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Research Article

CAN ARTIFICIAL INTELLIGENCE ACCELERATE THE TRANSITION TO A CIRCULAR ECONOMY?

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ABSTRACT

The world's current model of economic development is unsustainable. It promotes the inappropriate use of limited natural resources, encourages consumption and waste, causing serious damage to the environment and generating large amounts of waste. The circular economy, an economic model in which resources are recycled and reused as much as possible by following a circular path rather than a linear path during consumption, has been gaining popularity around the world in recent years. Artificial intelligence (AI), one of the most important developments of our time, can also play an important role in the realisation of the circular economy. AI can complement and extend the skills of humans. It helps people learn faster, deal with complexities more effectively, and better understand the abundance of data. AI can facilitate new circular business models within the circular economy and help design sustainable and robust products. The aim of this study is to seek answers to questions such as how artificial intelligence contributes to the transition to a circular economy and whether artificial intelligence can accelerate the transition to a circular economy. While seeking answers to these questions, we argue that artificial intelligence has significant potential in the transition to a circular economy and will play an important role in this transition.

Keywords: Sustainability, Circular economy, Artificial intelligence.

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INTRODUCTION

The concepts of digitalisation in the economy, Industry 4.0 and Society 5.0, Web 3.0, and the circular economy are concepts that have been developed in recent years and are closely related to each other. Technological developments are the main factor in the development of these concepts and allow them to be evaluated and considered together in terms of their mutual functioning and interaction.

Digital technologies, which entered our lives with Industry 4.0, continue to increase their usage areas as an important tool in terms of efficiency as well as making life easier. Technologies such as IoT (Internet of Things) and big data analytics, which are used especially in production processes, show how important artificial intelligence is for our future. These technologies, which have many important features from understanding consumer behaviour to efficient use of resources, from artificial intelligence algorithms that learn from mistakes and reduce the rate of making mistakes to cost reduction, have become an important part of our lives whether we like it or not.

Society 5.0 can be defined as a human-centered approach to society that balances the solution of social problems with economic development through a system that integrates cyberspace and physical space. In the context of Society 5.0, big data analysis, artificial intelligence applications, cyber security, the internet of things, robotic solutions, web 3.0, virtual reality and augmented reality bring radical changes in economic and social life.

The circular economy aims to model a system for economic life similar to the functioning of the biological system in nature. It is based on the intelligent design of materials, products, and systems in nature. Concepts such as lifespan and economic life have been replaced by concepts of repair, improvement, waste prevention, and reproduction. Therefore, the concept of recycling needs to be considered from the outset in the design, production, and use of business models, raw materials, intermediate goods, techniques, tools, and products. Environmental sustainability is a key concept in the circular economy. The European Union monitors circular economy performance in three areas: sustainable resource management (reducing resource demand, increasing resource security, reducing pressure on the domestic and international environment); societal behaviour (citizens' awareness and engagement in the circular economy); and business operation (eco-innovation activities in line with circular economy principles).

Industry 4.0, the circular economy, Society 5.0, and digital transformation are overlapping concepts. The synergy that emerges from the interaction of these concepts enables the development of smart systems and rapid solutions in all dimensions of social life. Technological development is today's great equaliser. The fact that the development of countries depends on the quality of human resources rather than natural resources, geographical location, and historical background has never been more evident in human history.

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The concept of the circular economy, where resources are kept in use for as long as possible and waste is minimised, is gaining more and more attention in the business world. Have you ever thought about how artificial intelligence contributes to the transition to a circular economy? How can artificial intelligence be used in applications to prevent waste generation, which is among the basic principles of the circular economy, to ensure maximum value production by keeping resources in the cycle and to increase biodiversity? This paper seeks answers to these questions. Accordingly, this paper first outlines the general framework of the concepts of the circular economy and artificial intelligence. Then, it explains how AI contributes to the circular economy and how it can accelerate the circular economy process. With the help of technology, especially artificial intelligence, businesses and other institutions can optimise resource use, reduce waste and emissions, and increase the efficiency of resource recovery and recycling processes.

CIRCULAR ECONOMY

In order to better understand the concept of the circular economy, it would be useful to first examine the non-circular, in other words, linear economy model. In the linear economy model, new (unprocessed) raw materials are procured to obtain any product, transformed into a product through various processes, the product is offered to the consumer, and waste is generated after consumption (Onder, 2018). Legal regulations such as restrictions on carbon emissions or bans on plastic products, interruptions in access to various raw material sources, and the increasing social and environmental sensitivity of consumers (OECD, 2019) pose significant risks for the business world in maintaining the linear production and consumption model described above. For example, a business that manufactures single-use plastic products will not be able to sustain its business if the government imposes a restriction on the sale of these products.

There are various definitions of the circular economy concept by different researchers and institutions. According to Jurgilevich et al. (2016), the circular economy is the reuse, repair, renovation, and recovery of existing materials and products, and the utilisation of materials that were previously seen as waste as a resource. According to a broader definition by the Organisation for Economic Co-operation and Development (OECD, 2020), the circular economy aims to: i) increase the value of materials and products circulating in the economy; ii) reduce the consumption of virgin materials, harmful substances, and materials that generate significant waste, such as plastics, food, electrical and electronic equipment; iii) prevent waste generation; and iv) reduce harmful components in waste and products. The Ellen MacArthur Foundation defines the circular economy as "a restorative model that aims to maintain the availability and preserve the value of products, components and materials" (Ellen MacArthur Foundation, 2015). The EU Action Plan for the circular economy describes a transition "where the value of products, materials and resources in the economy is preserved for as long as possible and waste generation is minimised" (EC, 2015).

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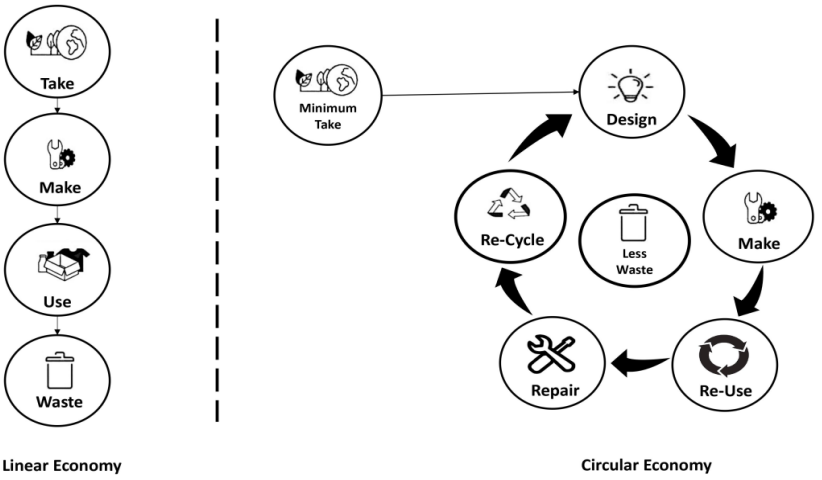
Figure 1. *Linear Economy and Circular Economy*



Source: Pathan et al., 2023

Table 1. *The Differences Between the Linear and Circular Economy*

Linear Economy	Circular Economy
The linear supply model is Buy-Build-At	The circular model is Reduce-Reuse-Recycle
The focus is to produce as much as possible quickly and at low cost	The focus is on reducing waste and maximizing the value of resources at every stage of production
Suppliers are selected based on the lowest cost and shortest lead time	Suppliers are selected based on sustainability criteria such as low waste generation, use of recycled materials and reduced carbon emissions
Products are usually disposable	Products are designed for long-term use, durability, recyclability, repairability
Transportation is designed for speed and low cost with no regard for the environment	Transportation is designed for sustainability and efficiency, with a focus on reducing carbon emissions and waste.
Consumers are responsible for waste management companies	Products and materials are repaired, reused or recycled
There is very limited communication between stakeholders at each stage in the supply chain	There are feedback loops along the supply chain with collaboration and data sharing between producers, consumers and suppliers
Waste is generated at every stage of the supply chain	Waste is minimized at every stage of the supply chain as the focus is on reuse and recycling of materials

Source: Pathan et al., 2023

The linear economic model, which dates back to the Industrial Revolution of 1760-1820, is largely framed around "consumption", where the product is "consumed" in use and then discarded; it is therefore analyzed within the framework of a "one-way production model" (Esposito et al., 2017). However, the circular economy represents a new paradigm in which waste is not completely eliminated through consumption, but rather recycled back into the production process. The circular economy represents a fundamental alternative to the currently dominant linear economic model.

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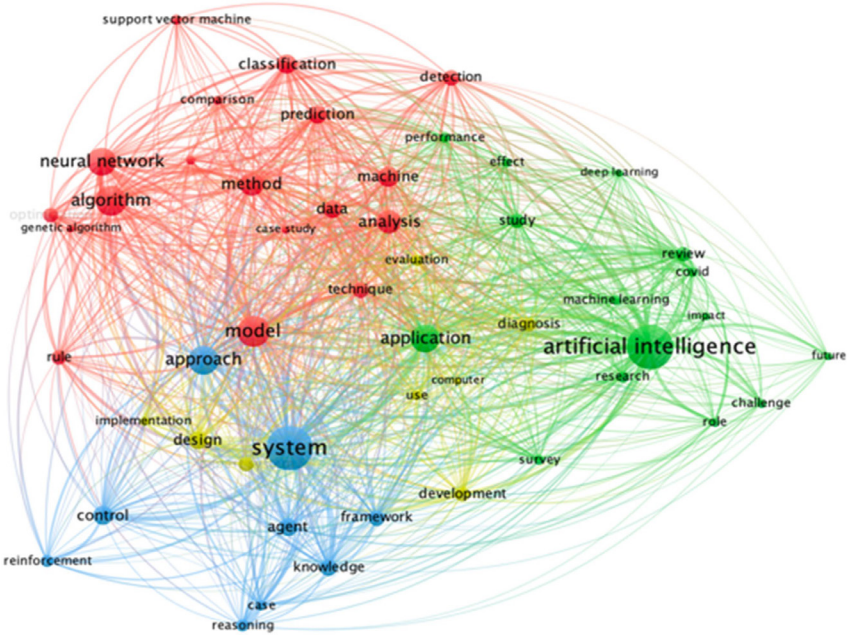
The circular economy model is defined as a model with a holistic process that enables the reuse of products and raw materials, where waste is recovered, energy and all resources are used efficiently, and clean production is carried out in a way that produces almost no waste. It is an important tool for sustainability. Based on the "cradle-to-cradle" approach, which involves an industry that operates without waste and without harming the environment, biomimetics, and industrial ecology, where the structure and function of natural systems inform industrial processes, the circular economy aims to maximise the added value of products and services in the economic value chain, minimise residual waste, and keep resources in the economy longer (Murray et al., 2017).

ARTIFICIAL INTELLIGENCE

Artificial intelligence is a technology that allows machines and computers to imitate the human brain, intelligence, and problem-solving abilities. AI, on its own or through sensors, geolocation, etc., can perform tasks that require human intelligence or intervention with other technologies. GPS guidance, digital assistants, and generative AI tools (like OpenAI's ChatGPT) are just a few examples of AI in our daily lives. Artificial intelligence is a branch of computer science that includes machine learning and deep learning (IBM, 2024). Artificial intelligence, considered a basic skill for the future, is used almost everywhere and in every field. During the 2018-2025 period, the AI market is predicted to reach 190 billion dollars by 2025, with a compound annual growth rate of over 36% (Jiang et al., 2022).

Artificial Intelligence appears as an interdisciplinary branch of science with var-

Figure 2. *Semantic Network of Artificial Intelligence*



Source: Jiang et al., 2022

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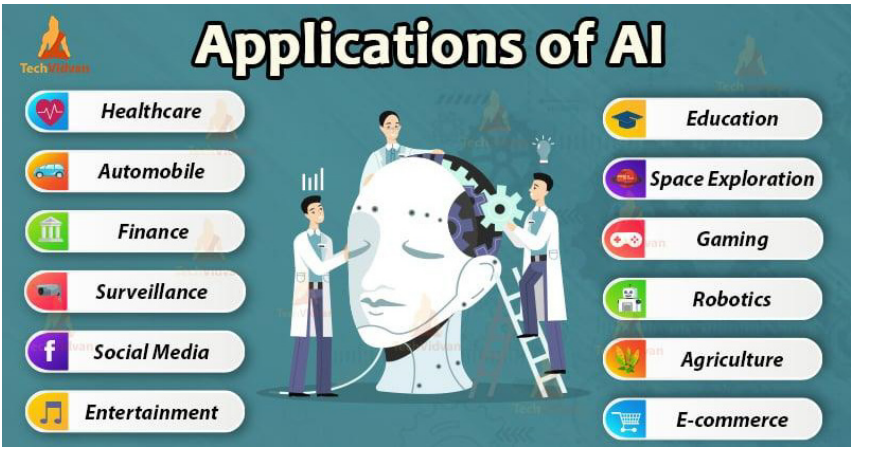
ious approaches. In particular, advances in machine learning and deep learning are creating a paradigm shift in almost every sector of the industry's technological development and applying artificial intelligence to business environments. Artificial intelligence is reducing the time spent on repetitive tasks, increasing employee productivity and improving the overall customer experience (Valavanidis, 2023).

Figure 3. *Applications of AI*



Source: Valavanidis, 2023

Today, there are many real-world applications for artificial intelligence systems. Among the most common of these applications are speech recognition, customer service, computer vision, supply chain and weather forecasting.

Automatic speech recognition (ASR) uses NLP to convert human speech into a written format. Numerous mobile devices incorporate speech recognition into their systems to provide greater accessibility for making voice calls (e.g., Siri) or messaging in English or many other commonly used languages. In customer service, online virtual agents and chatbots are replacing human agents throughout the customer journey. They answer frequently asked questions (FAQs) on topics such as shipping or provide personalised advice and recommend sizes for users. An example is Autodesk Inc. using IBM Watsonx Assistant to speed up customer response times by 99% (IBM, 2024).

Artificial intelligence technology for computer vision enables computers and systems to extract meaningful information from digital images, videos, and other visual inputs and take action based on those inputs. Computer vision powered by convolutional neural networks has applications such as photo tagging in social media, radiological imaging in healthcare, and driverless cars in the automotive industry. For example, ProMare uses IBM Maximo to determine a new route for ocean research (Jiang et al., 2022). Adaptive robots act on Internet of Things (IoT) device information and structured and unstructured data to make autonomous decisions. NLP tools can understand human speech and react to

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what is said. No longer just predictive, but hierarchical, search and pattern recognition algorithms analyze real-time data, helping supply chains react to machine-generated, augmented intelligence while providing instant visibility and transparency. For example, Hendrickson uses IBM Sterling to support real-time transactions. In weather forecasting, the weather models that broadcasters rely on to make accurate forecasts consist of complex algorithms run on supercomputers. Machine learning techniques improve these models, making them more applicable and accurate. We can see how Emnotion uses IBM Cloud to enable weather-sensitive organizations to make more proactive and data-driven decisions (Valavanidis, 2023).

THE ROLE OF ARTIFICIAL INTELLIGENCE IN THE CIRCULAR ECONOMY

AI's ability to help solve problems has increased dramatically since the 1950s due to increases in the availability of data and advances in processing power. Over the years, AI applications have evolved. It is now seen as a promising technology for many industries and businesses. Attracting $26 billion in investment in 2016, AI applications are projected to contribute $13 trillion to the global economy by 2030 (Bughin et al., 2018).

The concept of the circular economy is an important tool for reducing waste and promoting sustainable practices. In order to achieve a circular economy, it is necessary to analyse and deeply understand a multi-actor structure involving many complex processes. In addition, a successful circular economy process requires significant changes in production and consumption systems. This change includes data collection and sharing, investment in innovation, and the development of collaborative business partnerships. At this point, digital technologies are gaining prominence and attracting academic attention and empirical research. Recent studies have highlighted the growing importance of digitalisation in addressing the challenges of transitioning to a circular economy. The combination of digital tools such as artificial intelligence, blockchain, and IoT offers opportunities for the transparent realisation of the entire process of a product (Stankovic et al., 2017).

Artificial intelligence plays an important role in improving energy efficiency, supporting strategies used during the circular manufacturing process, and extending the life of products by encouraging the maximisation of resource use. Artificial intelligence helps decision-making for products and processes. It accelerates circular economy values through real-time tracking and monitoring of product residual value. In addition, artificial intelligence can help discover the still poorly understood benefits of a circular economy by enabling the creation of visual tools about data flows related to products, processes, and resources. These contributions to the circular economy can be explained by circular evolution, the development of circular infrastructure, and proactive management and maintenance approaches. In circular evolution, artificial intelligence enables a more comprehensive consideration of components and materials from a product and module-centric focus. This transformation is realised by machines through iterative learning processes. In the development of circular infrastructure, artifi-

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cial intelligence has an important role in optimising the infrastructure required for the efficient circulation and reuse of materials. In proactive management and maintenance, artificial intelligence empowers businesses to adopt proactive approaches to the management of circular models, leading to increased efficiency and sustainability (Zota et al., 2023).

To explore what role AI can play in the transition to a circular economy, it is necessary to understand how AI can be used to help design, operate and optimize a circular society.

Design of circular products, materials and components

Design is essential for the circular economy to always keep products, components, and materials at their highest utility and value by distinguishing between technical and biological cycles. Through design, we can strengthen the cycles of reuse, repair, refurbishment, and recycling of technical materials and the cascading and cyclical processes of biological nutrients. AI's machine learning-assisted design process enables rapid prototyping and subsequent testing. This can accelerate the development of new products and materials for the circular economy. This is achieved in two ways.

First, in the circular economy, the parameters of a product are designed and developed through the 9Rs. However, what is important in the design process here is to ensure the longevity of products and to increase the recycling potential by separating components (e.g., cardboard) from those that are part of the technical cycle (e.g., plastic) (Ellen MacArthur Foundation, 2019). Furthermore, through AI, new materials can be designed to substitute resources that contain harmful chemicals. This can facilitate the recycling of products at the end of their life cycle and increase their durability. The "Accelerated Metallurgy" project, prepared by the European Space Agency using artificial intelligence, is the best example of this. With this project, new metal alloy combinations were developed by taking into account circular economy principles such as reuse, extended lifetime, non-toxicity, and minimising waste. Through artificial intelligence, not only have new materials been produced, but also faster than ever before (Gailhofer et al., 2021).

Another company accelerating the materials design process by using artificial intelligence in materials development is Citrine Platform. Citrine Platform works with materials data to generate algorithms to use AI to develop new materials and chemistries for high-performance applications. For example, to find a 3D printable aluminum alloy for aerospace grade, it used its AI platform to narrow down the possible candidates for the alloy from 10 million to 100 (Ellen MacArthur Foundation, 2019).

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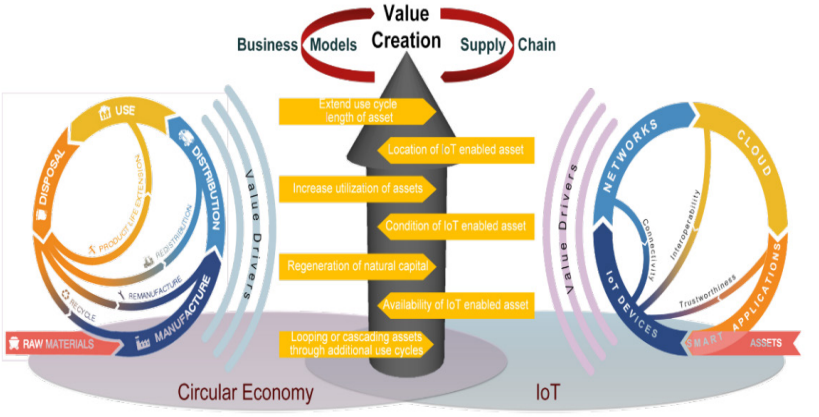
Figure 4. *The CE-IoT Ecosystem*



Source: Askoxylakis, 2018

Second, AI can be used in monitoring products and data-driven decision-making for the maintenance of products in the circular economy. For example, virtual models developed by AI that accurately reflect physical objects can help improve products in the circular economy. Since these systems use IoT sensors to collect data on functionality, they can help ensure longevity by understanding product performance in real-time (Askoxylakis, 2018). In short, AI monitors a product throughout its lifecycle, analyses the data collected, improves efficiency, and assesses whether the returned product can be reused or recycled (Blunck et al., 2019). An example of this is Apple. Since 2019, Apple has been enabling more efficient battery charging with machine learning for iPhone users. In this way, it claims that it can extend the life of the smartphone.

Operate Circular business models

Reverse logistics and remanufacturing efforts in circular business models require solving various problems, such as fluctuating demand and supply of used products and components, and returned components. For example, for a company to choose the next use cycle for each returned product, it needs to consider a combination of factors related to the condition of the product and the current brand status. By combining real-time and historical data from products and users, AI can help improve product circulation and asset utilisation through pricing and demand forecasting, preventive maintenance, and intelligent inventory management. With the capacity to collect large amounts of product and customer data and a powerful AI-based analytics model that can make sense of this data, a decision-making model can be implemented that can increase the competitiveness of circular business models.

AI can boost trade for the circular economy. AI can contribute to the operation of circular business models in the following areas.

First, developing profitable and successful circular business models requires organising business functions such as pricing, marketing, sales and after-sales services, and logistics according to circular economy principles (Ellen MacAr-

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thur Foundation, 2019). Artificial intelligence can be used to develop innovative approaches to the pricing system of circular business models. For example, suppose second-hand goods or recycled products are marketed. Considering that there are many factors that determine the price of a product, it is not possible to have standardised pricing for these products. Here, dynamic pricing algorithms can be created with artificial intelligence applications. These algorithms can help determine the best price by analysing variables such as the age of the product, market conditions, and wear and tear. Shopping sites such as eBay offer price suggestions to second-hand sellers based on the prices of similar products (Gailhofer et al., 2021).

Founded in Seattle in 2014, Stuffstr collects used clothing and household items and sells them in secondary markets in exchange for coupons that consumers can spend. This increases the reuse of products. Stuffstr uses artificial intelligence algorithms to price products both when buying them from consumers and when reselling them on secondary markets (Ellen MacArthur Foundation, 2019).

Second, in a functioning circular economy, AI can support recycling infrastructure, making it easier for firms working in the circular economy. In the stages of reusing, repairing, and recycling products, waste can be identified and separated with the image recognition processes of artificial intelligence, minimising resource loss. The recent partnership between Alibaba and Unilever is an example of this. In this joint project, different types of plastic are separated from each other with an AI-supported sorting machine (Moore, 2021). Additionally, Apple's Daisy robot can separate the materials of 200 iPhone devices per hour. In this way, these materials are recycled and brought to the secondary product market (Apple Recycling Program, 2018). The aim of such separations is to minimise the waste of a product at the end of its life cycle and provide materials for new circular products.

In existing business models, AI technology has significant potential to create circular value. With AI, inventory levels can be reduced without compromising the ability to meet customer demand. This can lead to a reduction in waste caused by unsold products, while at the same time reducing costs (Ellen MacArthur Foundation, 2019).

Finally, artificial intelligence can be used to ensure that the resources used in circular firms are also sustainable. Since processing and storing data is energy-intensive, AI's ability to optimize cooling and energy use can be leveraged to help these firms meet the environmental goals of the circular economy (Andrae and Edler, 2015). For example, in 2016, DeepMind developed an artificial intelligence system that adjusts the cooling systems of Google data centers according to the weather. With this system, there was a 40% reduction in energy bills (Jones, 2018).

CONCLUSION

The global economy still operates in a linear way and is characterised by the extraction, production, consumption, and disposal of materials. This is a problem

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given that we live on a planet with limited resources. However, the transition to a circular economy, where businesses recover or recycle the resources they use in their value chains, is still difficult, despite the opportunity to create trillions of dollars of value. Barriers include the low residual value of used products, the inability to collect materials, the prohibitive costs of sorting and processing materials, and the lack of traceability of recycled products and materials. Entrepreneurs and business leaders can accelerate the circular economy by using digital tools and artificial intelligence to remove these barriers and create entirely new markets and business models.

As artificial intelligence becomes more known and more established in society, it will not only affect businesses that adopt it, but will also have economic and social impacts on consumers. Currently, artificial intelligence is used by financial companies around the world to provide better service to customers and detect fraudulent activities; streamlining supply chains in factories by manufacturers; ensuring accurate detection of diseases in the healthcare system; and by authorities in cities to monitor and reduce urban problems such as traffic, crime, and environmental pollution.

Combining the power of artificial intelligence with the vision of a circular economy offers great opportunities to transform and revitalise our global economic system, which has been the subject of hundreds of economics books on its fragility, from linear to circular. Moreover, there is much more to be discovered when we consider the unabated developments in technological advancements and digitalisation. The three main ways to achieve a more circular economy, especially with AI, are: increased product utilisation, material efficiency, and the use of recycled materials.

Artificial intelligence plays an important role in advancing the circular economy by creating many advantages with the help of its algorithms. Providing real-time data analysis in supply chain management, performing process automation for reverse logistics, reducing carbon footprint and costs for sustainable development, separating materials in recycling activities, and optimising waste management are among the advantages of artificial intelligence in accelerating the transition to a circular economy. Artificial intelligence's adoption of recycling processes as well as the reuse and remanufacturing of products supports the transition to a circular economy.

Building a broader awareness and understanding of how AI can be used to support a circular economy, promoting practices that encompass and go beyond circular design spaces, making circular business models work, and optimizing circular infrastructure requires both collaboration between relevant stakeholders and a degree of oversight. This can ensure that data can be shared openly and securely, and that AI is developed and distributed in an inclusive and equitable way for all.

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