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THE ROLE OF ARTIFICIAL INTELLIGENCE IN FACILITATING THE TRANSITION TO A CIRCULAR ECONOMY

Doç. Dr. Tufan ÖZSOY

Adana Alparslan Türkeş Bilim ve
Teknoloji Üniversitesi, İşletme Fakültesi,
İşletme Bölümü

Adana/Türkiye

e-posta: tozsoy@atu.edu.tr

ORCID 0000-0002-0138-4179

ABSTRACT

The notion of a circular economy, which prioritizes the prolonged utilization of resources and the minimization of waste, is progressively garnering heightened recognition within the business community. Leveraging technology, notably artificial intelligence, enables businesses and various organizations to enhance resource utilization, diminish waste and emissions, and streamline the effectiveness of resource recovery and recycling procedures. The primary objective of this manuscript was to delineate the scope of artificial intelligence's capacity in facilitating the transition towards a circular economy. This review will begin by providing an overview of the circular economy concept and its potential benefits. It will then discuss the current challenges faced in realizing circular practices and how artificial intelligence can help overcome these challenges. Anticipated outcomes of this study include providing businesses and policymakers with valuable insights and recommendations on the efficient deployment of artificial intelligence in the context of transitioning towards a circular economy.

Keywords: Circular economy, artificial intelligence, sustainability, resource efficiency, waste reduction.

Jel Codes: O32, Q20, Q30, Q56.

DÖNGÜSEL EKONOMİYE GEÇİŞİ KOLAYLAŞTIRMADA YAPAY ZEKANIN ROLÜ

ÖZ

Kaynakların olabildiğince uzun süre kullanımda tutulduğu ve atıkların en aza indirildiği döngüsel ekonomi kavramı iş dünyasında giderek daha fazla ilgi görmektedir. Teknolojinin, özellikle de yapay zekanın yardımıyla işletmeler ve diğer kurumlar kaynak kullanımını optimize edebilir, atık ve emisyonları azaltabilir ve kaynak geri kazanım ve geri dönüşüm süreçlerinin verimliliğini artırabilirler. Bu çalışma, döngüsel bir ekonomiye geçişi kolaylaştırmada yapay zekanın potansiyeline ilişkin sınırları tanımlamayı amaçlamaktadır. Bu derleme çalışması, döngüsel ekonomi kavramına ve potansiyel faydalarına genel bir bakış sağlayarak başlayacaktır. Daha sonra döngüsel uygulamaların hayata geçirilmesinde karşılaşılan mevcut zorluklar ve yapay zekanın bu zorlukların aşılmasına nasıl yardımcı olabileceği tartışılacaktır. Çalışmanın döngüsel ekonomiye geçişte yapay zekadan nasıl etkili bir şekilde yararlanılacağı konusunda işletmeler ve politika yapıcılar için yol gösterici olacağı düşünülmektedir.

Anahtar Kelimeler: Döngüsel ekonomi, yapay zeka, sürdürülebilirlik, kaynak verimliliği, atık azaltma.

Jel Kodları: O32, Q20, Q30, Q56.

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INTRODUCTION

The dominant global economic model, characterized by a linear approach known as "take-make-waste," involves extracting natural resources for manufacturing and then disposing of them as waste, leading to resource overuse, unsustainable waste practices, and significant environmental and health issues (Pathan et al., 2023). Projections indicate a near doubling of global material resource consumption from 90 gigatonnes in 2020 to 167 gigatonnes by 2060, coinciding with an expected three billion more consumers by 2030 (Roberts et al., 2022). In recent times, there has been a widespread and growing fascination with the pioneering concept and developmental strategy called the circular economy (CE) on a global scale. The core aim driving this trend is to provide a more sustainable substitute for the currently dominant economic development paradigm (Ness, 2008). The CE is a multifaceted concept that draws on a variety of theoretical frameworks, including industrial ecology, cradle-to-cradle design, and systems thinking. This approach seeks to foster a more holistic understanding of the economic and environmental impacts of production and consumption, by emphasizing the interconnections between different systems and processes. Despite the potential benefits of a CE, such as new business models, innovations in product design and technology, and the creation of new jobs and industries, it also presents several challenges. These include the need for systemic change, the complexity of supply chains, and the necessity for collaboration among stakeholders. Organizations worldwide are increasingly prioritizing the shift toward a CE as a strategic imperative (Chauhan et al., 2022).

Digital technologies have the capacity to emulate human intelligence functions, providing valuable support for firms in implementing CE principles and enabling mass personalization, sustainable input selection, predictive maintenance for extended product lifecycles, enhanced customer experiences, waste reduction, and improved visibility across supply chain stages, ultimately fostering productivity and sustainability in local and global economies and enterprise-level business models (Wilts et al., 2021). The adoption of Industry 4.0 technologies, including artificial intelligence (AI) and big data, plays a pivotal role in facilitating the realization of CE objectives, specifically sustainable goals, through enhanced resource management, streamlined information sharing, and collaborative efforts among supply chain stakeholders (Khajuria, 2021). Among the various digitalization technologies, AI is recognized as the most influential in shaping the development of CE (Chauhan et al., 2022). AI holds significant promise in providing essential support for the overall infrastructure required to implement circular practices in practical contexts and drive the transition toward a regenerative economic model (Pathan et al., 2023; Ronaghi, 2022). AI has demonstrated its substantial role in advancing global sustainability efforts, positioning it as a valuable tool for addressing critical challenges within an intelligent circular economic system, spanning areas such as sustainable manufacturing, waste management, reverse logistics, energy source optimization, and supply chain management (Noman et al., 2022). Even if narrowing the focus solely to the realm of food, The incorporation of AI into food waste reduction efforts, as outlined in research from the McKinsey Global Institute (2019), has the potential to substantially increase annual top-line revenue, possibly reaching USD 127 billion by 2030, and could also contribute to an additional USD 13 trillion in global economic activity by that year (Onyeaka et al., 2023).

This study involves conducting a literature review on the significance of AI as a crucial strategic tool in the transition to a CE. To achieve this objective, various dimensions of the CE are considered, with a specific focus on the utilization of AIas a potent tool.

LITERATURE REVIEW

1. The Circular Economy

The conventional linear economic model fails to effectively regulate the equilibrium between the utilization and availability of natural resources. This discrepancy not only jeopardizes the sustainability of our planet but also exerts adverse impacts on both environmental and socioeconomic conditions (Elliot, 2011). The CE emerges as a solution to counteract the detrimental characteristics of the linear economic model (da Silva et al., 2022; Lacy and Rutqvist, 2015). At the heart of the CE lies the transformation from traditional, one-way resource-to-product-to-waste processes to systems that prioritize the reutilization, remanufacturing, and recycling of materials (Ghisellini et al., 2016). The CE vision, lauded as an ethical alternative to the linear economy, aims to minimize resource waste and emission leakages through a closed-loop system, advancing sustainability (Geissdoerfer et al., 2017). The CE is focused on reducing waste and optimizing resource usage by ensuring that products, components, and materials remain at their highest value and utility for as long as possible. By adopting a circular economic approach, organizations can create new opportunities for sustainable economic growth and contribute to the development of a more resource-efficient society. The World Economic Forum (2020) defines the CE as a regenerative economic system that optimizes resource use by keeping materials in use for as long as possible, minimizing waste and pollution, and regenerating natural systems. According to the European Commission (2019), the CE is a sustainable framework for production and consumption that prioritizes practices such as sharing, leasing, reusing, repairing, refurbishing, and recycling of existing materials and products. Overall, a CE is a restorative and regenerative economic system, as described by the Ellen MacArthur Foundation (2013), that aims to obtain the optimal utility and value of products, components, and materials, with the goal of reducing waste and conserving resources.

The key features of the CE, as defined by various scholars and experts, include:

Design for longevity and reuse: This feature emphasizes the importance of designing products that can be used for longer periods of time and can be easily repaired or upgraded. Ellen MacArthur Foundation (2019) define this principle as “to design out waste and pollution, keeping products and materials in use for as long as possible. This means designing for durability, repairability, and reuse."

Closed-loop material flows: This feature aims to keep materials in use for as long as possible, by recycling or repurposing them at the end of their life cycle. This principle defined by Kirchherr et al. (2018) as "closing the loop of material flows through product design, reverse logistics, recycling, and circular supply chains is an essential feature of the CE."

Regenerative systems: This feature aims to restore natural ecosystems and protect biodiversity. According to Leire (2018) "Regenerative design focuses on the health and resilience of ecosystems, emphasizing restoration, preservation, and enhancement of natural resources."

CE has several potential benefits for businesses, the environment, and society as a whole. It has practical applications in several areas, including product design, supply chain management, waste management, improved resource efficiency, new revenue streams, improved brand reputation, positive social impact. In product design, the CE can be applied by designing products that can be easily repaired, upgraded, or disassembled at the end of their life cycle. In supply chain management, the CE can be applied by creating closed-loop material cycles, optimizing logistics, and reducing waste. In waste management, the CE can be applied by diverting waste from landfills and incinerators, and by creating value from waste through recycling or repurposing. CE emphasizes the efficient use of resources, such as energy, water, and raw materials. By optimizing resource use and reducing waste, businesses can reduce their costs and improve their bottom line. CE can create new revenue streams for businesses by promoting product-as-a-service models, take-back programs, and other circular business models. These models can help businesses generate revenue while reducing waste and improving their environmental sustainability.

The adoption of CE practices can bring a range of benefits to businesses, including enhancing their reputation and promoting their commitment to sustainability and environmental responsibility. By implementing CE practices, companies can demonstrate their dedication to creating a more sustainable and resilient economy. This can attract customers, investors, and employees who are seeking to engage with socially responsible businesses that prioritize environmental stewardship. Furthermore, embracing CE practices can help organizations reduce costs, improve efficiency, and foster innovation, all of which can contribute to long-term economic success. CE can have a positive social impact by creating new jobs, promoting local economic development, and improving access to resources for marginalized communities. Several reports have highlighted the potential benefits of transitioning to a CE. According to Lacy and Rutqvist (2015), CE practices could generate $4.5 trillion of economic benefits by 2030. This significant revenue could be generated through practices such as recycling, reusing, repairing products, and reducing waste. Additionally, the International Labour Organization (ILO, 2018) reported that transitioning to a

CE could create 18 million new jobs globally by 2030 due to the increased demand for workers in areas such as recycling, remanufacturing, and repair services. The Ellen MacArthur Foundation (2022) also published a report stating that transitioning to a CE could reduce global carbon dioxide emissions by 45% by 2050. This significant reduction in emissions could help address the issue of climate change. In summary, transitioning to a CE could benefit the environment, generate significant economic benefits, and create new job opportunities.

2. Digitalization of CE

The CE necessitates precise coordination and optimization of the entire value chain, as highlighted by Fischer and Pascucci (2017). In this context, digital technologies offer decision-makers the potential to harness vast datasets to inform, refine, and promote sustainability in decision-making, all while efficiently overseeing the movement of information and materials (Ajwani-Ramchandani et al., 2021). Numerous studies (e.g., Antikainen et al., 2018; Bressanelli et al., 2018; Garcia-Muiña et al., 2018; Kintscher et al., 2020) in the existing literature emphasize that digitalization plays a vital role in facilitating the transition to the CE by translating CE principles into practical actions, enhancing decision-making, complementing human skills, enabling data-driven design for circularity, optimizing products and processes, and aiding in demand prediction, inventory management, waste reduction, and AI-driven recycling practices (Chauhan et al., 2022). Indeed, as indicated by literature analysis of Bressanelli et al. (2018), six pivotal Industry 4.0-based technologies associated with the CE are identified as cyber-physical systems, internet of things, artificial intelligence), big data analytics, additive manufacturing, and simulation. Certainly, scholars (e.g., Ajwani-Ramchandani et al., 2021; Chauhan et al., 2019; Ingemarsdotter et al., 2019) maintain that the integration of big data, AI, blockchain, the internet of things, and cloud computing within the digitalization transformation is closely connected to the core principles of shifting towards a CE (Chauhan et al., 2022). In their respective studies, Bag and Pretorius (2022) zoom in on the difficulties companies face when trying to digitize in order to achieve CE objectives. Kerin and Pham (2019) narrow their focus to the remanufacturing sector. Conversely, Awan et al. (2021) shed light on the digital tools that can ease the adoption of CE principles. Demestichas and Daskalakis (2020) delve into the synergy between the CE and information and communication technology. Considering the significance of Industry 4.0 is paramount. Industry 4.0 seeks to leverage disruptive technologies such as cloud services, IoT, big data, and AI to optimize the cost-effective production of high-quality goods. It introduces sustainable alternatives that diminish energy wastage, resource utilization, and environmental impact, presenting an innovative manufacturing approach that optimizes production while minimizing resource depletion (Han et al., 2023).

3. Artificial Intelligence for CE

The concept of the CE has gained momentum as a means of reducing waste and promoting sustainable practices. However, in order to achieve a CE, it is imperative to analyze a multi-actor structure with complex processes and to identify potential circularity enablers and relationships. Achieving a successful transition to the CE poses a formidable challenge, demanding profound and systematic changes in both production and consumption systems (Svorobej et al., 2019). This shift underscores the necessity for data collection and sharing, investments in innovation, and the cultivation of collaborative business partnerships (Toop et al., 2017). At this juncture, digital technologies assume a prominent position, garnering significant scholarly attention and empirical exploration. Recent studies emphasize the growing importance of digital technologies in strengthening CE solutions and addressing ongoing challenges (Kortelainen et al., 2019). The convergence of digitalization-driven technologies and innovative business models, as proposed by Arponen et al., (2018), creates significant opportunities for industries to enhance sustainability by focusing on value creation, value capture, and CE principles (Lanzafame, 2015). Additionally, the incorporation of digital tools such as AI, IoT, and Blockchain offers opportunities to improve transparency and tracking throughout a product's existence (Stankovic et al., 2017). In a digitally linked landscape, manufacturers can oversee, manage, assess, and enhance product performance through intelligent, interlinked products, gathering valuable insights into material, component, and product utilization (Porter and Heppelmann, 2014). Skillful utilization of these technologies can enhance the efficiency of reverse logistics, stimulate the reutilization of materials and products, and accelerate the worldwide acceptance of CE principles through eco-friendly recycling techniques that preserve finite resources (MacArthur, 2014). Within the CE framework, AI plays a pivotal role in automatically and remotely monitoring manufacturing processes' efficiency and product lifecycles, efficiently handling the vast volumes of data generated during manufacturing, product usage, and disposal (Ramadoss et al. 2018). Recognized by the Ellen MacArthur Foundation (2019), AI's ability to tackle complexity and improve data awareness makes it a valuable complement to human capabilities, enabling more effective learning from feedback loops. Artificial intelligence is a blend of mathematical reasoning and error-reduction capabilities (Noman et al., 2022). AI, wherein computers emulate human intelligence, constitutes an evolving paradigm with far-reaching implications for governments, the scientific community, and established political and economic strategies, and recent advancements in artificial intelligence, encompassing areas like deep learning, image recognition, machine learning, and natural language processing, suggest an enduring impact on daily lives (Sharma et al., 2021). McCarthy et al. (2006) define AI as the field that encompasses the development of intelligent machines, specifically intelligent computer programs,. AI involves machines simulating human intelligence, allowing them to think and act similarly to humans (Simmons and Chappell, 1988). The progress in AI significantly enhances an organization's capabilities and alters the expectations (Pluta and Rudawska, 2016). Furthermore, it's projected that AI could contribute a staggering $13 trillion to the global economy by 2030 (Bughin et al., 2018). (Ronaghi, M. H. (2022). AI's capacity to unlock value from waste within a CE is projected to reach approximately $127 billion annually by the year 2030 (Akinode and Oloruntoba, 2020) it's also predicted that its contribution to the global economy by 2030 could surpass the current combined production of China and India (Rao and Verweij, 2017).

AI plays a multifaceted role in supporting circular manufacturing strategies, enhancing energy efficiency, and prolonging product and component lifespan by maximizing resource utilization (Cioffi et al., 2020). AI aids decision-making for both goods and processes, facilitating the acceleration of CE values through real-time tracking and monitoring of product residual value (Mboli et al., 2022). Additionally, AI addresses transformation challenges by securely incorporating information into operational aspects and employing agile methods to enhance system adaptability (Wang, 2011). Furthermore, AI can promote the creation of visual tools that offer comprehensible insights into data flows related to products, resources, and processes, aiding in the exploration of the still not fully understood benefits of a CE (Bianchini et al., 2019). AI's ability to address intricate challenges and efficiently process extensive data has a profound impact on enabling the CE and fostering innovation. These contributions to CE can be summarized through three essential approaches: (Zota et al., 2023).

1. Circular Evolution: AI facilitates the transformation from product and module-centric focus to a more comprehensive consideration of materials and components. This transformation is driven by iterative learning processes conducted by machines.
2. Enhancing Circular Infrastructure: AI plays a critical role in optimizing the infrastructure essential for the efficient circulation and reuse of materials within the CE system.
3. Proactive Management and Maintenance: AI empowers businesses to adopt proactive approaches in managing circular models, leading to improved efficiency and sustainability.

The study of Akinode and Oloruntoba (2020) identifies three critical domains within the CE where AI can make a substantial impact:

1. Designing Circular Products: AI has the potential to accelerate the development of circular products, components, and materials by utilizing design processes driven by machine learning, thereby facilitating swift prototyping and testing.
2. Enhancing Circular Business Models: AI elevates the efficacy of circular economy business models, such as product-as-a-service and leasing, through its utilization of both real-time and historical data. AI optimizes various aspects, including product circulation, asset

utilization, pricing strategies, demand forecasting, predictive maintenance, and inventory management.

3. Optimizing Circular Infrastructure: AI plays a vital role in enhancing reverse logistics infrastructure, streamlining processes to promote a closed-loop system.

AI is instrumental in driving innovation within the CE in several key ways. Firstly, it enhances CE by optimizing logistics, reverse logistics, and remanufacturing processes, enabling recycling considerations at the design phase and facilitating product disassembly and sorting. Secondly, AI leverages various data sources, both historical and real-time, to improve product circulation, asset utilization, inventory management, predictive maintenance, and pricing and demand predictions, thereby enhancing circular business models. Lastly, AI supports the creation of more circular products by aiding in rapid prototyping, computer-aided design, and component selection, contributing to sustainable material choices and circular product design (Ellen MacArthur Foundation, 2019; Ghoreishi and Happonen, 2020).

In the transition to a CE, AI can be used in different scales and strategies. Acerbi et al. (2021) categorized the usability of AIinto three different scales (micro, meso, macro) based on different areas of use. The relevant taxonomy is shown in Figure 1.

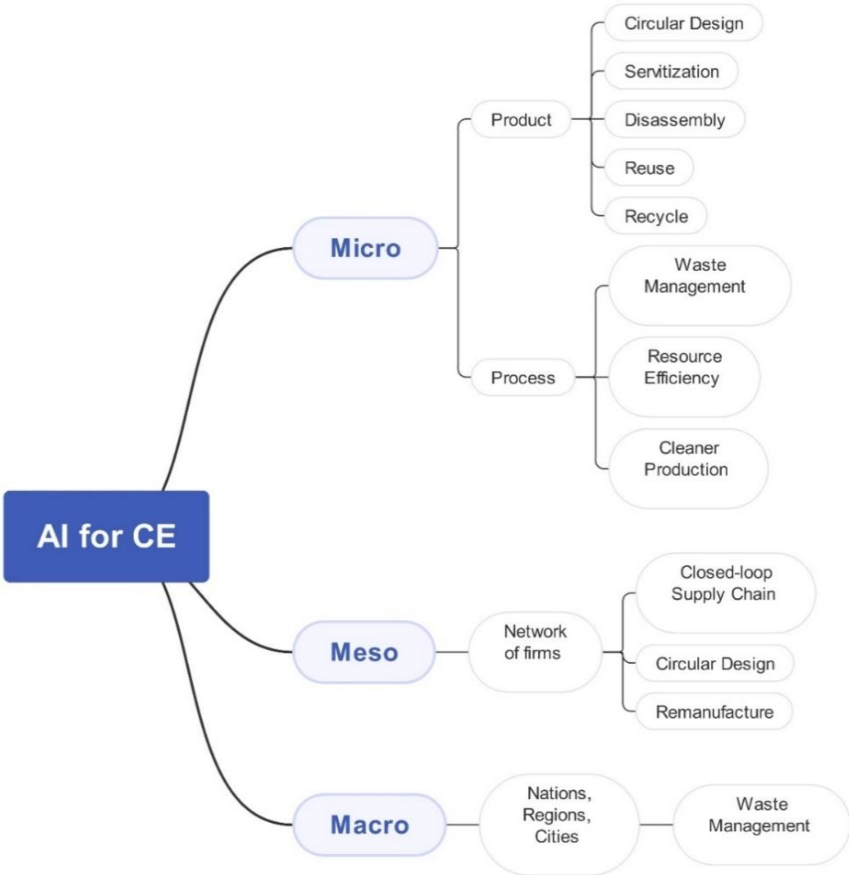
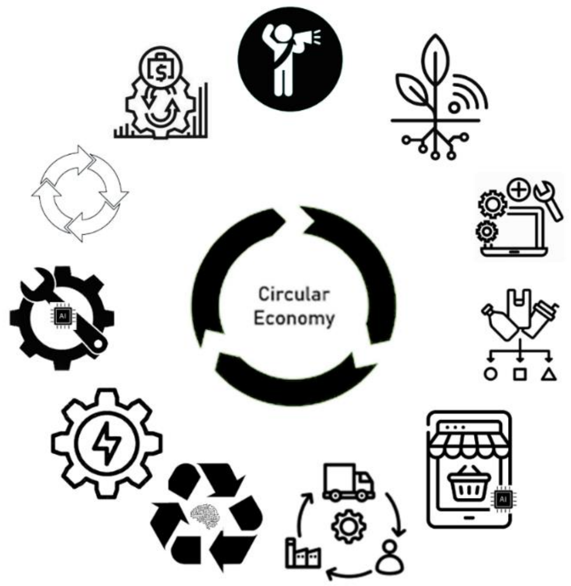
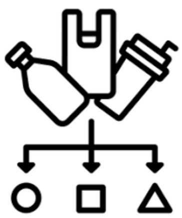


Figure 1. Using AI in different dimensions of CE

Source: Author

The existence, volume, and validity of potential circularity relationships can be analyzed and visualized through the use of AI to review the dynamically structured movements in a given region. The CE is a complex system that involves various interventions, and AI can offer various solutions in this regard. Here are some potential fundamental solutions for how AI can contribute to achieving a CE:



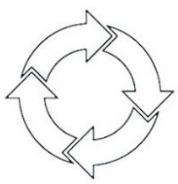


Smart Waste Management (AI - powered waste sorting systems)

AI plays a crucial role in various aspects of waste management, addressing challenges such as managing solid waste accumulation, predicting waste generation, monitoring trash containers, conducting compositional analysis, and enabling intelligent sorting (Ortega-Fernandez et al., 2020; Yigitcanlar and Cugurullo, 2020).

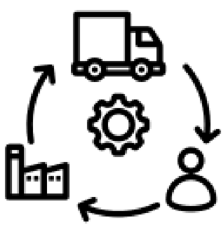
Automated Product Design and Optimization Tools

AI in CE streamlines monitoring and boosts manufacturing efficiency. It provides advanced learning and faster decision-making, aiding precise material reuse decisions. This enhances circular product design by reducing resource consumption and increasing material productivity. AI integration spans the product lifecycle, encompassing areas like design, operation, and management. It not only enhances manufacturing but also transforms companies into knowledge-based players in product markets (Blunck and Werthmann, 2017; Bressanelli et al., 2018; Kortelainen et al., 2019). These tools use AI to create sustainable and circular products that can be easily repaired, repurposed, or recycled. AI can help in designing products that are durable, modular, and can be easily disassembled.



Product Lifecycle Management

AI revolutionizes design by aligning customer preferences with product features, optimizing manufacturing processes, and elevating customer service to foster smarter, sustainable product-service ecosystems (Wang et al., 2021). The use of AI can assist businesses in tracking the lifecycle of their products, from raw materials to disposal, to ensure their effective reuse, recycling, or repurposing. This practice can minimize waste and decrease the environmental impact of the production process.



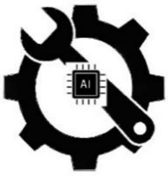
Circular Supply Chain

CE plays a pivotal role in sustainable supply chain management, focusing on material reuse, recycling, and remanufacturing to improve product utilization and manufacturing efficiency, while also dividing the life cycle of products and services within supply chains into five key stages: design and development, production, delivery, operation, and end-of-life (Liu et al., 2023). AI can assist businesses in creating a circular supply chain by optimizing logistics and transportation, reducing waste, and ensuring that products are effectively recycled or repurposed at the end of their useful life. AI can help predict demand, optimize inventory, and lower transportation and logistics costs, thereby reducing the environmental impact of businesses and improving their reputation.

Smart Energy Management Systems

AI can optimize energy consumption and waste reduction in buildings and communities through SEMs. AI has the potential to improve the effectiveness of the renewable energy sector by autonomously identifying and forecasting patterns, performing tasks without the need for explicit human direction, optimizing supply chain operations, and enhancing decision-making processes (Şerban and Lytras, 2020). AI algorithms can offer insights and recommendations to improve the energy efficiency of buildings and communities. Predictive analytics can be utilized to forecast energy demand and adjust energy distribution to balance the load. Energy usage data analysis can identify inefficiencies and optimize for greater energy efficiency. AI can detect and diagnose faults and malfunctions in the system and take corrective actions. Additionally, AI can be harnessed for the integration of renewable energy sources by forecasting the energy output from these sources and ensuring a balanced match between the generated energy and the energy demand.

AI-Driven Predictive Maintenance Systems



Human-centric approaches have gained significance in predictive maintenance, thanks to the integration of digital tools. This is particularly crucial as the workforce increasingly engages with emerging technologies like AI for monitoring equipment conditions in maintenance services (Chen et al., 2021). Predictive Maintenance is a technique that predicts when equipment or machinery is likely to fail, so that maintenance can be scheduled before the failure occurs (Achouch et al., 2022). By using AI algorithms and machine learning models, predictive maintenance systems can provide more accurate and reliable predictions. AI can enhance these systems by providing real-time insights, accurate predictions, and root cause analysis. Predicting maintenance needs in advance and optimizing maintenance schedules can minimize downtime and reduce maintenance costs, thereby improving the efficiency and reliability of the system.

AI-powered Marketplaces

The rise of platforms and the integration of AI tools into value chains are positioning companies that adopt AI-powered platforms for a competitive advantage. The fast-expanding B2B marketplaces, coupled with changing asset dynamics, emphasize the significance of this trend (Cerruti and Valeri, 2022). These marketplaces facilitate the exchange of materials and reduce waste by matching waste producers with waste consumers. AI can;

- help optimize product design for circularity.
- assist in identifying the best match for waste producers and consumers, optimizing the logistics of waste transportation, and reducing landfill waste.
- identify more recyclable materials or design products with modular components that can be easily disassembled and recycled.
- identify opportunities to reuse and recycle materials, reducing waste and minimizing the need for new resources.
- provide personalized recommendations on circular products and services, incentivizing customers to participate in circular marketplaces.
- create digital marketplaces for circular products and services, making it easier for businesses and consumers to access and purchase circular products.
- develop new financial models that incentivize CE practices.
- facilitate collaborative consumption, enabling businesses and consumers to share resources and reduce waste.

Intelligent Recycling Systems

AI-driven waste management technology and robotic solutions are transforming waste recovery and recycling processes. This includes scalable waste-processing plants integrating vision-assisted robotics with cloud-based AI systems, AI-guided robotic solutions with advanced vision systems for waste identification, municipal AI-powered waste-sorting stations, AI-supported MRFs (materials recovery facilities) employing sorting robots and optical sorters, robotic arms with grippers for recyclable sorting, and real-time retail waste brand-level logo detection and recognition through AI computer vision to bolster extended producer responsibility efforts (Hayes, 2021). AI can help identify the type of material, its composition, and the best way to recycle it. By using sensors and cameras to identify different materials, AI algorithms can sort waste streams in real-time, reducing the need for manual sorting. Analyzing data on the chemical and physical properties of different waste streams, AI algorithms can optimize processing conditions, improving the efficiency and quality of the recycling process. Additionally, AI algorithms can identify defects and impurities in the properties and composition of recycled materials, ensuring that recycled materials meet industry standards. AI can also identify potential issues and take corrective actions, reducing downtime and maintenance costs.

AI-powered Circular Business Models

CE business models offer pathways to achieve sustainable development goals by optimizing resource utilization through actions like closing loops, reducing consumption rates, enhancing resource efficiency, and minimizing material use. Successfully embracing the CE necessitates a strategic shift in how companies generate and extract value, resulting in the creation of a novel value-generation system and the emergence of inventive business models (Ghoreishi et al., 2023). AI plays a pivotal role in establishing sustainable infrastructural elements to support the foundation of circular businesses. It can contribute to the creation of innovative circular business models, such as AI-based dynamic pricing, and aid in the development and optimization of recycling infrastructure, which is essential for a thriving CE (Roberts et al., 2022). These models use data and analytics to identify new opportunities for circular business models (e.g. product-as-a-service, sharing economy). AI can play a crucial role in supporting circular business models by providing insights into customer behavior, optimizing resource use, facilitating closed-loop systems, designing sustainable products, and optimizing supply chains. AI can help in analyzing data from various sources, identifying trends, and predicting future demand. AI can be used to analyze customer behavior and preferences, providing insights that can be used to develop circular business models. By analyzing data on purchasing patterns, product usage, and customer feedback, AI can help identify opportunities for;

- circular product design, product-service systems, and closed-loop systems, to reuse, recycle, and reduce resource use,
- for reducing waste and minimizing the need for new resources, for closed-loop systems, and improve logistics.
- to design products that are more sustainable, recyclable, and repairable

Smart Agriculture Systems

Smart agriculture relies on diverse sensors to monitor environmental, crop, and soil conditions, with the data collected serving as the foundation for making decisions to enhance crop production. These sensors generate vast datasets, which can be effectively processed and analyzed using AI (Sabrina et al., 2022; Widianto et al., 2022). AI can help in predicting weather patterns, optimizing irrigation, and reducing pesticide and fertilizer use. AI can optimize crop production by providing real-time insights into crop health and growth. By analyzing data from sensors, drones, and satellite imagery, AI algorithms can:

- identify areas of the field that require irrigation, fertilization, or pest control, reducing resource use and improving crop yields.
- detect early signs of disease or pest infestation, allowing farmers to take preventive actions and reduce crop losses.

- provide accurate forecasts of rainfall, temperature, and other weather variables, allowing farmers to optimize planting and harvesting schedules.
- provide customized recommendations to farmers, improving their decision-making and optimizing crop production.

AI-driven Circular Education And Awareness Campaigns

Achieving a transition toward a CE requires contributions from a diverse range of stakeholder groups. To integrate a CE into society and the global economy, it's essential to make complex and dynamic changes in both technical and behavioral aspects. Environmental awareness should be a fundamental part of education at all levels, and CE education can be incorporated into various educational levels (Tiippana-Usvasalo et al., 2023). The importance of education in guiding societies towards sustainable development was first emphasized during the inaugural Earth Summit in Rio de Janeiro in 1992 (Kirchherr and Piscicelli, 2019). AI can play a vital role in engaging socities and educating them about CE principles. By analyzing customer behavior and preferences, AI can provide personalized recommendations on circular products and services, which can incentivize customers to participate in circular marketplaces. Additionally, AI can help identify the most effective channels for communication, analyze engagement data, and optimize campaigns for maximum impact.

The use of AI in the transition to a CE requires a systematisation. This systematic approach, which is mainly based on the identification of possible exchange relationships between production/consumption units in a given region, is shown in the figure below.

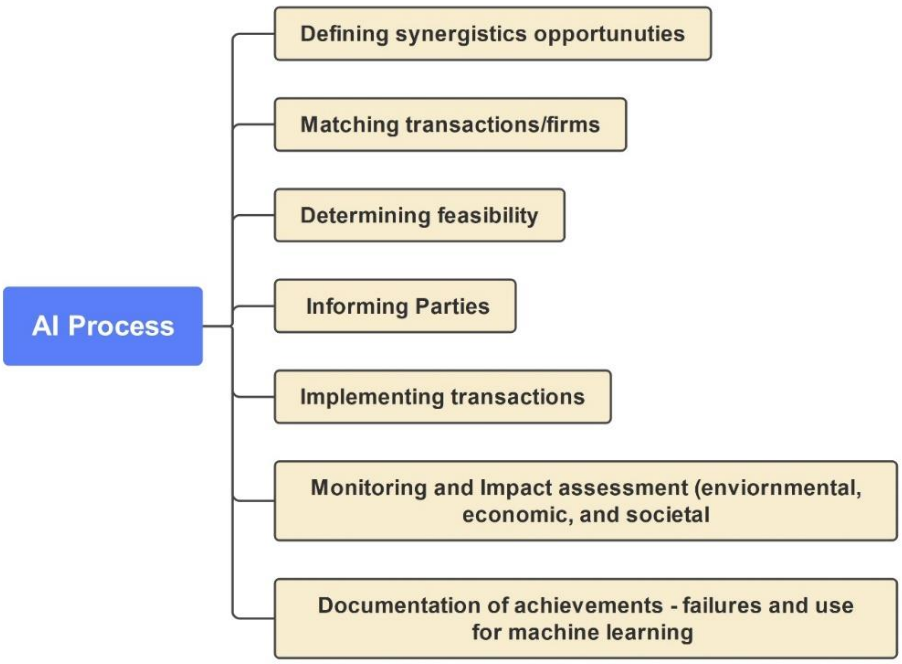


Figure 2. AI process for CE

Source: Author

To achieve regional CE, several types of input and output information are needed as shown in Table 1.

Table 1. Information types needed by AI

Input information	
Resource availability/ demand	includes information on the types, quantities, and locations of resources, such as waste materials, renewable energy sources, and other inputs needed for CE activities. can help businesses and organizations identify opportunities for resource recovery, reuse, and recycling, and develop circular business models.
Product/ service demand	includes information on the types and quantities of products and services that are in demand in the region. can help businesses and organizations develop circular products and services that meet customer needs while reducing waste and resource use.
Infrastructure and logistics	includes information on the used resources, energy, transportation and logistics infrastructure (roads, railroads, ports, waste management and recycling facilities). can help businesses and organizations identify opportunities for collaboration and resource sharing, energy sharing and develop more efficient and sustainable logistics systems.
Output information	
Produced goods	includes information on the types, quantities, and locations of final products and by-products generated after process. can help businesses and organizations identify opportunities to define possible barter relations.
Waste and emissions	includes information on the types, quantities, and locations of waste and emissions generated by businesses and organizations in the region. can help businesses and organizations identify opportunities to reduce waste and emissions, and develop circular strategies for managing waste and emissions.
CE performance	includes information on the economic, social, and environmental performance of CE initiatives in the region, such as the amount of waste diverted from landfill, the reduction in resource use and emissions, and the creation of new jobs and economic opportunities. can help businesses and organizations track their progress and identify areas for improvement

Source: Author

There is a direct relationship between the volume of big data and the number of identifiable relationships that can be established. Therefore, it is crucial to have data sets that accurately describe the input-output processes of production and consumption units per unit area. Expanding the database with relevant data sets can maximize synergy by revealing a significant number of possible exchange relationships, including resources, energy, infrastructure, common logistics, and the advantages of joint action. Below is an example of a database architecture that includes the identity of the actor and the details of the inputs and outputs.

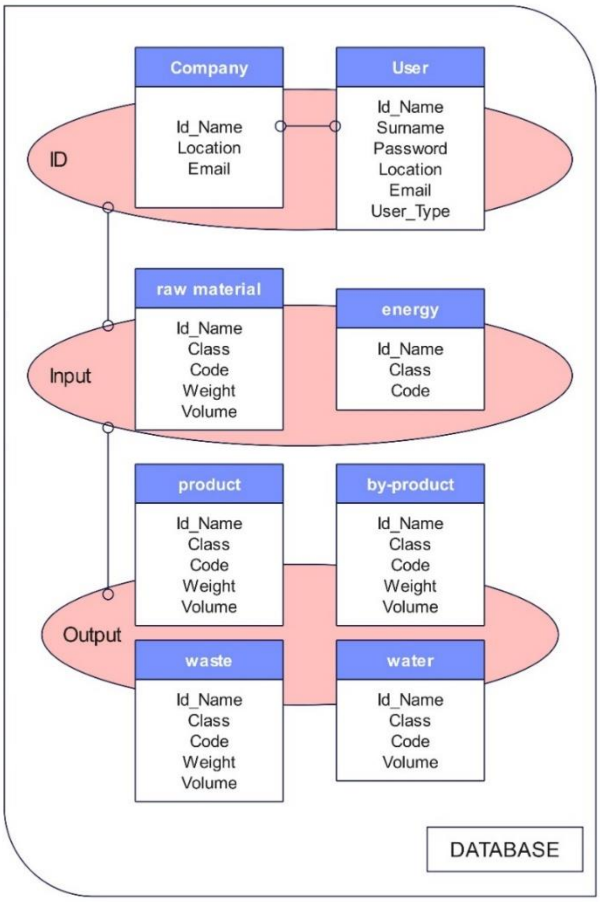


Figure 3. Database architecture to detect relational probabilities

Source: Author

After the creation of the database, the stage of managing AIcan now begin. AI possesses potential tools to support the implementation of CE practices and strategies at the regional level in several ways, with different target-specific approaches that can be employed. The main possible approaches are outlined below.

Predictive analytics: AI can analyze data from various sources, such as supply chain data and waste management systems, to identify patterns and trends in resource flows and waste generation. This information can be used to develop predictive models that help anticipate future resource needs and waste generation, thereby optimizing resource management and reducing waste. By using AI to achieve predictive analytics, regions can identify potential resource shortages and waste generation hotspots, allowing them to take proactive measures to address these issues.

Resource mapping: AI can be employed to identify and map the availability of resources, such as raw materials, energy, and water, within a region. Real-time monitoring of resource flows and waste generation by AI can provide insights that can aid stakeholders in making informed decisions. This information can help identify potential sources of input materials and waste streams that can be used as inputs for CE processes. AI can accomplish resource mapping by analyzing data from various sources, such as geospatial data, satellite imagery, and geological surveys. Some ways in which AI can support resource mapping include data integration, machine learning, predictive analytics, visualization, and optimization. AI can:

• Integrate data from multiple sources, such as geological surveys, land use data, and satellite imagery, to create a comprehensive map of resource availability in a region.

• Applying algorithms of machine learning to examine information and detect regularities and tendencies in the accessibility of resources. (e.g., analyzing data on soil composition and topography to identify areas with high potential for agricultural production).

• Use predictive analytics to forecast resource availability based on historical data and trends (e.g., analyzing weather patterns and water consumption data to forecast water availability for agricultural use).

• Use visualization tools, such as interactive maps and dashboards, to present resource availability data in an easily understandable format (e.g., aiding stakeholders in informed decisions about resource management and utilization).

• Optimize resource use by analyzing data on resource availability and demand, and identifying opportunities for resource efficiency (e.g., analyzing data on energy consumption and suggesting energy-efficient processes and technologies aimed at decreasing energy usage and mitigating greenhouse gas emissions.).

By utilizing AI to achieve resource mapping, regions can identify and use resources more efficiently, reducing waste and promoting a more CE. However, it is essential to ensure that resource mapping is carried out in a responsible and ethical manner, with a focus on maximizing the social and environmental benefits of resource utilization.

Decision-making support: AI can support decision-making processes by providing real-time insights and recommendations on the most efficient and sustainable use of resources. For example, AI has the ability to scrutinize energy consumption data and propose energy-efficient procedures and technologies that can lower energy consumption and curb greenhouse gas emissions.

Circular product design: The analysis of product lifecycle data and the identification of opportunities for material substitution and product redesign can be facilitated by AI, which can contribute to the design of circular products. AI can enable designers to create products that are more sustainable, resource-efficient, and circular, through material selection, design optimization, end-of-life management, performance monitoring, and collaboration. By using AI to achieve circular product design, designers can create products that help reduce waste, conserve resources, and promote a more CE. However, it is important to ensure that circular product design is done in a responsible and ethical way, with a focus on maximizing the social and environmental benefits of product design.

Supply chain optimization: AI can help optimize supply chains by analyzing data on logistics, transportation, and production processes. By optimizing supply chains, companies can reduce waste, minimize transportation emissions, and improve resource efficiency. AI can enable businesses to optimize their supply chain operations, reduce waste, and improve efficiency. Here are some ways in which AI can support supply chain optimization: demand forecasting, inventory management, route optimization, and supplier management.

Overall, AI has the potential to support the implementation of CE practices and strategies at the regional level by providing insights and recommendations that optimize resource management, reduce waste, and improve sustainability. However, it is important to ensure that AI is used in a responsible and ethical way, with a focus on maximizing the social and environmental benefits of CE initiatives.

4. Barriers to the use of AI in the transition to a CE

Despite the potential benefits of using AI in CE, there are several obstacles that need to be addressed. Multiple studies (Antikainen et al., 2018; Ingemarsdotter et al., 2019; Kazancoglu et al., 2021; Rosecký et al., 2021; Ranta et al., 2021; Sineviciene et al., 2021; Umeda et al., 2020; Xiong, 2020; Zhang et al., 2019) have identified barriers to implementing digitalization technologies, including policy-specific challenges and international platforms requiring local government attention. Firms encounter obstacles when adopting CE and digitalization business models, such as data management issues and high adoption costs. Regulatory gaps, limited environmental education, lack of conservation culture, and low market demand pressure pose further challenges to CE-driven digitalization. Technological and strategic barriers, as well as negative consequences of disruptive technologies, like predictability issues and data quality variations, hinder CE adoption. Governmental support is often lacking, compounded by insufficient data on material flows, hampering policy efforts to address environmental concerns (Pathan et al., 2023).

Here are some of the basic obstacles of using AI in CE:

Data quality/ Data volume/ Data privacy and security: To effectively use AI for CE, high-quality data is required. This includes data on resource flows, waste streams, product lifecycles, and other factors. However, such data may not always be available, or it may be difficult to obtain. Additionally, the data collected may not always be relevant or applicable to the specific context in which it is being used. To effectively implement AI technology in a CE, large amounts of data are needed. However, such data may not be readily available, especially in developing countries or in industries that are not yet fully digitized. Data privacy and security are also significant concerns when using AI for CE. The collection and processing of personal data may raise privacy concerns, and the use of AI may increase the risk of data breaches and cyber-attacks.

Bias and discrimination: AI algorithms can be biased if they are trained on incomplete or biased data. This can result in unfair outcomes, particularly for marginalized or vulnerable communities.

Lack of technical expertise: The development and implementation of AI applications require technical expertise, including data science, machine learning, and programming. There may be a shortage of people with these skills, making it difficult for some organizations to adopt AI technology.

Cost: The development and implementation of AI applications can be costly, particularly for smaller businesses and organizations with limited resources.

Ethical considerations: The use of AI in a CE raises ethical questions regarding privacy, data security, algorithmic bias, potential impact on employment, and the displacement of workers, as well as the impact on social and environmental justice. Addressing these concerns is crucial in building trust in AI technology and ensuring that its benefits are widely shared.

Dynamic structure of economies and societies: AI models may not always be able to account for external factors that can affect CE outcomes, such as changes in policy, market conditions, or consumer behavior. Additionally, AI models may not always capture the social and economic concerns related to the CE.

To overcome these limitations, it is essential to use AI in conjunction with other tools and approaches and to develop context-specific and tailored AI models that meet the needs and goals of specific communities and regions. Moreover, it is important to use AI in a responsible and transparent manner and incorporate social and ethical considerations into its development and implementation.

CONCLUSION

The circular economy (CE) is an emerging economic model that offers significant potential for reducing resource consumption and environmental impacts. While it faces several challenges, it also presents several opportunities for innovation and sustainability. As the CE continues to gain attention and momentum, further research and collaboration will be needed to fully realize its potential. AI plays a pivotal role in advancing the CE by offering various advantages through its algorithms. These benefits include real-time data analysis for supply chain management, cost and carbon footprint reduction for sustainable development, process automation for reverse logistics, waste impact assessment for waste management, and material sorting for recycling. AI also supports the transition from a linear economy to a CE by embracing recycling, reusing, and remanufacturing strategies. It enables autonomous monitoring of manufacturing efficiency and product lifecycles, leveraging data generated during manufacturing, usage, and disposal for process improvement. AI-driven circular design tools and methods further enhance product circularity. Researchers have explored these AI-driven strategies to facilitate the shift towards a CE model (Noman et al., 2022; Ramadoss et al., 2018). An AI-powered CE model has the potential to significantly improve resource efficiency, reduce waste and emissions, and create a more sustainable future. By leveraging AI in the design, production, and waste management processes, companies can achieve a CE that keeps resources in use for longer and minimizes environmental impacts. AI can be used to determine possible matching opportunities in a region to achieve CE by analyzing data on the availability and demand for resources, products, and services. Here are some ways in which AI can support matching opportunities for CE initiatives:

- Resource mapping: By analyzing data on the availability of resources, such as waste materials and renewable energy sources, and identify potential matches with businesses or organizations that could use these resources as inputs for their operations.
- Product and service matching: By analyzing data on the demand for products and services, and identify potential matches with businesses or organizations that could supply these products and services in a circular manner.
- Market analysis: By analyzing data on market trends, consumer preferences, and other factors, and identify potential matches between supply and demand in the CE.
- Collaboration and networking: By facilitating collaboration and networking between businesses and organizations that are interested in CE initiatives, helping to build partnerships and promote circularity in the region.

To achieve a regional CE, businesses and policymakers need to collect and analyze data on waste and resource usage, as well as the environmental impact of production and consumption. This can include data on material flows, energy usage, greenhouse gas emissions, and water consumption. By gaining a better understanding of these factors, businesses and policymakers can identify opportunities for circularity and develop strategies to optimize resource usage and reduce waste. Additionally, stakeholder engagement and collaboration are important for the success of CE initiatives, as they can help build support and create a shared vision for a sustainable future. AI can be used to help identify potential matching opportunities in a region to achieve CE by analyzing large datasets and identifying patterns that may not be immediately apparent to humans. For example, AI can analyze data on waste and resource usage, as well as production and consumption patterns, to identify potential synergies between different businesses and industries. This can include identifying opportunities for waste reduction, resource optimization, and product reuse or repurposing. AI can also help optimize logistics and transportation, reducing waste and ensuring that products are recycled or repurposed at the end of their useful life. By identifying these opportunities, businesses and policymakers can develop strategies to create a CE environment. However, it's important to note that AI should not be seen as a replacement for human decision-making and stakeholder engagement, but rather as a tool to complement and enhance these processes.

In addition, barriers to the use of AIin the transition to a CE need to be taken into account. One is the lack of data and information on waste and resource usage, which can limit the effectiveness of AI in identifying opportunities for circularity. Another challenge is the high cost of implementing AI technology, which may put it out of reach for smaller businesses or those operating in developing countries. Additionally, there may be concerns around data privacy and security, as well as the potential for AI to displace human jobs. These obstacles need to be carefully considered and addressed in order to maximize the potential of AI in CE.

Positioned as a prominent driver in the Fourth Industrial Revolution, AI offers a versatile toolkit that prompts a reevaluation of information integration, data analysis, and their subsequent application to enhance decision-making processes. AI's transformative potential is anchored in its capacity to complement human abilities, amplifying their skill set and extending their cognitive capabilities. This manifests through expedited learning from feedback mechanisms, enhanced management of intricate scenarios, and the deciphering of copious datasets, ultimately fortifying the endeavor to transition to a CE. However, it is important to ensure that the data collected and stored in relational databases are accurate, reliable, and secure, and that privacy and data protection regulations are respected.

AI stands as a pivotal facilitator in the journey towards realizing the fundamental tenets of the CE, chiefly the optimal utilization of resources at their highest utility. While there has been considerable discourse regarding the potential of AI in CE, there remains a lack of concrete understanding regarding its practical applications within the CE framework (Pathan et al., 2023). Exploring the practical implementation of AI across diverse sectors and levels as a catalyst for transitioning towards a CE warrants attention in future research endeavors.

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EXTENDED ABSTRACT

GENİŞLETİLMİŞ ÖZET

DÖNGÜSEL EKONOMİYE GEÇİŞİ KOLAYLAŞTIRMADA YAPAY ZEKANIN ROLÜ

Giriş ve Çalışmanın Amacı (Introduction and Research Purpose): Potansiyel döngüsellik ilişkilerinin varlığı, hacmi ve geçerliliği, belirli bir bölgedeki dinamik olarak yapılandırılmış hareketleri incelemek için yapay zekâ kullanılarak analiz edilebilir ve görselleştirilebilir. Döngüsel ekonomi, çeşitli müdahaleleri içeren karmaşık bir sistemdir ve yapay zekâ bu konuda çeşitli çözümler sunabilir. Yapay zekanın CE'ye ulaşmaya nasıl katkıda bulunabileceğine ilişkin bazı potansiyel temel çözümlerinin ve olası engellerin tanımlanması literatürün gelişimi açısından değerlidir.

Kavramsal/kuramsal çerçeve (Literature Review): Döngüsel ekonomi, endüstriyel ekoloji, beşikten beşiğe tasarım ve sistem düşüncesi gibi çeşitli teorik çerçevelerden yararlanan çok yönlü bir kavramdır. Bu yaklaşım, farklı sistemler ve süreçler arasındaki karşılıklı bağlantıları vurgulayarak, üretim ve tüketimin ekonomik ve çevresel etkilerinin daha bütüncül bir şekilde anlaşılmasını sağlamayı amaçlamaktadır. Endüstriyel ekoloji, kapalı döngü malzeme döngüleri yaratarak kaynak kullanımını ve çevresel etkileri azaltmayı amaçlarken, sistem düşüncesi daha esnek ve uyarlanabilir ekonomik, sosyal ve çevresel sistemler kurmaya çalışır. Beşikten beşiğe tasarım, yaşam döngülerinin sonunda kolayca demonte edilebilen, geri dönüştürülebilen veya yeniden kullanılabilen ürünler tasarlamanın önemini vurgular. Döngüsel bir ekonominin yeni iş modelleri, ürün tasarımı ve teknolojisindeki yenilikler ve yeni iş ve endüstrilerin yaratılması gibi potansiyel faydalar sunmasına ragmen bunun nasıl gerçekleştirilebileceği henüz net değildir. Yapay zekanın CE'ye geçişte kullanılması bir sistematizasyon gerektirir. Temel olarak belirli bir bölgedeki üretim/tüketim birimleri arasındaki olası mübadele ilişkilerinin belirlenmesinde yapay zekâ başarı ile kullanılabilir. Büyük veri ile olası değişim ilişkilerinin tanımlanması mümkündür. Bu nedenle birim alana düşen üretim ve tüketim birimlerinin girdi-çıktı süreçlerini doğru bir şekilde tanımlayan veri setlerine sahip olunması çok önemlidir. Veri tabanını ilgili veri kümeleriyle genişletmek, kaynaklar, enerji, altyapı, ortak lojistik ve ortak eylemin avantajları dahil olmak üzere önemli sayıda olası değişim ilişkisini ortaya çıkararak sinerjiyi en üst düzeye çıkarabilir.

Yöntem ve Bulgular (Methodology and Findings): Bu çalışmada yapay zekanın döngüsel ekonomi faaliyetlerini daha verimli hale getirmede bir araç olarak nasıl kullanılabileceği, sınırlılıklar ve potansiyel geliştirici unsurlar ile birlikte bir model olarak ifade edilmeye çalışılmıştır. Döngüsel ekonominin göreceli yeni bir akademik araştırma alanı oluşu ve yapay zekâ uygulamalarının giderek artan kullanım alanı ve etkinliği bu iki başlığın bir arada olacağı akademik araştırmaları özgün ve nitelikli hale getirebilir. Bu sebeple bu araştırmada mevcut yapay zekâ uygulamaları ile döngüsel ekonomide olası iyileştirmelerin nasıl geliştirilebileceğine odaklanılmıştır. Büyük veriden istifade edecek bir ilişkisel veri tabanı yönetimi önerilmiştir. Araştırma ampirik nitelikte olmamasına rağmen sonraki ampirik çalışmalar için motive edici olabilir.

Sonuç ve Öneriler (Conclusions and Recommendation): Döngüsel ekonomi, kaynak tüketimini ve çevresel etkileri azaltmak için önemli bir potansiyel sunan, gelişmekte olan bir ekonomik modeldir. CE Çeşitli zorluklarla karşı karşıya olsa da yenilik ve sürdürülebilirlik için eşsiz fırsatlar sunmaktadır. Yapay zekâ destekli bir CE modeli, kaynak verimliliğini önemli ölçüde artırma, atıkları ve emisyonları azaltma ve daha sürdürülebilir bir gelecek yaratma potansiyeline sahiptir. Tasarım, üretim ve atık yönetimi süreçlerinde yapay zekadan yararlanan şirketler, kaynakları daha uzun süre kullanımda tutan ve çevresel etkileri en aza indiren bir CE'ye ulaşabilir. Yapay zekâ CE girişimlerinde potansiyel değişim ilişkilerini tanımlayabilmek üzere; kaynak haritalama, ürün ve hizmet eşleştirme, pazar analizi, iş birliği ve ağ oluşturma yaklaşımlarını kullanabilir. Bölgesel bir CE'ye ulaşmak için işletmelerin ve politika yapıcıların atık ve kaynak kullanımı ile üretim ve tüketimin çevresel etkisi hakkında veri toplaması ve analiz etmesi gerekir. İşletmeler ve politika yapıcılar, bu faktörleri daha iyi anlayarak döngüsellik fırsatlarını belirleyebilir ve kaynak kullanımını optimize etmek ve israfı azaltmak için stratejiler geliştirebilir. Ek olarak, paydaş katılımı ve iş birliği, sürdürülebilir bir gelecek için destek oluşturmaya ve ortak bir vizyon oluşturmaya yardımcı olabileceğinden, CE girişimlerinin başarısı için önemlidir. AI, büyük veri kümelerini analiz ederek ve insanlar tarafından hemen fark edilemeyebilecek kalıpları belirleyerek CE'ye ulaşmak için bir bölgedeki potansiyel eşleştirme fırsatlarını belirlemeye yardımcı olmak için kıymetli bir araçtır. Örneğin yapay zekâ, farklı işletmeler ve endüstriler arasındaki potansiyel sinerjileri belirlemek için atık ve kaynak kullanımı ile üretim ve tüketim modellerine ilişkin verileri analiz edebilir. Bu, atık azaltma, kaynak optimizasyonu ve ürünün yeniden kullanımı veya amacına uygun hale getirilmesi için fırsatların belirlenmesini içerebilir. AI ayrıca lojistik ve nakliyeyi optimize etmeye, atıkları azaltmaya ve ürünlerin kullanım ömürlerinin sonunda geri dönüştürülmesini veya yeniden tasarlanmasını sağlamaya yardımcı olabilir. İşletmeler ve politika yapıcılar, bu fırsatları belirleyerek bir CE ortamı oluşturmak için stratejiler geliştirebilir.

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Yazarların Listesi / *List of Authors*

Sıra No	**Adı-Soyadı** *Name - Surname*	**Katkı Oranı** *Author Contributions*	**Çıkar Çatışması** *Conflicts of Interest*	**Destek ve Teşekkür (Varsa)** *Support and Acknowledgment*
1	Tufan ÖZSOY	%100	Yoktur	-