"), technologies for matching the strengths of Artificial Intelligence and the human brain; etc.).
- Bio-inspired technologies and smart materials allow materials with embedded sensors and enhanced features while being recyclable.
- Digital twins and simulation, real-time-based digital twins and simulation: to model entire systems (optimise production, test products and processes and detect possible harmful effects, e.g., Digital twins of products and processes, virtual simulation and testing of products and processes).
- Data transmission, storage, and analysis technologies (e.g., cyber security/safe cloud IT infrastructure, big data management) that are able to handle data and system interoperability.
- Artificial intelligence, e.g., to detect causalities in complex, dynamic systems, leading to actionable intelligence.
- Technologies for energy efficiency, renewables, storage and trustworthy autonomy, e.g., in support of the energy usage of the above-named technologies (European Commission, Müller, 2020).

The list of key enablers of Industry 5.0 can be grouped as follows according to Trstenjak et al. (2023) with similar content to that of the above list:

- Human-centred approach (human knowledge and skills as one of the most treasurable resources and competitive advantages).
- Flexibility and modularity (digital twins, self-optimisation, and collaborative robots).
- Human factors, ergonomics, well-being and ethical technology (worker motivation, improve workers' health and minimise the impact of stress-related diseases which lead to absence from work).

- Innovation management (market competitiveness, flexibility and adjustment to the demands and needs of the market, reducing production costs, increasing product quality and shortening time-to-market).
- Green and sustainable manufacturing (use of sustainable energy sources and increase of energy efficiency; circular economy concept).

Environmentally sustainable enterprises use advanced technologies and transform their production flow, avoiding environmental degradation (Ahmad & Satrovic, 2023; Arshad et al., 2023; Charfeddine & Umlai, 2023). The technologies must be accepted and trusted, and people must be trained to use them. Sustainable enterprises represent a true contribution to corporate social responsibility. All this suggests trustworthiness and represents a layer of ethical business practices which can attract customers.

The use of Industry 5.0 technologies translates into increased circular manufacturing. Unfortunately, in the area of waste management, the risks associated with the implementation of Industry 5.0 involve an increase in the volume of generated e-waste (De Giovanni, 2023). Accordingly, the research question is as follows:

Q2: Is there a correlation between the level of circular manufacturing and the amount of generated e-waste?

2. RESEARCH METHODS

Data from the Eurostat database (2023) were analysed. The set of variables is presented in Table 2.

To examine the level of circularity manufacturing, a synthetic measure of development was estimated, which included backfilling operations in addition to recycling operations. It was assumed that the various countries of the European Union are open economies in which waste is imported and exported, i.e., it is collected in one country and then processed and recovered in another. The data used to estimate the synthetic measure represent the flows of materials used in the economy and discharged into the environment or reintroduced into economic processing. The data concerns three categories related to flows in the economy: inputs into the economy, processed materials, and outputs from the economy.

Data in the category of inputs into the economy include the flow of products from the rest of the world's economy into the domestic economy. This flow also includes waste sent for processing (e.g., conversion into recyclable materials) in the receiving country. This category also includes quantities of material resources extracted from the environment by production units in the country, especially materials such as biomass metal ores, non-metallic minerals and fossil energy materials/carriers. Imports, together

Tab. 2. Set of variables

CATEGORY	VARIABLE SYMBOL	VARIABLE NAME	VARIABLE CHARACTER (S – STIMULANT, D – DESTIMULANT)
Inputs into the economy	IMP_T	Imports of waste for recovery — recycling	S
	EIMP_T	Imports excluding imports of waste for recovery — recycling	S
	DE_T	Domestic extraction	D
Processed materials	MAC	Material accumulation	D
	WTR_T	Waste treatment recovery — recycling	S
	WTB_T	Waste treatment recovery — backfilling	S
Outputs from the economy	EXP_T	Exports of waste for recovery — recycling	S
	EEXP_T	Exports excluding exports of waste for recovery — recycling	S
	EMI	Emissions	D
	DFL	Dissipative flows	D
	WTD_T	Waste treatment disposal — landfill	D
Waste electrical and electronic equipment	EEPM	Waste arising only from separate collection of EEE — products put on the market	D
	WEER	Waste arising only from separate collection of EEE — recovery	S
	WEERT	Waste arising only from separate collection of EEE — recovery/ waste arising only from separate collection of EEE — products put on the market	S

with domestic extraction, are direct material inputs to the economy.

Processed materials were defined as the sum of accumulated material that is collected before it is used and secondary materials, i.e., recycled and backfilled materials. The processed materials can be exported or used in the country. According to Eurostat's methodology, it was assumed that only the flows of recycling and pit filling close the loop of the circular economy (circular economy — material flows, 2022).

The economy's results included the weight of exported products, total emissions reflecting solid, liquid and gaseous material flows, dissipative flows, i.e., materials dispersed into the environment as an intentional or unavoidable consequence of product use, and the amount of waste landfilled.

A linear ordering method used in the area of multidimensional data analysis was applied to assess the level of circular manufacturing. This is because it was assumed that this potential can be expressed by a synthetic variable, which consists of the effects of each country's actions in the use of material streams in the production process. Twenty-seven countries of the European Union were covered in the study. They were assumed to be regions characterised by the peculiarities of the production process organisation, as well as by different social and cultural conditions shaping the pro-ecological awareness of the organisation of these processes. It was also assumed that the effects achieved in a given country in the scope analysed are a direct result of the companies' activities. This is because the synthetic variable considers variables that determine the level of effects achieved through the implementation of sustainability-oriented measures in companies, as defined by all kinds of interstate and national policies. European Union countries (characterised by a number of variables determining the level of circular manufacturing) were therefore ordered in terms of preference (dominance) relationships. The synthetic variable was determined for the years 2013–2021. The determined synthetic variable was used to create a ranking of European Union countries according to the level of circular manufacturing for each year. It was performed in the following steps:

1. A matrix of diagnostic features observed for each country of the European Union was constructed x_{ij}, i=1, 2, …, 27; j=1, 2, …, 11 (n — the number of countries, m — the number of variables). To make the data more comparable, they were presented as intensity indicators (tons per capita).

2. The variables were unitarised to free their titers and standardise the orders of the values they took, according to the formula:

$$z_{ij} = \frac{x_{ij} - \bar{x}_j}{s_j},$$

$$(i=1, 2, \ldots, 27; j=1, 2, \ldots, 11) \qquad (1)$$

where:

z_{ij} — the standardised value of variable X_j,

$\bar{x}_j$ — arithmetic average of variable X_j,

s_j — standard deviation of variable X_j.

3. Euclidean distances of individual objects from the model object were determined:

$$d_{i0} = \sqrt{\sum_{j=1}^{m}(z_{ij} - z_{0j})^2} \qquad (i = 1, \ldots, 27), \quad (2)$$

where

$z_{0j} = \max_i z_{ij}$, for stimulant variables and

$z_{0j} = \min_i z_{ij}$, for destimulant variables.

To measure the distance, it was assumed that all variables affected the level of the analysed phenomenon with equal force.

4. A measure of development was estimated for each object according to the formula:

$$m_i = 1 - \frac{d_{i0}}{d_0} \qquad (i = 1, \ldots, 27). \qquad (3)$$

Where:

d_0 — the distance between the pattern and anti-pattern of development:

$$d_0 = \sqrt{\sum_{j=1}^{m}(z_{ij} - z_{\_0j})^2} \qquad (i = 1, \ldots, 27), \quad (4)$$

where $z_{\_0j} = \min_i z_{ij}$, for stimulant variables and

$z_{\_0j} = \max_i z_{ij}$, for destimulant variables.

The level of use of Industry 5.0 technologies was expressed in the variable "Waste electrical and electronic equipment", and in particular in the variable "Waste arising only from separate collection of electrical and electronic equipment (EEE) — Products put on the market". This is because it was assumed that Industry 5.0 technologies in the context of the circular economy and material flows are expected to reduce waste rather than increase effectiveness (Dwivedi et al., 2023; Voulgaridis et al., 2022). Because apart from waste generated in the current production and consumption, previously stored waste is used in the production process, the analysis also covered the variable expressing the relationship of "Waste arising only from separate collection of EEE — recovery/waste arising only from separate collection of EEE — products put on the market". This relationship expresses the balance between the amount of waste that can be reintroduced into the production system or, more broadly, into the economic system and the amount of waste that remains in the environment (does not return to the production process).

The values of variables were determined for each year of the 2013–2021 period, and the dynamics of changes in their formation were examined. For this purpose, the estimations focused on the index of dynamics for 2021 in relation to 2013 and the average annual rate of change. The analysis of the dynamics made it possible to identify trends in the level of circular manufacturing and the level of e-waste during the period under study.

Also, correlations were examined between the level of circular manufacturing and the amount of e-waste and between the dynamics of change for the variables. The correlation analysis made it possible to check whether increasing the effectiveness of circular manufacturing efforts translates into reduced generation of e-waste, which would be a positive effect of using information technology.

Ranges were built based on the dynamics measures for the measure of development and the amount of e-waste introduced into the market class. They were used to create a systematic division of the country according to conditions for developing environmentally sustainable enterprises and the constancy of this development (the dynamics of change of the synthetic measure). The dynamics of the amount of e-waste recovered provided the basis for dividing countries according to the criterion of the positive use of information technology in creating circular manufacturing cycles. It was recognised that:

- The value of the first quartile indicates economies with poor conditions for the development of environmentally sustainable enterprises, the value of the second quartile — average conditions, and the value of the third quartile — good conditions.
- A measure of dynamics in the range from 95 % to 105 % was considered indicative of a constant situation in the level of circular manufacturing (thereby, constant situation in the development of environmentally sustainable enterprises) and the amount of e-waste, whereas a measure lower than 95 % indicated regression in the level of circular manufacturing and a positive effect in terms of the amount of e-waste, and a value higher than 105 % indicated progress in the level of circular manufacturing and a negative effect in terms of the amount of e-waste.

3. Research results

Table 3 presents the value of the synthetic development measure for the European Union countries in 2013–2021. The highest level of circular manufacturing in all analysed years was observed for Luxembourg. The next three positions were taken by the Netherlands, Belgium and Slovenia. The measure of development for Luxembourg far exceeded the others, indicating that the country can be considered a model.

Table 4 presents waste arising only from a separate collection of EEE — products put on the market for individual European Union countries in the years 2013–2021.

The amount of waste arising only from separate EEE collection reintroduced into economic processing increases per capita with the industrial and economic development of the country.

Similar patterns are observed for the amount of waste arising only from separate collection of EEE recovered — the amount increases with the industrial and economic development of a country (Table 5).

Table 6 shows the dynamics of measures for the selected variables. An increase in the development measure in 2021 compared to 2013 was observed only for two countries of the European Union (Bulgaria and Slovenia), which means that only these countries had an average annual increase in the level of circular manufacturing in 2013–2021. Positive trends are observed for the amount of e-waste recovered; only Portugal and Sweden saw an average annual decrease in e-waste recovery, but it was insig-

Tab. 3. Results of linear classification — a measure of the development of the European Union countries according to the level of circularity manufacturing in 2013–2021

Countries	**Measure of development in the year**								
	2013	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Luxembourg	0.692	0.648	0.612	0.626	0.625	0.638	0.622	0.610	0.605
Netherlands	0.522	0.516	0.480	0.478	0.483	0.482	0.490	0.478	0.498
Belgium	0.483	0.474	0.442	0.435	0.434	0.437	0.451	0.468	0.469
Slovenia	0.443	0.433	0.408	0.396	0.417	0.435	0.437	0.435	0.446
Austria	0.401	0.386	0.366	0.347	0.349	0.351	0.363	0.372	0.378
Malta	0.369	0.350	0.332	0.323	0.343	0.354	0.354	0.354	0.359
Czechia	0.358	0.339	0.314	0.309	0.318	0.331	0.339	0.344	0.354
Latvia	0.364	0.333	0.309	0.308	0.302	0.309	0.314	0.327	0.339
Slovakia	0.353	0.328	0.303	0.300	0.302	0.306	0.322	0.330	0.339
Germany	0.368	0.357	0.334	0.325	0.319	0.322	0.329	0.315	0.329
Lithuania	0.352	0.334	0.314	0.310	0.305	0.309	0.313	0.318	0.323
Sweden	0.365	0.349	0.328	0.326	0.310	0.304	0.305	0.312	0.316
Denmark	0.344	0.319	0.285	0.278	0.284	0.294	0.296	0.299	0.314
France	0.364	0.349	0.324	0.314	0.305	0.308	0.311	0.310	0.313
Croatia	0.314	0.299	0.274	0.271	0.270	0.273	0.282	0.297	0.306
Italy	0.332	0.316	0.292	0.286	0.283	0.286	0.291	0.296	0.299
Hungary	0.325	0.296	0.272	0.271	0.272	0.268	0.277	0.296	0.296
Poland	0.329	0.319	0.293	0.276	0.265	0.264	0.285	0.276	0.295
Spain	0.333	0.319	0.291	0.280	0.283	0.287	0.287	0.284	0.293
Estonia	0.331	0.287	0.256	0.258	0.247	0.250	0.270	0.299	0.291
Greece	0.301	0.283	0.254	0.251	0.253	0.265	0.269	0.275	0.285
Cyprus	0.316	0.297	0.280	0.272	0.255	0.259	0.248	0.259	0.266
Portugal	0.308	0.276	0.254	0.255	0.246	0.248	0.253	0.264	0.264
Bulgaria	0.240	0.216	0.202	0.227	0.219	0.217	0.228	0.232	0.253
Ireland	0.233	0.219	0.202	0.192	0.187	0.193	0.188	0.197	0.204
Finland	0.233	0.239	0.216	0.193	0.206	0.203	0.218	0.205	0.196
Romania	0.275	0.247	0.202	0.198	0.204	0.201	0.175	0.169	0.184

nificant, i.e., 0.84 % for Portugal and 3.09 % for Sweden. The volume of e-waste put on the market in the case of these two countries was unfortunately higher in 2021 compared to 2013. Generally, an average annual increase in the amount of e-waste recovered is observed for all European Union countries, with the exception of Luxemburg and Malta. However, in countries such as Denmark, Germany, Italy, Lithuania, Hungary, Netherlands and Romania, the volume of waste put on the market is growing faster than the amount of waste recovered.

Pearson's linear correlation coefficients were estimated to determine the relationship between the synthetic measure of development and the amount of e-waste put on the market (Table 7) and the dynamics of change for these two measures.

The values of the correlation coefficients do not confirm the existence of a relationship between the

Tab. 4. Waste arising only from a separate collection of EEE — products put on the market of the European Union countries in 2013–2021

Countries	**Waste arising only from separate collection of EEE — products put on the market (kilograms per capita)**								
	2013	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Bulgaria	7.8	9.08	9.47	10.14	10.58	11.65	12.78	12.57	13.46
Latvia	8.86	9.2	9.68	9.56	11.85	12.59	14.42	14.89	16.04
Lithuania	9.31	10.75	10.69	11.19	11.87	12.7	14.13	15.03	16.09
Cyprus	11.15	10.29	11.52	7.21	13.37	13.8	13.92	15.49	16.23
Greece	11.37	12.8	11.56	12.1	12.5	13.59	15.54	16.06	16.87
Slovakia	8.51	9.84	9.72	12.12	12.55	13.56	14.84	15.72	17.16
Croatia	9.38	9.25	10.62	12.01	13.17	14.99	15.14	16.43	17.8
Malta	34.2	39.44	29.7	22.48	23.91	21.4	23.14	21.06	19.65
Romania	6.85	7.01	8.49	10.19	12.15	13.41	15.34	17.54	20.07
Luxembourg	21.68	21.68	20.66	20.34	21.38	20.99	20.59	20.55	20.39
Portugal	11.66	11.72	12.59	13.33	15.34	17.6	19.82	20.62	22.37
Slovenia	13.83	14.75	15.22	17.09	16.18	17.44	20.07	21.07	22.38
Spain	10.9	11.99	12.99	13.48	14.32	15.44	18.43	21.21	23.33
Czechia	17.3	17.04	17.26	17.74	19.21	18.52	22.14	24.6	25.87
Ireland	18.39	19.21	18.37	20.29	22.56	20.83	22.71	24.94	26.05
Estonia	10.6	11.52	11.79	12.09	12.56	14.46	17.22	23.52	26.36
Italy	14.06	14.54	15.02	16.69	16.96	24.54	23.81	26.26	28.71
Hungary	8.08	9.43	10.57	11.78	13.65	23.53	24.45	24.91	29.26
Finland	25.3	23.1	21.54	22.31	22.57	24.08	22.92	28.79	29.33
Sweden	25.28	24.54	26.22	26.1	27.71	28.31	30.58	28.93	29.49
Belgium	24.19	23.23	23.86	24.52	25.69	27.23	29.68	29.01	29.77
Poland	12.78	13.65	13.87	15.36	15.99	17.39	20.86	27.29	30.41
Austria	18.38	19.34	21.6	23.8	24.02	26.41	27.14	30.36	32.62
France	23.64	23.44	25.19	26.2	28.1	28.72	31.08	32.26	33.73
Germany	19.95	21.16	23.23	23.78	25.18	28.65	31.17	34.25	37.00
Denmark	24.66	27.	27.24	27.69	29.85	30.35	35.61	39.25	41.94
Netherlands	18.21	18.97	20.23	21.82	24.37	28.56	36.82	43.29	48.99

level of circular manufacturing and the amount of e-waste put on the market. None of the correlation coefficients proved statistically significant (at the significance level of p<0.1). Also, the correlation coefficient between the average annual rate of change in the synthetic development measure and the average annual rate of change in the amount of e-waste of -0.23812 proved statistically insignificant (at the significance level of p<0.1).

It was assumed that for economies for which the average annual rate of change for the measure of development was in the range (-5 %; 5 %), invariant conditions for the development of environmentally sustainable enterprises were observed. For all countries, the average annual rate of change was within the range, which means that all countries were characterised by a fairly constant level of circular manufacturing and, thereby, a constant level of development of

Tab. 5. Waste arising only from separate collection of EEE —Recovery of the European Union countries in 2013–2021

Countries	**Waste arising only from separate collection of EEE — recovery (kilograms per capita)**								
	2013	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Portugal	4.53	4.99	5.59	6.15	6.18	6.51	4.37	4.27	4.23
Romania	1.5	1.47	1.52	2.03	2.29	2.87	3.27	3.72	4.24
Malta	4.01	4.38	2.9	5.55	4.55	4.82	5.09	4.27	4.31
Lithuania	4.16	6.18	4.87	3.98	4.15	4.46	5.12	5.16	5.32
Greece	3.29	3.5	4.06	4.6	4.37	4.7	5.33	5.07	5.39
Latvia	2.17	2.23	2.03	2.19	3.89	4.25	5.01	5.13	5.8
Cyprus	2.13	2.4	3.18	2.78	4.28	3.45	3.97	5.2	5.91
Italy	6.47	4.41	5.01	5.3	5.8	6.13	6.6	7.23	7.35
Slovenia	2.23	4.38	4.52	5.68	6.11	6.17	6.49	6.41	7.45
Hungary	4.46	4.67	4.71	5.14	5.54	6.01	7.26	7.88	8.55
Spain	2.79	3.21	4.07	5.02	5.44	6.4	6.65	7.45	8.57
Slovakia	3.68	3.87	3.96	4.76	4.99	5.24	6.53	7.93	8.85
Luxembourg	8.91	9.27	9.62	9.96	9.7	9.5	9.32	9.66	9.77
Estonia	2.5	4.2	5.21	6.29	6.65	7.23	7.68	8.68	10.37
Bulgaria	4.08	5.06	7.56	7.21	6.79	6.47	8.21	9.36	10.54
Croatia	3.53	3.59	5.23	8.98	8.43	9.26	9.15	9.6	11.07
Czechia	4.72	4.8	5.94	9.27	8.97	7.61	9.09	9.97	11.09
Poland	3.44	3.38	3.69	5.06	5.39	5.94	9.67	9.71	11.26
Belgium	9.25	8.87	9.15	9.36	9.35	10.	10.41	11.41	11.76
Netherlands	6.68	8.12	8.21	8.7	9.31	9.64	9.31	11.24	12.11
France	6.31	7.06	8.31	9.76	9.95	10.05	10.83	11.23	12.19
Ireland	8.	8.31	9.69	10.42	9.88	11.45	11.73	11.92	12.62
Germany	8.52	8.52	7.98	9.19	9.82	10.01	11.09	12.25	12.9
Sweden	16.89	13.78	13.46	15.09	12.91	13.04	14.83	13.56	13.14
Denmark	11.49	11.48	11.74	11.75	11.24	11.1	11.77	12.93	13.15
Finland	10.36	10.94	10.89	10.29	11.17	11.44	12.71	15.19	16.04
Austria	8.13	8.4	8.57	8.9	12.36	12.22	14.07	14.81	16.13

environmentally sustainable enterprises. Fig. 1 shows a systematic breakdown of the country according to the conditions for the development of environmentally sustainable enterprises and the e-waste effect. The figure also indicates the effects of changes in the level of e-waste put on the market based on the average annual rate of change.

Most countries have average conditions for the development of environmentally sustainable businesses, but at the same time, they show negative trends in the volume of e-waste generated. Given that an increase in e-waste means an increase in the level of digitisation, including digitisation of enterprises, a high level of circular manufacturing and, therefore, good conditions for the development of environmentally friendly enterprises can be expected. Unfortunately, assuming that all countries show a stable level of circular manufacturing (slight changes in the synthetic measure of development in 2013–2021), it can be argued that the development of IT infrastructure

Tab. 6. Change dynamics for the selected variables in the years 2013–2021

Countries	Dynamics index for 2021 (2013 = 100%)				Average annual rate of change			
	Measure of development	EEEPM	WEER	WEERT	Measure of development	EEEPM	WEER	WEERT
Belgium	97%	123%	127%	103%	-0.39%	3.04%	2.63%	0.40%
Bulgaria	106%	173%	258%	150%	0.71%	12.59%	7.05%	5.17%
Czechia	99%	150%	235%	157%	-0.13%	11.27%	5.16%	5.82%
Denmark	91%	170%	114%	67%	-1.15%	1.70%	6.86%	-4.83%
Germany	89%	185%	151%	82%	-1.40%	5.32%	8.03%	-2.50%
Estonia	88%	249%	415%	167%	-1.59%	19.46%	12.06%	6.61%
Ireland	88%	142%	158%	111%	-1.64%	5.86%	4.45%	1.35%
Greece	95%	148%	164%	110%	-0.66%	6.37%	5.06%	1.25%
Spain	88%	214%	307%	144%	-1.59%	15.06%	9.97%	4.63%
France	86%	143%	193%	135%	-1.87%	8.58%	4.54%	3.87%
Croatia	97%	190%	314%	165%	-0.33%	15.36%	8.34%	6.49%
Italy	90%	204%	114%	56%	-1.33%	1.60%	9.33%	-7.08%
Cyprus	84%	146%	277%	190%	-2.14%	13.60%	4.81%	8.39%
Latvia	93%	181%	267%	148%	-0.87%	13.08%	7.70%	5.00%
Lithuania	92%	173%	128%	74%	-1.06%	3.13%	7.08%	-3.69%
Luxembourg	87%	94%	110%	117%	-1.67%	1.16%	-0.76%	1.94%
Hungary	91%	362%	192%	53%	-1.17%	8.47%	17.45%	-7.64%
Malta	97%	57%	107%	187%	-0.32%	0.90%	-6.69%	8.14%
Netherlands	95%	269%	181%	67%	-0.59%	7.72%	13.17%	-4.82%
Austria	94%	177%	198%	112%	-0.76%	8.95%	7.43%	1.41%
Poland	90%	238%	327%	138%	-1.35%	15.98%	11.45%	4.07%
Portugal	86%	192%	93%	49%	-1.91%	-0.84%	8.49%	-8.60%
Romania	67%	293%	282%	96%	-4.89%	13.86%	14.38%	-0.46%
Slovenia	101%	162%	334%	207%	0.07%	16.28%	6.20%	9.49%
Slovakia	96%	202%	240%	119%	-0.52%	11.59%	9.16%	2.23%
Finland	84%	116%	155%	134%	-2.17%	5.62%	1.86%	3.69%
Sweden	87%	117%	78%	67%	-1.78%	-3.09%	1.95%	-4.94%

Tab. 7. Correlation coefficients

Years	Correlation coefficient between the synthetic measure of development and the amount of e-waste put on the market
2013	-0.03254
2014	0.01772
2015	-0.12553
2016	-0.07153
2017	-0.05261
2018	-0.07122
2019	-0.11140
2020	-0.05592
2021	-0.05712

		THE CONDITIONS FOR THE DEVELOPMENT OF ENVIRONMENTALLY SUSTAINABLE ENTERPRISES		
		BAD	AVERAGE	GOOD
E-WASTE EFFECT	NEGATIVE	Bulgaria, Greece, Portugal, Romania	Denmark, Germany, Estonia, Spain, Croatia, Italy, Latvia, Lithuania, Hungary, Poland, Slovakia	Czechia, Netherlands, Austria, Slovenia
	AVERAGE	Ireland, Cyprus, Finland	France, Sweden	Belgium, Luxembourg
	POSITIVE			Malta

Fig. 1. Systematic breakdown of the country according to the conditions for the development of environmentally sustainable enterprises and the e-waste effect

does not translate into an increase in the level of circular manufacturing. Positive trends are observed for Malta, Belgium and Luxembourg, which create good conditions for the development of environmentally sustainable businesses and, at the same time, introduce a smaller or fairly constant amount of e-waste to the market. A large increase in e-waste can be observed in Bulgaria, Greece, Portugal and Romania, but unfortunately, the increase is not matched by a high level of circular manufacturing.

4. Discussion of the results

Research indicates that digitalising all types of activities promotes circular e-waste management, including prevention, collection, and treatment (Bagwan, 2024). Unfortunately, the amount of e-waste continues to grow, becoming an environmental problem. Therefore, it can be concluded that, on the one hand, information and communication technologies foster closed production cycles, and on the other hand, they are a source of pollution, including e-waste. A lot of research is devoted to the issue of linking the Industrial Revolution (in particular Industry 4.0) to sustainable development, including the reduction of the negative impact of economic activities on the environment. These studies mainly focus on the problem of whether and how Industry 4.0 technologies support sustainable development (Calabrese et al., 2023; Piccarozzi et al., 2023). In this article, research is also devoted to the relationship between information technologies and environmental sustainability, except that it analyses variables that can underpin the measurement of circular manufacturing and the magnitude of e-waste streams as an effect of Industry 5.0 implementation.

The article analyses the European Union economies according to the level of circular manufacturing and its dynamics. Measuring the effects of circular manufacturing can be a problem. Although the waste reduction effect of circular manufacturing is measurable, it is difficult to consider it as a measure of circular manufacturing or, more broadly, the circular economy. The level of circular manufacturing is expressed in terms of a synthetic measure consisting of variables representing the flows of materials used in the economy and discharged into the environment or reintroduced into economic processing. This way of measuring circular manufacturing level differs from the ways proposed in the literature. The basic measure of the circularity of the economy in the European Union is the circular material use rate (CMUR). It is defined as the ratio of the amount of waste recycled at domestic recovery facilities minus the amount of imported waste for recovery plus the amount of exported waste intended for recovery abroad to the amount of materials consumed. Considering CMUR, the only waste treatment operations contributing to the circular economy are those producing recyclable materials. These operations include recycling only and do not include backfilling. Furthermore, CMUR does not involve waste imported to be recovered domestically.

The European Commission identifies ten key indicators of a circular economy relating to different stages of product lifecycle and aspects of competitiveness. The indicators are divided into four groups: (1) production and consumption, (2) waste management, (3) recyclable materials, and (4) competitiveness and innovation (Communication from the Commission…, 2018). It should be noted, however, that the links between some indicators and the circular economy are indirect, even though they provide information on the circularity of the economy.

The literature offers many indicators relating to circularity at the microeconomic level. A review of 40 indicators was offered by Syu et al. (2022), five of which were checked for suitability in a manufacturing company:

- Material Reutilisation Score (MRS) — an indicator determining the share of secondary and recyclable or biodegradable materials in the product;
- Circular Economic Value (CEV) — an indicator determining the level of consumption of materials and energy in the production process;
- Product-Level Circularity Metric (PLCM) — an indicator representing the ratio of recirculated economic value to total product value;
- Quantitative Indicators and Value Assessment (QIVA) — an indicator determining areas of interventions in manufacturing processes based on production data, e.g., the volume of material flows feeding the process, their characteristics, costs associated with environmental management;
- Material Circularity Indicator (MCI) — an indicator determining the degree to which the linear flow should be minimised and the circular flow maximised.

However, the listed indicators only allow monitoring of selected material streams in the production process of enterprises, e.g., material and energy consumption, without considering the complexity and comprehensiveness of circular flows. The disadvantage of these indicators is the selective perception of circular processes, as they only consider the streams that constitute the input to the production system or its output. The synthetic measure of development proposed in the article allows circular manufacturing to be measured by considering the flows of all materials used in the economy and discharged into the environment or reintroduced into economic processing (research question Q1). This is obviously not a perfect measure. It does not show, e.g., the negative environmental impact of materials reintroduced into the production process (as a result of processing operations). It also does not indicate the correct proportions between input and output to the system.

Scrap electrical and electronic equipment is the fastest-growing waste category, becoming a massive environmental problem. Reducing the amount of generated e-waste seems impossible due to advances in technology and ever-increasing demands for digitisation (Dixit et al., 2023). The high value of waste arising only from separate EEE collection, which is reintroduced into economic processing per capita in industrialised and economically developed countries, is, on the one hand, a manifestation of positive processes with regard to the promotion of circular manufacturing in the context of the use of information technology, because it is indicative of:

- high environmental awareness of the society,
- feeding the production process with non-natural resources,
- protection of valuable resources,
- taking actions that are most beneficial from the point of view of the waste hierarchy,
- digitisation development.

On the other hand, however, e-waste is seen as a source of toxic substances that seriously threaten the environment. From an environmental perspective, the amount of electronic waste introduced into processing should be as low as possible, provided that this low value does not result from improper disposal of this waste type. Its volume, however, is higher for developed countries. This may be due to the higher availability and use of electronic equipment, which, therefore, indicates that production processes are supported by information technology.

Unfortunately, no statistically significant correlations have been observed between the level of circular manufacturing and the amount of e-waste put on the market in the European Union countries (research question Q2). These findings support research showing that sustainable practices do not significantly mitigate the impact of Industry 4.0 technologies on sustainable performance (Yavuz et al., 2023). That breeds the need for an integrated measurement system to monitor and evaluate the sustainable development of new technologies, also, and perhaps especially, in the context of the dynamics of Industry 5.0 technologies (Ghobakhloo et al., 2023). Industry 5.0 stakeholders should be able to assess both its complexity and dynamics to implement modern information solutions in line with broader sustainability goals.

The vast majority of countries, however, show an average annual increase in e-waste (Fig. 1), which is a negative trend from an environmental perspective. It is assumed that revenues from e-waste recovery will open up prospects of ventures aimed at environmental benefits and the transition to a circular economy (Al-Salem et al., 2022). Unfortunately, the value of waste is still seen mainly in economic terms (Edirisinghe et al., 2023). Therefore, it is important to reduce waste by redefining its value in socio-ecological rather than monetary terms (Savini, 2023). Even more so, the creation of circular economic cycles does not lead to a reduction in either production or consumption, which means it does not reduce waste but increases the level of recovery. Therefore, it is necessary to find ways to reduce e-waste, mainly avoiding their generation.

CONCLUSIONS

The study was conducted to assess material flows in the production process reflecting the circular manufacturing level in the European Union countries and to investigate whether there is a relationship between the circular manufacturing level and the e-waste amount put on the market as an effect of implementing the Industry 5.0 technology. The level of circular manufacturing in the European Union countries was assessed, and the relationship of this level with the amount of generated e-waste was examined. A synthetic development measure, which considers material flows in the circular economy, was proposed to determine the circular manufacturing level.

Based on a synthetic development measure, the European Union countries were ordered according to the effects of activities in the use of material streams in the production process, in particular imports of waste for recovery and recycling, domestic extraction, material accumulation, waste recycling, waste backfilling, exports of waste for recovery and recycling, emissions, dissipative flows, and waste landfill. For all economies, the level of circular manufacturing was found to remain unchanged in the analysed 2013–2021 period. The level of use of Industry 5.0 technology is expressed in the amount of waste arising only from separate collection of EEE and put on the market. Industry 5.0 is a consequence of technological advances, digitisation and the need to instil environmentally friendly behaviour in manufacturers and consumers. Modern information technologies also support activities that will reduce the amount of waste going into the environment. Unfortunately, they are a source of waste, so their use should also be controlled in terms of environmental consequences. In the context of circular manufacturing, the use of Industry 5.0 technology should significantly reduce the amount of waste generated, including e-waste.

In addition, based on trends in the e-waste amount introduced into the market and the level of synthetic development measure, economies were broken down according to the effects on e-waste streams and conditions for developing environmentally sustainable businesses.

The research provided several practical and policy implications. First, companies should look for measures of the effect of implementing solutions that foster closed production cycles. The indicated synthetic measure of the circular manufacturing level considers material flows, which should result in lower consumption of production resources. Using it at the enterprise level will allow for observing trends in this area and diagnosing possible irregularities. It is also crucial to find a method to determine how implementing Industry 5.0 technology translates into these effects. Another important task is to change the way waste is viewed, as it should be considered primarily in social and environmental terms and not in economic terms. Enterprises mainly reach for methods related to the handling of waste already generated. They try to mitigate the environmental impact of their activities by subjecting waste to reuse and recycling processes. Such actions lead to restoring the use value of waste while giving it monetary value. However, the right action would be to avoid waste generation. Unfortunately, studies conducted indicate that the amount of waste per capita (especially e-waste) is increasing, especially in developed countries. This should be the impetus for efforts to avoid waste in general. Any waste poses a threat to the environment, as handling methods, even such as reuse and recycling, generate certain environmental and social consequences.

Second, government entities should promote cooperation among Industry 5.0 stakeholders, i.e., manufacturers, technology providers, the public and law-making entities in developing and implementing sustainability principles to create closed production cycles. The article points out the roles of material flows in the circular economy context. The stimulants and destimulants influencing volumes of individual material streams were identified through the proposed synthetic measure of the circular manufacturing level. This can be a guideline for individuals creating a political-administrative framework for sustainable development, and the circular economy in particular, in terms of planned guidelines. Creating incentives for using environmentally friendly solutions will help change companies' mindset towards implementing green solutions that favour the environment in various areas of their operations.

A limitation of the research is that it takes the level of e-waste volume to affect the implementation of the Industry 5.0 technology to increase the circular manufacturing level. It is a problem because the level applies to all e-waste generated in a country, not just that generated as a result of implementing Industry 5.0 technologies. Another problem is quantifying the level of application of Industry 5.0 technology in enterprises because it is a qualitative variable. It is also necessary to investigate relationships other than linear between the amount of e-waste (or, more broadly, the use level of Industry 5.0) and the circular manufacturing value. Another downside is the short analysis period of only nine years. Solutions, especially Industry 5.0, are only in the implementation phase, so the visible effects of technology implementation have yet to be seen, especially in terms of national economies. Therefore, the future research direction will be to analyse the effects of circular manufacturing in enterprises in the context of Industry 5.0 technologies implemented for this purpose using statistical regression models. In addition, analyses have been conducted at the level of European Union countries. Future research should focus on organisational networks. Creating a circular manufacturing system goes beyond the boundaries of a company and undermines established relational structures. Companies in a circular economy are seen as partners creating a value network, which means that the product supplier and the customer cannot be clearly separated as the customer can simultaneously become a supplier and thus change the power structure of the entire value chain (Mauss et al., 2023).

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