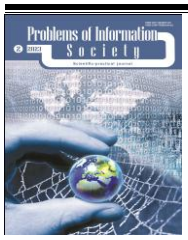

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Formation of a digital circular economy on the Industry 4.0 platform

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ABSTRACT

This article analyzes a circular economy, its digitization features and development models. It interprets the digitalization of the circular economy in the context of green development concepts. The article shows the importance of increasing resource efficiency and stimulating the use of renewable resources in the transition process of enterprises to the green and circular economy. The importance of reducing waste generation through prevention, reduction, recycling and reuse, and production is emphasized. The international experience on the development of the digital circular economy, various scientific trends and relevant related studies are analyzed. The structure of the integration of digital technologies into the circular economy is built. The introduction of new ICT technologies into the development of circular economy, such as the Internet of Things, machine learning, deep analytics, 3D printing, blockchain, etc. are explored. The integration model of Industry 4.0 and digital circular economy is schematically developed. The main structural elements of the digital circular economy with circular Industry 4.0 are presented. The article also studies the structural elements of the circular economy, such a business models, digital transformation, lifecycle management, resource efficiency, smart services, supply chain management, etc. It explores the ways to increase the sustainability of the digital circular economy through digital transformation technologies. In this regard, relevant proposals and recommendations are made, taking into account the technological requirements and priorities for the further development of the Industry 4.0 platform elements.

1. Introduction

In recent decades, the leading countries of the world have started relevant work towards the implementation of the Concept of Sustainable Development adopted at the UN Conference on Environment and Development (United Nations Conference on Environment and Development, 1992). The great interest of researchers, political and social figures, and entrepreneurs in the essence and importance of this phenomenon has led to the emergence of hundreds of different interpretations of sustainable development in local and foreign literature (Mochalova, 2020; Alguliyev et al., 2014).

Scientific interpretation of the problem of sustainable and continuous development in many cases requires the determination of the research object. Consequently, this issue can be viewed as a social-ecological economic system of various levels and goals, which consists of a combination of society and environment in a certain form.

In terms of continuous development of the socio-ecological economic system, the maximum adaptation of the system to the effects of external and internal factors and its capacity to meet various economic needs are of particular importance. Balanced development requires achieving the sustainability of a large number of multi-component socio-ecological economic

systems spanning the entire world, country, region, city or enterprise. Social and economic development should be contributed to by eliminating the excessively wasteful lifestyle of the population in developed countries and by increasing the resource intensity of production in developing countries, that is, taking into account existing environmental limitations. All this has led to the establishment of the circular economy concept, which is rapidly developing in the world in recent years, and focusing on its development.

In the 21st century, sustainable and continuous development has been adopted as a key concept for envisioning the future. Greening of economic development covers all regions of the world being a strategic priority for many countries. Nowadays, many countries are performing relevant implementations to increase resource efficiency and reduce the negative effects of economic growth on the environment (Lavrikova et al., 2021). Searching for ways to reconcile the goals of environmental policy and economic development is now very urgent. Sustainable development is recognized as a global challenge that must be addressed at the international level. In accordance with the interests of the entire world community, the goals of economic, socio-political mutually beneficial cooperation between countries also serve sustainable development. The green and circular economy formed in this direction also determines the priorities of green development concepts and a long-term economic approach supported by national legislation. Their mission is to increase resource efficiency, promote the use of renewable resources, reduce waste generation through prevention, reduction, recycling and reuse, greening the industrial sector and promoting more sustainable agriculture, transforming global food systems and developing medical technologies. is to create a foundation. Among other things, priority should be given to the active involvement of various business activities in the process, which can play a key role in achieving the Sustainable Development Goals-SDGs) (The Sustainable Development Goals Report, 2020).

To stimulate business participation, particularly the transition of enterprises to a green, circular economy, it is necessary to solve mainly organizational, legal, financial, cultural, historical, geographical, infrastructural, environmental, and other factors (Alguliyev et al., 2017; Aliyev, 2019). Therefore, it is necessary to look for effective ways of sustainable and continuous economic development and improve them regularly (Chiappetta et al., 2020).

Continuous technological development around the world is rapidly expanding the global value chain. The expansion of its geography enables timely, high-quality and low-cost delivery of global goods and services to the end consumer. Consumers of the digital society can track the products/services they want and order throughout the value chain. By benefiting from these types of factors, it will be possible to support the integration of the country's economy into the global value chain (Socio-Economic Development Strategy of the Republic of Azerbaijan in 2022-2026; Decree on improving management in the field of digital transformation in the Republic of Azerbaijan, 2021; Decree on some measures related to the improvement of management in the field of digitization, innovation, high technologies and communication in the Republic of Azerbaijan, 2021).

Greening processes in the global economy ensure new opportunities for the development of non-resource economies. Acceleration of these processes may affect the country's further oil revenues. Decreasing demand for oil in the global energy market requires both deep diversification of the non-oil/gas sector and compensation of declining oil revenues through non-oil/gas foreign currency earnings. Fight against climate change, efficient use of natural resources, protection of biodiversity, etc. are the most basic principles of sustainable and stable economy. Sustainable Development Goals (The Sustainable Development Goals Report, 2020), the requirements of the Paris Agreement on climate change, the plan for realizing the country's development priorities, increasing the effective use of renewable energy sources, and other similar principles entail the use of environmentally friendly and efficient energy technologies (Socio-Economic Development Strategy of the Republic of Azerbaijan in 2022-2026).

In this regard, the main task and problem of the presented research work are to increase the efficiency of the use of material resources used in the production process, to accelerate the application of digital transformation technologies in the field of implementing technological solutions in the field of waste recycling, as well as in raw material processing, and to improve the methodological apparatus and development of new ones for determination of the environmental and economic efficiency of all these processes.

2. Related work

Various reports and many scientific publications on the circular economy are currently available (A new Circular Economy Action Plan For a cleaner and more competitive Europe, 2020; United Nations Environment Programme, 2019; Popova, 2022; Sinelnikova, 2022; Shkarupeta et al., 2022; Kuznetsova, 2022; Milova et al., 2021; Lü et al., 2021; Hettiarachchi et al., 2022; Nascimento et al., 2019; Gennari, 2022; Shkarupeta et al., 2022; Konstantinos et al., 2022; Piscicelli, 2023; Ronaghi, 2022; Khan et al., 2022; Tang et al., 2022).

Although most of them are of a general character, some of them address specific problems. Despite the popularity of the circular economy paradigm, it has not yet been properly established. Scientific literature still lacks a systematic multidisciplinary analysis of its conceptual foundations. Therefore, available theoretical and practical aspects of the circular economy concept should be further analyzed in order to comprehend its content more adequately. It is also necessary to study the establishment aspect and semantic content of available concepts in this field, as well as to analyze the perspectives and limitations of the transition to a non-linear scheme of production and consumption.

In (Shkarupeta et al., 2022), one of the striking research works, the model, strategies, platforms and technologies relevant to the concept of Digital circular economy are analyzed. It emphasizes that although the Russian national program "Digital Economy" has been implemented since 2017, in 2022 the federal project to move to a closed economy and a circular economy was launched. Thus, studies on the formation of a digital circular economy and the efficiency of circular development are of interest. Therefore, attempts should be made to conceptualize the digital circular economy. The methodology of this research is formed by combining the facts extracted from scientific studies, scientific knowledge based on analysis and synthesis methods using appropriate clustering methods, and scientific research analytics tools. Its main method is a systematic literature review based on standardized compliance. A systematic review of the literature takes place based on the management of research data according to the principles of discovery, accessibility, interoperability and reuse. The mentioned article (Shkarupeta et al., 2022) offers governing the hypothesis of a relationship between digitization and circularity, which constitutes the essence of the digital circular economy and is represented in the mathematical model. Such a model assesses whether the digital transformation is capable of creating a circular economy or not. Circularity helps the digital transformation process. Strategies, business models, frameworks, technologies and architectures refer to the tools for the digital circular economy. It can be concluded that the digital circular economy is based on the combination of the Internet of Things, big data and machine learning, artificial intelligence and the blockchain that promotes sustainability and development according to the principles of circularity. The presented work also presents many recommendations for the implementation of the digital circular economy in the context of the transition to Industry 4.0 and Industry 5.0 platforms in order to organize production with zero emissions and a circular economy.

(Konstantinos et al., 2022) analyzes the principles, applications and problems of IoT and digital circular economy. The study of digital circular economy models is of an urgent nature. The application of Internet of Things technologies in this sphere particularly increases its impact and consequences in modern society. New development opportunities have been created by taking the first step from Industry 4.0 to Industry 5.0 solutions so far. Circular approaches have been recognized as an imperative platform in this area. To fully comprehend the digital circular economy, every aspect of it must be explored. Here, its business models, applications, and relevant features can be studied by conducting systematic research with a comprehensive analysis of the connections of the Internet of Things technologies with the Digital circular economy.

(Piscicelli, 2023) highlights the impact of the digital circular economy on sustainability. Currently, digital technologies, i.e., the Internet of Things, big data, deep analytics, smart manufacturing, 3D printing, blockchain and online platforms, are considered the key opportunities for the circular economy. This article analyzed several scientific papers published in recent years to identify the various degrees of sustainability effects of the digital circular economy. Environmental impacts and the environmental usefulness of production processes, such as resource efficiency, reduction of emissions, waste and materials, should be strictly explored.

However, attention to the social and economic sphere is limited. Available scientific literature also has some shortcomings. A proper assessment of the actual impact and a more balanced consideration of negative (positive) impacts can bring more benefits to human-nature interactions.

(Ronaghi, 2022) explores the impact of the application of artificial intelligence on circular economy practices in industrial production. To achieve sustainable development, the circular economy seeks to manage the flow of materials and energy in closed systems. The circular economy has led to the formation of sustainable business models. The capabilities of artificial intelligence are changing business operations, information flow and organizational processes. This study aims to determine the impact of the application of artificial intelligence on circular economy practices in an organization. Here, research questions include: What are the factors affecting artificial intelligence in manufacturing companies? How does the application of artificial intelligence affect the circular economy in the organization? At the first stage, a conceptual model is developed based on previous studies. In the second step, the research model is evaluated among the manufacturing company. The results show technology characteristics, organizational capabilities, and the external environment to have a positive effect on the application of artificial intelligence, and the application of artificial intelligence to have a positive effect on circular economy practices. Artificial intelligence technology can be the solution to modify the production process and reduce the destructive effects of the industry on the environment. Managers of manufacturing companies can use the capabilities of machine learning, Big Data, cloud, Internet of Things, and neural networks to manage resources and optimize production.

(Khan et al., 2022) highlights the practical experiences of digital technology and circular economy, as well as the future issues of supply chains in this sphere. Research on the use of digital technologies in the circular economy has recently proliferated. The capacity to fully utilize circular resources has been possible by the development of advanced digital manufacturing technologies. The studies on the impact of digital technology on building a circular economy in a supply chain context are currently limited. These studies attempt to examine the impact of technological innovations on circular economy practices and assess their relationship with the environment and economic performance. The article develops a conceptual structure based on literature analysis and uses quantitative method to evaluate the theoretical foundation. This study uses questionnaire data from respondents of small and medium-sized enterprises located in the People's Republic of China and Pakistan to examine a model explaining the relationship between technological innovation, circular economy practices, and performance. SMART PLS version 3.3.3 is used for data analysis. Test results show that circular economy practices lead to positive economic and environmental performance. The outcomes can help policy makers and business professionals to respond appropriately to successfully implement and manage circular economy practices. Relatedly, this study also concludes that businesses need to integrate circular economy practices with digital technology solutions to accomplish their long-term financial and environmental goals.

(Tang et al., 2022) explores the business management strategies for environmental sustainability in the context of Industry 4.0 technology and circular economy practices. Obviously, the circular economy and Industry 4.0 are among the most discussed and researched topics in recent decades. They have attracted the attention of scientists, practitioners and politicians from all over the world. This study examines the impact of Industry 4.0 on circular economy practices and blockchain technology. The partial least squares method and structural modeling are used to demonstrate the results of the study. The results show that blockchain technology significantly improves circular economy practices in terms of green manufacturing, recycling and remanufacturing, and green design. In addition, Industry 4.0 has the potential to significantly improve business operations, as well as financial performance and environmental performance. The article also presents some recommendations for enterprises to achieve long-term targets by incorporating Industry 4.0 into the production systems.

In general, appropriate mechanisms should be developed taking into account the recommendations of international organizations, as well as the new management models of the Industry 4.0 platform, the prospects for the application of new technological components, to solve the problems related to the circular economy. In this regard, the studies on the characteristics and principles to form the transition to a circular economy within the

framework of the green economy concept should be improved.

Despite numerous difficulties in solving the existing problems in this field, there are also opportunities and potential. These problems and their solutions should be identified and incorporated into the functional cycle. In general, although certain scientific research has been conducted on the regional, international and global scale in the analysis of the characteristics of the transition to the circular economy within the framework of the green economy concept, this area has been rather poorly studied. There is a great demand for conducting deep scientific-technical and practical research in a similar sphere.

3. Challenges and prospects of the transition to the digital circular economy concept

The digital circular economy is characterized by the use of digital technologies to promote resource efficiency and circulation. Digital technologies such as the Internet of Things (IoT), blockchain, artificial intelligence and big data analytics can provide real-time information on resource usage and enable their efficient use. IoT technology can enable tracking and monitoring of resources throughout their entire lifecycle, from production to disposal. Blockchain technology can empower secure data sharing, which can increase transparency and accountability in the use of resources. Artificial intelligence and big data analytics can optimize resource utilization by identifying patterns and predicting future trends. The digital circular economy also involves sharing economy models that enable the use of digital platforms and the resources' allocation and provide waste reduction.

Some implications and challenges of transition to a digital circular economy to be addressed are given below.

1. Technology transfer, application, adoption of new production methods and modernization of manufactured products. The transition to a digital circular economy requires a significant implementation of digital technologies in all sectors of the economy, which may be difficult for some businesses and individuals.

2. Data privacy and security. The use of digital technologies to optimize resource use requires the collection and management of large volumes of data, which can pose challenges for data privacy and security.

3. Adjustment problems. The transition to a digital circular economy may entail changes to available regulations and policies, which may be problematic to implement.

4. Government policies and regulations. Government policies and regulations play an important role in promoting the transition to a digital circular economy. Governments can support the transition by encouraging businesses to adopt digital and circular economy practices and invest in the research and development of new digital technologies.

We can emphasize that the timely solution of the mentioned problems related to the transition to the digital circular economy may provide effective results with the application of digital technologies in its development. Given this, the relevant recommendations and proposals worked out for the development of the circular economy based on modern digital platforms will lead to the study of the characteristics of the development of the circular economy with the application of digital technologies and the effective management of its activities.

4. Integration of digital technologies into the circular economy

Integrating digital technologies into the circular economy can increase its effectiveness and dynamism. In the digital circular economy, digital technologies such as the Internet of Things (IoT), artificial intelligence and blockchain are applied to optimize the use of resources and reduce waste. Digital technologies can provide:

1. Optimization of resources. Digital technologies can ensure efficient use of resources such as energy, water and raw materials by tracking and analyzing resource usage.

2. Waste reduction. Digital technologies can reduce waste by optimizing production processes, enabling recycling and reducing material losses.

3. Business opportunities. Digital technologies can create new business opportunities in resource optimization, waste reduction and recycling.

Gartner analysts find out that the circular economy (https://cio.osp.ru/news/230420-Gartner-tsirkulyarnoy-ekonomike-neobhodimy-tsifrovye-tehnologii) is a business model in which the opportunities for economic growth are separated

from the consumption of natural resources. The terms "cyclical economy" and "closed economy" are also used here. The circular economy minimizes waste by continuously recycling materials, and the need for additional resources is reduced. The circular economy generates an ecosystem of materials, i.e., what was previously considered waste gains value. However, such ecosystems are complex and contain many dependencies and feedback loops.

Therefore, digital technologies are particularly necessary to build such ecosystems, manage them effectively and make business decisions. More than a third of companies now estimate digital technology as a key factor in implementing circular economy strategies. However, they are rarely used (https://cio.osp.ru/news/230420-Gartner-tsirkulyarnoy-ekonomike-neobhodimy-tsifrovye-tehnologii).

Nowadays, the application of digital technologies in the development of the circular economy is of great importance. Studies show that the digital technologies commonly used in the development of the circular economy include deep analytics, 3D printing, Internet of Things, machine learning, and blockchain technologies. Digital technologies are used in 46% of companies in product delivery, logistics and other processes.

In general, the digital circular economy concept consists of two convergent processes as 1) the transformation of the circular economy into a digital economy, 2) the transformation of the digital economy into a circular economy (Figure 1).

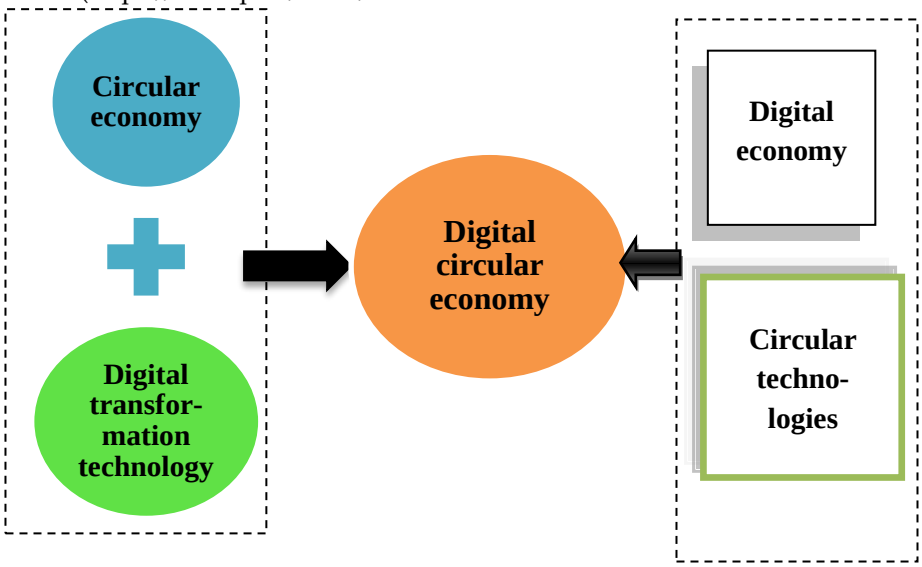

Fig. 1. Formation trends of digital circular economy

In other words, the digital circular economy is formed and developed as a result of the transformation of the digital economy into the circular economy or, in parallel, the transformation of the circular economy into the digital economy (Shkarupeta et al., 2022).

A digital circular economy is a circular economy that uses digital technologies. Digital technologies play a key role in the development of circular business models. To develop and expand the circular economy, it is necessary to integrate digital technologies such as IoT, Big Data and artificial intelligence into available circular business approaches.

As a whole, digital transformation provides opportunities for industry to build competitive and innovative business models based on circular economy principles. Table 1 presents the digital circular economy technologies (Shkarupeta et al., 2022; Alguliyev et al., 2013; Schöggl et al., 2023).

The presented digital circular economy technologies can be integrated into various architectures. A circular architecture model combining blockchain and IoT technologies supported by computing mechanisms can be developed. IoT nodes installed in a digital circular environment, supported by blockchain applications that verify the collection, storage and exchange of operational data, build a proper infrastructure for a circular economy (Shkarupeta et al., 2022).

Table 1: Technological foundations of the digital circular economy formation

Digital techno-logies	*Examples of use in circular strategies and business models*
Internet of Things (IoT) technology	• Product life cycle data used to improve product service; • increasing the processing efficiency by using additional data; • applying energy efficient management issues and sustainable manufacturing practices of the company; • controlling and monitoring the state of products; • collecting the data necessary for product design; • collecting life cycle information for data-driven recycling and making logistical decisions
Machine learning technology	• Green supply chain management and environmental impact assessment; • preventive and predictive maintenance to extend product life; • increasing the energy efficiency of equipment; • analyzing and evaluating consumer behavior; • improving data quality and assessing data variability; • inventory management, transportation optimization, demand analysis and assessment; • acquisition of new knowledge from databases to improve the efficiency of energy and operations management, social sustainability data collection, design, production and service processes.
Artificial intelligence technology	• assisting manufacturers to select the best possible sustainable supplier and improve manufacturer sustainability; • environmental impact assessment; • providing traceability during the product life cycle; • energy and environmental impact forecasting
Blockchain technology	• Testing fair practices in production; • keeping a transparent record of the product's origin/history; • trading based on smart contracts; • material tracking; • creating new business models.

5. Additive production methods applied in the circular economy formation

Additive manufacturing methods applied in the the circular economy formation are one of the most rapidly changing technologies in modern society (Angioletti et al. 2016). This technological production should be described in terms of the life cycle management support of products and processes where necessary. In many cases, some researchers propose additive manufacturing to improve current recycling processes. They present it as a new sustainability tool, a new type of production process digitization or management strategies. The idea of widespread use of additive manufacturing to support the remanufacturing of products or components has great prospects (Paolo et al., 2020).

Additive manufacturing, commonly known as 3D printing, has emerged as a transformative technology with the potential to reshape the global economy. The role of additive manufacturing in advancing the principles of the circular economy has been recently recognized.

As mentioned, the circular economy is a new economic model that aims to minimize waste and maximize resource efficiency by keeping products and materials in use for as long as possible through recycling, reuse and recovery. Additive manufacturing methods, which have been widely used in recent years, correspond to the principles of the circular economy in several ways. Thus, additive manufacturing produces goods on demand in a decentralized form. Instead of mass production and its waste, the products are manufactured as needed. This reduces overproduction and inventory waste, helps to adjust production to actual demand, and minimize excess production and subsequent disposal (Hettiarachchi et al., 2022).

Additive manufacturing ensures precise control over the use of materials. This provides using the right amount of material required for a certain optimized product, reducing material waste. In addition, 3D printing can use recycled or biomaterials, which continuously encourages the cyclical use of materials. This type of manufacturing has design flexibility to generate complex and customized products. Here, principles for recycling can be integrated into the design process. As a result, recovering valuable

materials from products at the end of their life cycle becomes easier.

Additive manufacturing can support local production and reduce carbon emissions. Instead of manufacturing products in a centralized location and shipping them globally, 3D printing can enable local production close to the consumption point. This can reduce transportation distances and the environmental impact of logistics by shortening supply chains.

Note that additive manufacturing alone cannot fully achieve the goals of the circular economy. It must be integrated into a wider system that includes materials recovery, recycling infrastructure and efficient waste management practices.

By continuously promoting additive manufacturing, it is possible to reduce waste, optimize resource usage and develop a circular economy. By adopting the principles of the circular economy, additive manufacturing can revolutionize traditional manufacturing processes, making them more sustainable and resource efficient. Nevertheless, addressing the issues related to material quality, technological advances, and supportive policy can realize the full potential of additive manufacturing in the circular economy (Hettiarachchi et al., 2022).

Collaboration between stakeholders, including producers, policymakers and researchers, is crucial for optimizing the potential of additive manufacturing within a circular economy.

The Internet of Things (IoT) is considered one of the modern digital technologies that support the transition to a circular economy together with additive manufacturing. Many papers focus on generalizing the potential uses of IoT to extend product life. There is also a general interpretation that IoT can spread its potential effects to areas related to the circular economy. One option is applying IoT to trigger new waste management strategies in smart areas, create collaboration and improve the cycle level of processes. To take advantage of IoT, circular economy practices must be digitized by implementing smart industrial environments or dynamic feedback control loops. The Internet of Things is suitable for the development of new services and circular business models. Supply chain management performance optimization and remanufacturing processes should be reviewed by experts (Paolo et al., 2020; Alguliyev et al., 2013).

6. Aspects and perspectives of applying Industry 4.0 technologies to the development of the circular economy

In some cases, commonly agreed definitions identify the circular economy as a global economic model for minimizing the consumption of limited resources, focusing on the intelligent design of materials, products and systems. The circular economy aims to overcome the dominant linear (e.g., take, make and throw away) economy model (i.e., the elaborate traditional open economy model without an internal bias towards recycling). The circular economy is also the only process followed in the conceptualization, design, development, use and disposal of traditional (linear) life cycle products. This economy has progressively replaced closed-loop patterns and old industrial practices with a new paradigm entirely focused on balancing economic, environmental, and social impacts (Paolo et al., 2020).

The circular economy and Industry 4.0 represent two of the most important industrial paradigms that have driven science and industry in recent years. A circular economy is a commonly agreed upon system. The circular economy enables businesses to dissociate economic growth from resource constraints by providing opportunities for new ways of creating value, generating revenue, reducing costs, becoming resilient and building legitimacy.

The integration of digital technologies in the industrial context can enable numerous important improvements such as manufacturing technologies, assets, financial performance, market expansion, supply chain management, product life cycle management, workforce empowerment, business models, etc. to increase competitiveness.

Given the importance of the two paradigms gained over time, many scientific studies discuss the circular economy and Industry 4.0 from several aspects. However, there is still a big gap between theory and practice. Scholars describe the challenges, opportunities, structures, models and best-in-class companies related to the perspective of the circular economy. However, very limited contributions are provided on the types of technologies, which can support the implementation of the circular economy, particularly in small and medium-sized enterprises. Many contributions related to the perspective of Industry 4.0 demonstrate the potential support that underlying technologies can offer to companies.

By applying Industry 4.0 technologies in the development of the circular economy, wide opportunities can be created for increasing its efficiency and prospective development. The formation and development of the circular economy based on the relevant digital platforms of Industry 4.0 can seriously stimulate increasing the sustainability of the digital innovation economy.

We believe that attention should be paid to how the areas related to the circular economy are compatible with Industry 4.0 technologies. In addition to the most general views describing this aspect, scientists focus on the compatibility of Industry 4.0 technologies with a specific area related to the circular economy. The main goal here is also to detect hidden correlations.

Researchers on the circular economy digitization prefer to keep the broadest potential developments of the specific Industry 4.0 technology in the future. Only in some cases, experts used to pay attention to several technologies.

Additive manufacturing is the most discussed topic. Next is big data, deep analytics and IoT. Additive manufacturing is adopted to develop new types of production processes (Dutta et al. 2001) or management strategies (Unruh, 2018).

Big data and analytics support responsible business management (Salminen et al., 2017) and industrial symbiosis (Tseng et al. 2018). IoT enables the development of industrial networks (Hatzivasilis et al., 2018; Reuter, 2016). Additive manufacturing appears to be mostly related to the digitalization of the company's internal processes. In contrast, big data, deep analytics and IoT support the digitization of relationships between industrial companies.

Figure 2 illustrates the integrative aspects of the digital circular economy with Circular Industry 4.0. Two perspective concepts of circular economy and Industry 4.0 are viewed here (Paolo et al., 2020).

However, depending on the analysis perspective, the integration of the circular economy with Industry 4.0 can be described differently. Here, the primary focus is on Industry 4.0 technologies, and the "digital circular economy" is one of the main issues discussed. (Figure 2).

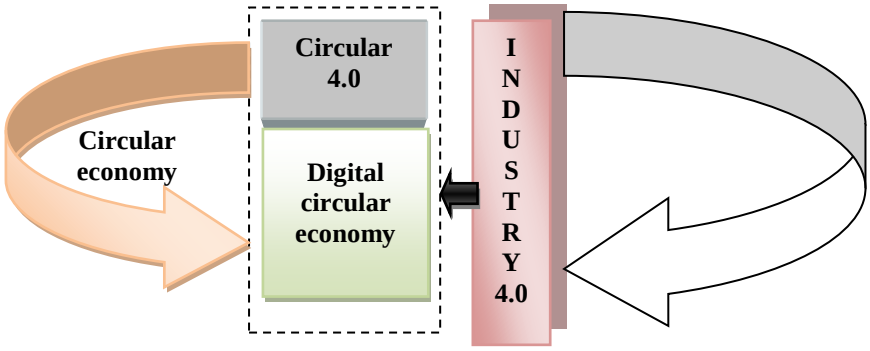

Fig. 2. Integration of Industry 4.0 and digital circular economy

Scientific literature clearly shows the relationships between the circular economy and Industry 4.0. In general, Industry 4.0 is recognized as a facilitator of the circular economy. Furthermore, there is an obvious gap in the literature regarding the contribution offered by Industry 4.0 to the circular economy. Correspondingly, scientific literature presents the structural elements of the sub-elements of the digital circular economy and circular Industry 4.0. Their systematic review shows that there are many benefits and strategies that can potentially be used and achieved from the integration of the circular economy and Industry 4.0. Analytical studies focus on some experiments on the possibility of repeating their performance.

The main components of Circular Industry 4.0 include: Additive manufacturing, Big Data and analytics, cyber-physical systems, Internet of Things (IoT), Simulation, Industry 4.0 technology, etc.

The main structural elements of the digital circular economy include: circular business models, digital transformation, life cycle management, recycling, remanufacturing of industry 4.0 technology, resource efficiency, reuse, smart services, supply chain management, etc. (Paolo et al., 2020; Kristoffersen et al., 2020).

In promoting the transformation from a traditional economy to a circular one, digital technologies assist to achieve the goals ahead. They provide good performance in the application of monitoring, control, optimization and automation tool.

"Cyber-physical manufacturing system" involves the integration of various systems to achieve high automation, increasingly reducing the boundaries between the virtual world and the real one.

The goal of Industry 4.0 is to use key technologies such as cloud services, IoT, Big Data and big data analytics and artificial intelligence to interact with one another and improve the manufacture of high-quality products at minimal cost. Industry 4.0 offers alternatives to sustainable production and consumption minimizing energy losses, resource consumption, and environmental degradation (Han et al., 2023; Aliyev, 2023; Ghobakhloo, 2020).

Industry 4.0 presents a new perspective on how production can benefit from new technologies to create value with maximum output and minimum resource use. The digital technologies of the Industry 4.0 platform can be described as in Figure 3.

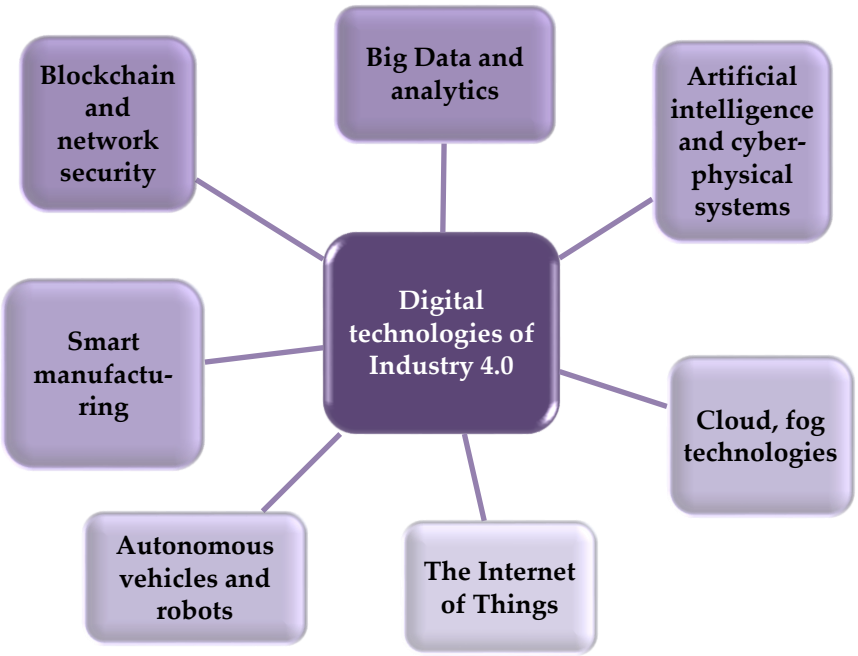

Fig. 3. Digital technologies of Industry 4.0

The application of digital technologies of the Industry 4.0 platform can extremely stimulate the increase of sustainability of the circular digital economy. Accordingly, the application of the elements of the Industry 4.0 platform and digital transformation technologies is of particular importance for the digital circular economy formation.

The application of digital technology trends of the modern world, namely, artificial intelligence, Internet of Things, cloud, Big Data, etc. can be viewed as a contribution to the solutions to the existing problems in the development of the circular economy. The circular economy formation, its prospective sectors and development can be achieved by applying these technologies. This can lead to the formation of a digital circular economy and more effective results for its sustainability and continuity.

7. Conclusion

Ensuring the innovative development of the economy based on digital technologies requires studying the features of the digital circular economy formation in terms of the Information Society and building its development models. Despite the worldwide recognition of this development trend, there is still a need to promote, discuss, and use this problem by large population groups at the regional and national levels.

Further studies should cover the improvement of the efficient management of the circular economy with the digital transformation technologies such as digital twin, artificial intelligence, Internet of Things, etc., and present

recommendations on its perspective development trends. The key targets should include the development of a conceptual model of the formation and expansion, as well as an effective management of the digital circular economy based on digital technologies.

The application of advanced ICT corresponding to the Industry 4.0 platform should be stimulated in the formation and development of the digital circular economy. In the formation and development of the digital circular economy in terms of the Information Society, the benefits they can bring should be extensively explored to justify the improvement of its operational efficiency by means of digital technologies such as the Internet of Things, artificial intelligence and machine learning, big data analytics.

Interaction forms between Industry 4.0 technologies and the environment should be improved. New digital technologies have a profound impact on the industry. The first is the use of data (big data and open data), connectivity (IoT) and computing power (cloud computing), and the second is mining of collected data. The third is the interaction between people and machines (visual representations of data and augmented reality). The fourth is the transition from data to reality (artificial intelligence, 3D printing, etc.). The circular economy model observes the entire life cycle of products and focuses on the high level of recycling of industrially produced materials. In the design phase of digital technologies for the new product life cycle, the combination of remanufacturing, reuse and recycling dramatically changes the cyclical characteristics of the production process. IoT technology enables the reintegration of maintenance processes, as well as the reuse of components and products.

Digitization enables the optimization of logistics, greatly improving the flexibility and response times of industrial and logistics systems. Digital technologies play an important role in environmentally sustainable operational decisions, and the synergy and sustainability of Industry 4.0 can further strengthen a sustainable society. Integrating the Industry 4.0 platform into circular business models can advance logistics, resource efficiency, safety and product quality. As Industry 4.0 features vertical integration, virtualization, automation, traceability, flexibility and energy management, data-driven Industry 4.0 technology can be used to solve circular economy issues. As a component of Industry 4.0., machine learning and analogous methods are comprehensively applied in the circular economy. The application of artificial intelligence technology in the analysis of the formation features of the digital circular economy in terms of the Information Society can contribute to the effective use of resources by optimizing production and distribution processes. This will lead to better management of the circular economy in the context of digital transformation, reducing waste and increasing its efficiency.

The problems of efficient management of the circular economy based on digital technologies and prospective development trends can be applied to the expansion of other regional enterprises and in building solution mechanisms.

The application of digital technologies in the efficient management of the digital circular economy, the analysis of the results of the application of other innovative technologies in its formation and development can serve as a platform for a comprehensive assessment of the activities of other areas as a whole. The basis is established for making appropriate management decisions related to the development of recycling in production at regional and field enterprises, the effective use of resources, and the introduction of digital transformation technologies in its operation.

The proposed methodological and conceptual approach to efficient management of the formation of the digital circular economy based on innovative technologies can be applied to other economic systems. This can achieve more efficient results in a certain sphere and can be characterized as scientific support for management decisions in terms of economic diversification, investments in real economic sectors and enterprises, and ensuring regional technological sovereignty.

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