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Review

The Role of Artificial Intelligence within Circular Economy Activities—A View from Ireland

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Abstract: The world's current linear economic model is unsustainable. This model encourages improper use of limited natural resources and causes abundant waste production resulting in severe harm to the environment. A circular economy (CE) is a sustainable, restorative, and regenerative alternative to the current linear economy and is gaining popularity worldwide. Amongst various digital technologies, Artificial intelligence (AI) is a crucial enabler for CE and can aid significantly with the adoption and implementation of CE in real-world applications. In this paper, we describe the intersection of AI and CE and policies around implementing CE principles using AI. As a means of grounding the discussion, we discuss some initiatives taken by the Irish government to adopt circularity and explore the role AI plays in these. We present a number of practical examples of AI and CE from Ireland. We argue that digitalisation has potential in CE and it has a major role to play in the transition towards CE. We close the paper by reflecting on future steps around practical implementations of AI-based CE processes.

Keywords: circular economy; Ireland; digitalisation; artificial intelligence

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1. Introduction

The world's economy operates largely upon linear economic principles. A traditional linear economy follows the "take-make-waste" approach where the natural raw materials are extracted and then manufactured into products. These products are used for a certain period of time and eventually discarded as waste [1]. This economic model encourages over-consumption of material resources, creates unsustainable waste management practices, and creates serious health, biodiversity, and climate problems [2,3]. It is estimated that by 2060, the amount of material resources consumed worldwide will almost double from 90 gigatonnes in 2020 to 167 gigatonnes while the number of consumers will increase by three billion by 2030 [4]. This over-consumption leads to higher demands for resource extraction which in turn increases the levels of greenhouse gas emissions from mining and extraction, worsening air quality and accelerating habitat destruction [5]. Minerals and fossil fuels will eventually run out because they are non-renewable. Oil, for example, is estimated to run out by 2052 [6]. The build-up of waste occurring from these rapid production and consumption patterns is also a big concern. Heavy waste generation can have various negative environmental impacts such as methane gas emissions generated from organic waste rotting in landfill [7]. This abundant waste production has been shown to limit economic growth. Around 45 million tonnes of electronic waste (e-waste) was produced globally in 2016 with a raw material value of EUR 55 million. Only 20% of this was sorted and recycled properly [8].

A solution to overcome the many negative aspects of the linear economy is called the circular economy (CE). CE is an economic system operating on the principles of restoration and aims at reduced material consumption and waste elimination while promising economic development [9,10]. The European Union (EU) defines CE as "an economy in which the value of products, materials and resources is preserved for as long as feasible, by designing durable products that can be reused, repaired, and recycled". This sees the replacement of the 'end-of-life' approach [11]. Furthermore, in CE, the waste from one product is seen as a resource for another. This greatly reduces the value of consuming finite material resources [12]. CE is restorative and is regenerative by its design. It reduces natural resource depletion, negates waste production, and enables green and sustainable economic development [13]. The objectives of CE are similar to those of the Sustainable Development Goals (SDGs), such as SDG 12, 13, 14, in the promotion of economic growth without depleting the earth's resources by 2030 [14].

The adoption of CE is now more important than ever; reflecting this, CE is gaining attention worldwide [15]. Following this trend, Ireland is actively striving to implement CE principles nationwide. Several steps have been taken by the Irish government to fully adopt circularity at industrial, sectoral, and institutional levels [16], for example, government-led initiatives such as Extended Producer Responsibility (EPR) (https://www.gov.ie/en/publication/63441-extended-producer-responsibility/, accessed on 13 March 2023) schemes for dealing with a number of waste streams under which manufacturers and importers bear a level of responsibility for the environmental impact of goods they circulate within the economy. For example, in Ireland a plastic bag levy (https://www.revenue.ie/en/companies-and-charities/plastic-bag-environmental-levy/index.aspx, accessed on 13 March 2023) and taxes on landfills have proved to be important steps in shifting towards more circular waste and recycling practices. Several Irish cities have implemented circular programmes and local authorities are in a good position to lead this transition in an organised manner. For instance, Dublin City Council's Corporate Plan (2020–2024) has prioritized CE as one of the sectors to support, along with tourism, food, and business. Furthermore, government-sponsored funding programmes such as the Circular Economy Innovation Grant Scheme (2021) (https://www.gov.ie/en/service/b3faa-apply-for-the-circular-economy-innovation-grants-scheme-ceigs/, accessed on 13 March 2023), Green Enterprise Fund (2021) (https://www.epa.ie/our-services/monitoring--assessment/circular-economy/green-enterprise/, accessed on 13 March 2023) , and Innovation Fund (between 2020 and 2022) promoted CE practices across enterprises, organisations, and business (https://circuleire.ie/circuleire-innovation-fund-2022/, accessed on 13 March 2023) . The impact of various government policies and initiatives has seen landfilling drastically reduced in Ireland from 80% of municipal waste in 2002 to 16% in 2019 (https://www.epa.ie/pubs/reports/waste/municipal/municipalwastemanagementinireland2019.html, accessed on 13 March 2023) . This can significantly help Ireland to meet a commitment to net-zero carbon emissions by 2050. Furthermore, it is estimated that a 5% increase in resource efficiency would bring the Irish economy an additional EUR 2.3 billion revenue annually (https://www.epa.ie/publications/research/waste/research-128-roadmap-for-a-national-resource-efficiency-plan-for-ireland.php, accessed on 13 March 2023) . Ireland is showing an improvement in circular material usage rate (https://ec.europa.eu/eurostat/web/main/home, accessed on 13 March 2023) , as shown in Table 1.

Table 1. Eurostat Circular Material Use Rate Data: 2015–2021.

Eurostats: Ireland	
Year	**Circular Material Use Rate** **% of Material Input for Domestic Use**
2015	1.9%
2016	1.7%
2017	1.7%
2018	1.6%
2019	1.6%
2020	1.7%
2021	2.0%

There are various drivers to support the transition to CE at a larger level in Ireland and one of the most important factors is digitalisation. Digital technologies, such as the Internet of Things (IoT), Big Data, Cloud Computing, Blockchain, and other online digital platforms, all falling under the broader category of Industry 4.0 (I4.0) technologies, are seen to be the primary factors in the transformation of CE approaches [17,18]. Digitalisation enables new and greater forms of control, optimisation, and collaboration, helps in informed decision–making around production and consumption, and uncovers a broad range of possibilities in terms of CE. As outlined in the report of Digital Europe (https://www.digitaleurope.org/resources/digital-action-climate-action-8-ideas-to-accelerate-the-twin-transition, accessed on 13 March 2023), the usage of digital technologies could help to achieve a 20% reduction of global carbon emissions by 2030. Of all the possible technologies within the digitalisation domain, the field of artificial intelligence (AI) is seen as having the greatest potential to influence the development of CE [19]. AI is a critical technology with the potential to support the broader infrastructure needed to implement circularity in real-world practices and to accelerate a shift towards a regenerative economic model [20,21]. Despite a great deal of discussion around the use of AI in CE, there is actually little clarity on how AI is being used in a practical sense within the CE. We propose addressing this gap by considering and seeking to understand how AI can be used to facilitate the implementation and digitisation of CE. Our ongoing research is tasked with discussing how AI can positively impact the transition towards CE and understanding the current usage and status of AI within CE practices in Ireland. Within this context, the contributions of this paper are, therefore, summarised as follows:

- To promote discussion, within the AI community and beyond, about how AI techniques can be used to enable and enhance CE innovations at various levels.
- To describe the practical use of AI in CE through the discussion of examples, and of real-world implementations.

Much discussion has taken place in the literature [22,23] around the transformative power of AI for CE. However, these discussions remain at a conceptually high level without really outlining what types of AI are used, the barriers and obstacles to AI use, and the sustainability of these approaches going forward. It must be properly acknowledged that AI is already playing an advanced role in CE and this brings about the need to investigate the implementation of AI in these settings.

The remainder of the paper is structured as follows: In Section 4, we discuss some initiatives taken by the Irish government around CE where AI has an explicitly defined role. Section 3 gives some of the most popular examples of where AI is currently being used in CE initiatives, with a focus on Ireland provided in Section 5. The paper closes in Section 6 and Section 7 by outlining challenges still faced in combining AI and CE. However, we make recommendations on how this synergy can be made more effective and we reflect on areas of future research opportunities.

2. Circular Economy

The general operation of the linear economy (LE) is based on the traditional understanding of the supply chain, which begins with (1): extraction of raw materials such as metals, minerals, or agricultural products which are then used as a source of supply for manufacturing, (2): manufacturing of the collected raw materials which are then processed through various procedures to be transformed into finished products (3): distribution and transportation of the finished products to distributors who are then responsible for inventory management before selling to retailers, and finally (4): the consumption of the product by the end users. Once the product has exceeded its end of useful life, it are typically discarded as waste [24,25]. This economic model/approach aims at turning limited natural resources into waste using production systems, which is a flawed economic approach. This results in the depletion of natural resources, pollution, and waste which can have major environmental and economic impacts [26]. This economic system is a one-way flow of materials, energy, and information. According to Boulding, the linear economy is an economy known as a "cowboy economy" [27].

On the other hand, the CE is an alternative economic model which aims at designing a restorative economic system that dissociates economic growth from the consumption of finite resources by keeping products and their materials in use for longer periods of time and by negating waste and pollution [9,10]. The fundamental idea of CE is to maintain the value of materials and products at their highest state for as long as is practical. This is achieved either by extending the useful lives of products or by looping back the components of products into the systems for recycling and/or reuse [28]. A clear difference between the working models of linear and circular economy models is illustrated in Figure 1. Adding to this, in the literature of CE, the supply chain is regarded as one of the key factors that facilitates the implementation of CE [29]. CE can be related to a modern approach which is more integrated and collaboratively seeks to increase efficiency by adopting circular practices such as reuse, recycling, and closed-loop systems [30]. Table 2 outlines the key differences between the linear economy and CE at each step of the supply chain.

As the global demand for sustainable solutions reaches a critical point, the transition towards CE from LE is emerging across the world [31]. The move from LE to CE has been emphasized by the European Commission as "a crucial contribution to the European Union's efforts to establish a sustainable, low carbon, resource-efficient, and competitive economy" [11]. However, transitioning to a CE entails more changes than only those related to lessening the negative effects of LE. Instead, it requires a change in infrastructure that can increase long-term resilience, provide efficient business opportunities, and offer environmental and societal benefits. In order to fully benefit from CE, there are several indicators (https://www.oecd.org/cfe/regionaldevelopment/Ekins-2019-Circular-Economy-What-Why-How-Where.pdf, accessed on 13 March 2023) that can be considered to make a suitable transition towards CE. They include circular products, circular business models, consumer behaviour, and financing. We briefly describe each of these indicators below.

- **Circular Products:** CE places a strong focus on a product's sustainability impact during its consumption and end-of-life cycles. However, such an impact is usually decided in the early stages of production, i.e., the design and conception phase [32]. Eco-design is one of the fundamental pillars of the CE and is aimed at economic actors, that is to say, producers of goods or services. Eco-design is a systematic approach in which the products are designed in such a way as to reduce their environmental impact during their life cycle [33]. It provides product designers with eco-design guidelines and strategies focused on improving the products' end-of-life potential, such as design to allow re-manufacturing, repairing, and recycling, and to be biodegradable [34]. It is not only the end-of life phase of the product which is focused on in this design strategy. Eco-design strategies can also be used at each step of the supply chain to improve the overall production. The eco-design guidelines are often classified as "design for X" approaches, where X stands for the different phases in the life cycle of the product [35].

- **Circular Business Models:** Business model innovation has an important and substantial role [36]. Organisations that are willing to adopt CE need to implement new types of business models that can help achieve an ideal state of resource utilisation while generating and capturing value. There are several circular business models (CBM)s for organisations who look to become more sustainable by redesigning their supply chains [37]. These business models include the resource recovery model where valuable resources from waste or discarded materials are recovered and recycled rather than using non-renewable natural resources every time for production processes. This business model has been shown to reduce greenhouse gas emissions by up to 90%. By **re-manufacturing** products that have reached their end of life, up to 80% less natural resources are extracted and less waste is generated in comparison to manufacturing new products. The **sharing or leasing** of already existing products also seems likely to lead to lower environmental burdens. This encourages the reuse of products and reduces waste.
- **Consumer Behaviour:** There is a significant research emphasis on the importance of the role of customers and users when adopting a CBM [33]. Business models and policies that encourage shared use, reuse, repair, and recycling are directly linked with the public interest in creating a more sustainable or circular society [38]. To create effective policies to encourage consumer to adapt CE, policy makers should have a thorough understanding of the elements (https://www.circularinnovationlab.com/post/consumer-behaviour-is-key-to-developing-a-circular-economy, https://www.labopen.fi/lab-pro/the-role-of-consumer-behavior-in-circular-economy/, accessed on 13 March 2023) influencing consumer behaviour. These factors include both **economic** and **decision-making factors**. With economic factors, circular options are not always the best economic ones, and in some cases they are more expensive than linear ones because of the extra processing which can add risks to circular product usage. In terms of decision making, full access to information regarding the source of circular products for consumers is required to understand the distinctive characteristics of circular solutions.This also helps them make more informed choices when purchasing products. Finally, there must also be a fit between needs and offerings. It should always be considered to what extent the availability, quality, performance, and characteristics of products and services meet consumer needs and their preferences. This includes analysing whether the product fulfills consumer needs.
- **Financing:** The transition to a CE needs resources to drive the uptake of new business models, support the development of innovative technologies, and motivate behavioural change within society [39]. Financing will be required to support scaling of the CE and capitalize on the opportunities it offers [40]. Governments and financial institutions have the scale, reach, and expertise to stimulate and support businesses to make the shift [41]. Governments can help CE projects and initiatives through incentive subsidies, grants, and loans by decreasing the cost of capital for circular investments and removing information barriers. Financial institutions such as central banks and financial regulators can integrate circular concepts into risk assessments and modelling. This could also facilitate exploring CE integration into less conventional methods such as green quantitative easing.

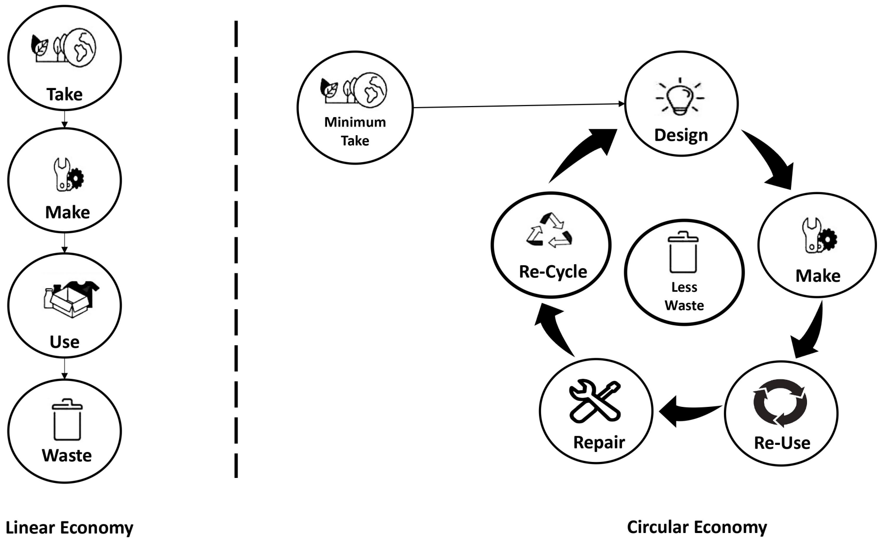

Figure 1. An illustrative comparison between the Linear Economy and Circular Economy Model.

Table 2. The differences between the Linear and Circular Economy at each step of the supply chain.

Linear Economy	Circular Economy
Linear supply chains follow a Take-Make-Waste model.	Circular supply chain follows a Reduce-Reuse-Recycle model.
Focus is on producing as much as possible, quickly and at a low cost.	Focus is on reducing waste and maximizing the value of resources at each step of production.
Suppliers are chosen based on the lowest cost and quickest lead time.	Suppliers are chosen based on sustainability criteria, including use of recycled materials, low waste generation, and reduced carbon emissions.
Products are designed for single-use and obsolescence.	Products are designed to be used for longer periods increasing its durability repairability, and recyclability features.
Transportation is designed for speed and low cost without taking the environment into account.	Transportation is designed for efficiency with sustainability. There is a focus on reduced carbon emissions and waste.
Consumers are responsible for disposal or waste management companies.	Disposal is minimized with increased reuse, repair, or recycling of products and materials.
A very limited communication between stakeholders between each stage in the supply chain.	Feedback loops are integrated throughout the supply chain, with data sharing and collaboration between suppliers, manufacturers, and consumers.
Waste is generated at each stage of the supply chain.	Waste is minimized at every stage of the supply chain. There is a focus on recycling and repurposing materials.

3. The Role of Artificial Intelligence in the Circular Economy

Digitalisation has been widely recognised as one of the most important ways to unlock the benefits of a more inclusive and sustainable economy [42]. Digitalisation is the use of digital technologies to enhance business processes by leveraging digital technologies and digitized data [43]. Effective utilisation of digital technologies such as Big Data, Blockchain, the IoT, Cloud Computing, and Online Digital Platforms sometimes referred as I4.0 technologies enable circularity in a number of ways. These technologies can create knowledge about the material composition of products, their origin and properties, their location, condition, and availability, as well as their respective manufacturing processes and conditions for maintenance, dismantling, and recycling [44,45]. Digitalisation is disrupting the parameters of the current economic system by transforming business processes, facilitating data-driven decisions, affecting consumer behaviour, and mitigating some environmental effects. Figure 2 illustrates the role of digital technologies in enabling some CE activities.

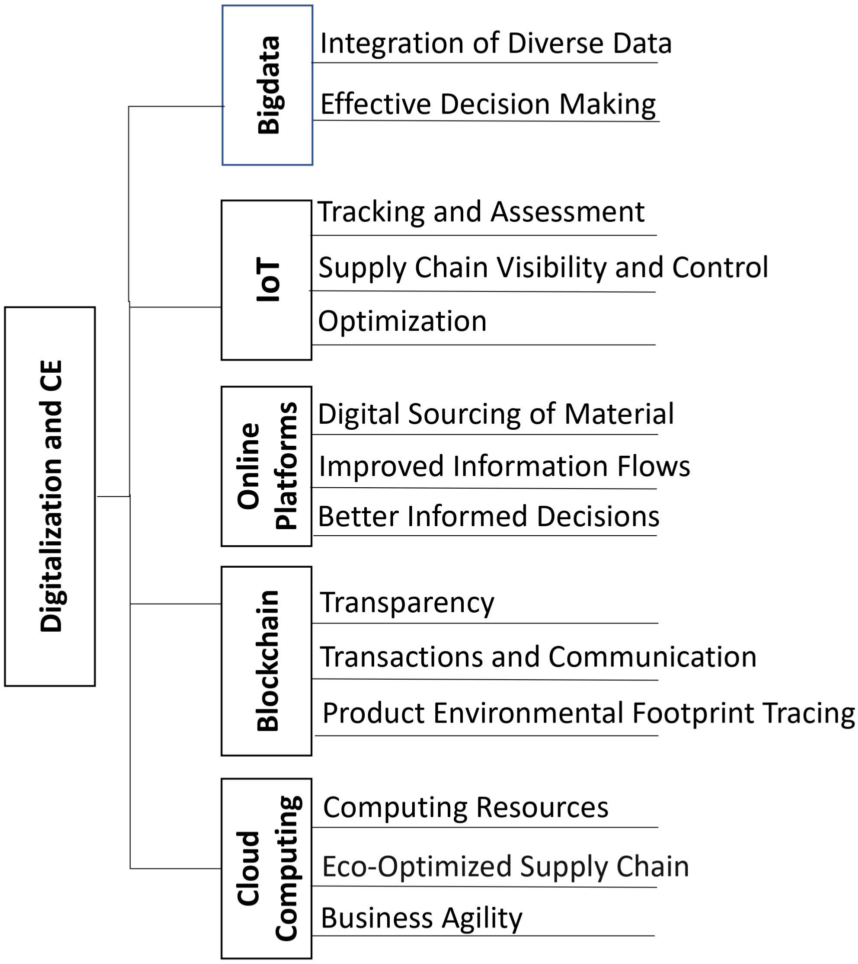

Figure 2. The role of various digital technologies in Circular Economy activities.

In addition to the digital technologies mentioned above and illustrated in Figure 2, many scholars have explored the integration of AI in CE [46,47]. AI is a broad area of computer science that focuses on creating intelligent machines and computer programmes that are capable of performing tasks that are commonly associated with human beings [48]. One of the most attractive characteristics of AI algorithms is their ability to perform specific tasks and improve themselves iteratively based on the data or information they are collecting or accessing. The potential applications of AI are numerous. However, the most impactful and well known include: computer vision [49], natural language processing [50], recommendation systems [51], and optimisation [52]. AI holds transformational potential for CE in many diverse ways including: hidden pattern identification, data analysis, predictive analysis, reverse logistics, improved process optimisation, and enhancing responsiveness [19,22]. This section explores, in a practical sense, the important role AI can play in the transition to a CE and how it can be further used to optimise a circular infrastructure. We see that AI can unlock three high-potential CE opportunities [53], namely:

1. **Design of new circular products**: CE puts a strong focus on innovative design to maintain the utility and value of products, components, and materials at all times [22]. Such designs can empower increased cycles of reuse, repair, and recycling of many products and their constituent materials. This is a difficult task. However, AI can be a helpful tool in enabling product designers to manage this complexity through iterative assisted design processes. These processes allow for rapid prototyping and testing,

leading to better design outcomes in a shorter period of time [53]. In this way, new products can be formed through circular design and these products can then be safely maintained and preserved in the economy for a longer period of time. As a result, the amount of resource extraction and waste production associated with excessive product development can be reduced substantially. AI can also help in predicting how materials change over time, such as their overall durability and potential toxicities [54]. This type of information can help in advancing the reverse logistics and maintenance of products.

2. **Operating circular business models**: Developing sustainable business models requires organisations to run business processes such as manufacturing, marketing, pricing, sales, and logistics using CE principles. AI has already been involved in introducing new business models underpinned by CE principles [55]. For example, by analysing massive real-time consumer data, AI can help in setting product pricing and demand predictions appropriately [56]. AI supports predictive maintenance which can prolong the lifetime of equipment by minimizing the cost and use of spare parts [57]. AI-assisted circular business models such as asset sharing, product-as-a-service, and take-back have provided new opportunities for circularity [58]. This in turn helps save money and resources.
3. **Optimizing circular infrastructure**: One of the most important aspects of CE is that materials and products are repeatedly used rather than being consumed and disposed of, as illustrated in Figure 1 above. In order to do this, an extensive circular infrastructure of collection, sorting, separating, and treatment is needed. This infrastructure then supports and integrates the efficient reusing, repairing, and recycling of products. [59]. There are numerous areas where AI can help optimize the infrastructure required to circulate products and materials in the economy. Many of these focus on the capabilities of AI-powered image recognition algorithms [60]. One leading example is mixed-material stream-sorting using AI image recognition techniques combined with robotics [61]. Automated multi-part disassembly of products, considering the condition of the products using cameras and sensors embedded with AI [62], is also used. As commented by some authors, the decisions made during the design phase of products have an important role to play in improving the future re-manufacturing and recycling opportunities for many products [63].

3.1. AI Techniques to Advance CE

In the previous section, we considered CE opportunities for AI and discussed the role AI played within these processes. In this section, we will discuss some of the key AI techniques used for CE along with the characteristics of each technique. We comment on the aspects of these techniques that makes them appropriate for advancing CE solutions.

- **Machine learning**: Machine learning (ML) is a branch of AI that provides computers with the ability to learn from data, analyse and draw inferences from complex data patterns, and make predictions with minimal human intervention [64]. ML algorithms are provided with data and then through the use of statistical formulas, the algorithms are trained to derive results. This training process can be repeated and configured to improve the quality of derived results. ML algorithms can detect significant dependencies between the data features of real-time datasets and this ability can identify opportunities for circular solutions [65]. For example, ML approaches can be used to forecast the demand for a product as per consumer purchasing behaviour [66]. Within agricultural settings, ML can be used to predict the right time to sow crops by using data related to the quality of the soil, weather, and possible future market conditions for the crop output [67].
- **Artificial Neural Networks**: An artificial neural network (ANN) is a computational model based on biological neural networks. ANNs imitate the way nerve cells function in the human brain [68]. ANNs employ learning algorithms capable of independently making adjustments or *learning* as more data are input and explored. This makes

ANNs very effective for a diverse range of complex problems. ANNs are a very popular technique in AI and are used in many real-world applications. Many examples already exist within the CE domain [69]. ANNs utilising ML algorithms can be used to classify waste streams for recycling, track or predict the end-of-life traceability of a material, and support the prediction of new product purchasing [70].

- **Convolutional Neural Networks**: Convolutional neural networks (CNN)s are a class of ANN that are equipped with advanced digital image processing functions and are commonly applied to analyse visual imagery [71]. CNNs can be used in the CE to capture an entry image, assign relevance (weigh and biases can be learned) and object traits, and subsequently be able to define the differentiation among objects in the image(s) [72]. CNNs can be applicable in sorting objects that are to be recycled or reused from a waste stream. They can be used to detect the growing characteristics of crops, thereby helping in optimising food production [73] and in urban waste management, such as automatically detecting when waste bins are full [74], and so on.
- **Timeseries Analysis**: Timeseries Analysis is an AI technique capable of working with variables evolving over time. This technique is very efficient in identifying specific trends in historical data in order to predict future events [75]. Methods include lines of Best Fit, Auto Regression, Moving Average, and more advanced Deep Learning (DL) models such as Long Short-Term Memory (LSTM). Applications can be found in predicting food demand based on consumption patterns to minimize food waste [76], predictive maintenance of equipment for reduced maintenance costs, and increasing the overall lifespan of equipment.

4. Initiatives for AI in CE in an Irish Context

Ireland is at a turning point in its transition towards the CE [16]. A number of strategies, sustainability and climate policies, and programmes are being implemented by the Irish government to promote the CE nationwide. Ireland's first national strategy to realize a CE is "The Whole of Government Circular Economy Strategy" (2022–2023) (https://www.gov.ie/en/publication/b542d-whole-of-government-circular-economy-strategy-2022-2023-living-more-using-less/, accessed on 13 March 2023). This strategy is an important part of the government's efforts to cut greenhouse gas emissions overall by 51% by 2030 and move toward net-zero emissions by no later than 2050. This strategy was mentioned as an explicit commitment in the Waste Action Plan for a Circular Economy (https://www.gov.ie/en/publication/4221c-waste-action-plan-for-a-circular-economy/, accessed on 13 March 2023) (WAPCE) (2020–2025). The WAPCE investigates the possibilities for circularity across the government and beyond. It outlines the development of a policy framework that can assist in translating a circularity vision into concrete actions and outcomes. The Circular Economy Programme (https://www.epa.ie/publications/circular-economy/resources/the-circular-economy-programme-2021-2027.php, accessed on 13 March 2023) (2021–2027) of the Environmental Protection Agency (EPA) aims to aid Ireland's transition to a CE through the provision of innovation grants, sponsorships, and seed-funding. The Circular Economy and Miscellaneous Provisions Act (https://www.oireachtas.ie/en/bills/bill/2022/35/, accessed on 13 March 2023) 20,225, which was recently passed into law in July 2022 supports Ireland's transition from a "take-make-waste" model to a more sustainable pattern of production and consumption. This landmark legislation defines the CE for the first time in Irish domestic law and provides a legal basis for many of the actions that the Irish government will take to support the circular transition. Apart from these high-level strategies and plans, the Irish government has implemented some important initiatives domestically to implement circularity, a few of which are listed in Table 3.

Table 3. Initiatives Related to the Circular Economy in Ireland, data taken from [16].

Initiative	Type of Activities	Characteristics and Objectives
Landfill levy	Prevention	Anti-litter levy aimed at reducing the use of disposable plastic bags.
Circular Economy Innovation Grant Scheme (CEIGS)	Prevention Reuse Recycling	Financially supports CE-based projects in order to raise awareness of the need for transition to a CE.
CIRCULÉIRE Innovation Fund	Prevention Reuse Recycling	Financially supports large-scale systems-level innovation for circularity in the manufacturing sector.
MyWaste.ie	Prevention Reuse Recycling Disposal	Provides information and advises households and businesses on options for reusing, recovering, and disposing of a wide range of materials.
ReMark	Reuse	Aims to give consumers the confidence to buy from reuse organisations via labelling.
Government Climate Toolkit 4 Business	Prevention Reuse Recycling Disposal of materials	Supports businesses in analysing, understanding, and taking action on their carbon footprint.
Rediscovery Centre	Prevention Reuse Recycling	Ireland's National Centre for the CE organises workshops for students and thematic workshops to citizens and provides policymakers with data and information on the non-waste reuse sector in Ireland.
NWPP	Prevention Reuse Recycling	Seeks to prevent waste and drive the CE by delivering national-level strategic programmes with high visibility, impact, and influence.

As Ireland looks to realise the ambitious targets to reach net-zero emissions by 2050, it is now an opportune time to accelerate the shift to long-term sustainable growth by taking advantage of impactful digital technologies. According to a McKinsey report (https://www.mckinsey.com/featured-insights/europe/shaping-the-future-of-work-in-europes-nine-digital-front-runner-countries, accessed on 13 March 2023), nine European "digital frontrunner" economies, including Ireland, stand to gain EUR 550 billion (or 1.2% annually) in GDP between 2016 and 2030 as a result of new *digitally enabled automation* . AI is part of this automation. AI is already being used within the Irish context of CE ambitions. The recent publication of the Irish government's (2021) (https://enterprise.gov.ie/en/publications/publication-files/national-ai-strategy.pdf, accessed on 13 March 2023) *AI: Here for Good* carefully, but ambitiously, sets out how Ireland can be an international leader in using AI to benefit the Irish economy and society. The strategy aligns closely with an EU white paper on AI published in 2020 (https://ec.europa.eu/info/sites/default/files/commission-white-paper-artificial-intelligence-feb2020, accessed on 13 March 2023) where using AI is emphasised for different areas including CE. Ireland has strong industry–academic collaborations in the shape of Science Foundation Ireland (SFI (https://www.sfi.ie/)) Research Centres where internationally renowned researchers and industry experts are working on developing solutions addressing environmental challenges. One leading example from an SFI research center is that of VistaMilk (https://www.vistamilk.ie/) where researchers are working to develop new algorithms to predict grass growth to support sustainable dairy farming and providing decision-support technologies that will have a real impact in Irish farms. Furthermore, Irish-based stakeholders such as: CIRCULÉIRE (https://circuleire.ie/), Irish Manufacturing Research (IMR) (https://imr.ie/) and Environmental Protection Agency (EPA) (https://www.epa.ie/) Ireland have been instrumental in driving Ireland's circular transition with digital technologies by engaging with a wide range of authorities and sectors to promote new and innovative circular business models. It is now very clear that AI is viewed as a critical factor by the Irish government in achieving the vision of a green and circular economy.

5. Examples of Usage of AI for CE in Ireland

In Ireland, an increasing number of companies are moving towards digitalisation and incorporating AI into their business operations. A Eurostat report in 2021 indicated that Ireland has the highest share of enterprises (23%) in Europe using AI (https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20210413-1, accessed on 13 March 2023). In this section, we present some examples from Ireland where AI techniques are being used to drive circular ambitions. By highlighting some of these real-world examples, we believe this can can help create a greater awareness of the use of AI in Ireland for CE. This can also encourage other stakeholders to explore opportunities for AI in CE applications relevant to their area of interest or industry. The examples are not an exhaustive list but provide a interesting and thought-provoking sample of the use of AI for CE in Ireland. Table 4 shows how the examples mentioned are using AI techniques in different ways to achieve a number of CE goals. By focusing on a single jurisdiction, we can also more effectively explore how AI in CE can operate in practice within an economy and reach more general conclusions that are of relevance across jurisdictions.

1. **Advanced Manufacturing Control Systems (AMCS):** This is a software solutions provider company, headquartered in Limerick, Ireland. It holds a leading position in the global environmental, waste, recycling, and resource industries. AMCS offers smart digital solutions for the waste and recycling sector and provides solutions to streamline complex logistics operations. AMCS's Vision AI (https://www.amcsgroup.com/solutions/amcs-vision-ai/, accessed on 13 March 2023) is an automated waste management solution that uses AI to optimize the waste management process, reduce waste, and increase recycling rates. Vision AI utilises both Computer Vision and AI technologies to analyse waste material streams to automatically detect waste contamination for more sustainable waste management. Vision AI uses an AI monitoring unit and recording device that can be integrated or installed into a variety of assets, such as waste collection vehicles and material recovery facility plant equipment. The monitoring unit records images with the embedded AI engine analysing these images to detect target patterns such as contamination. Insights are then provided on the AMCS cloud portal. Using this automated waste material detection to identify contamination in recycling materials, Vision AI helps increase the overall quality of material salvaged and reduces landfill contamination. This in turn reduces disposal costs and increases revenue from future material sales.
   Summary: Contamination occurs when recycling materials are not properly cleaned or when materials are sorted into the wrong recycling bin. In some cases, the recycled content may be so contaminated that the entire load is consigned for landfill or incineration disposal. AMCS's Vision AI has the potential to greatly reduce contamination levels from the recyclables. Vision AI reduces the amount of waste going to landfill which in turn reduces greenhouse gases, prevents pollution, preserves natural resources, and increases revenue.
2. **Positive Carbon:** Positive Carbon is a Dublin-based start-up company providing intelligent technology for commercial kitchens capable of tracking food waste in great detail. Positive Carbon's (https://www.siliconrepublic.com/start-ups/positive-carbon-food-waste-technology-ai-lidar-sensors, accessed on 13 March 2023) technology uses AI and Light Detection and Ranging (LIDAR), a type of sensor often used in self-driving cars, to determine the extent of food waste. The technology collects and logs data about food thrown into the bin. It records every piece of food waste on a reporting dashboard. In this way, users are given feedback on the type of food and the

corresponding amounts they are wasting. This can have the positive effect of encouraging the user to change their purchasing behaviour while more carefully considering their food preparation and consumption patterns. This company is certain that its technology will help decrease food waste by half while simultaneously reducing costs and advancing business sustainability goals. The system is already in use in various universities, restaurants, and offices in Ireland. This project is also supported through the Green Enterprise Innovation for a Circular Economy Programme by EPA.
Summary: An estimated 1 million tonnes of food waste is generated in Ireland each year (https://www.epa.ie/publications/circular-economy/resources/NWPP-Food-Waste-Report.pdf, accessed on 13 March 2023), with about a quarter of this coming from the food service sector. This wastage costs the industry EUR 300 million per year and emits 875, 000 tonnes of CO_2. Positive Carbon uses AI technology to tackle food waste, helping the food sector improving its production and consumption, which leads to economic and environmental benefits.

3. **BAM:** This is the largest multinational construction company in Ireland and a global leader in quality and sustainability. BAM (https://www.bamireland.ie/our-work/bim/, accessed on 13 March 2023) aims to improve safety in the workplace and provide environmentally sustainable projects by applying sophisticated industrial techniques and the use of digitalisation. BAM Ireland is utilising AI in a number of ways to promote sustainability. By making use of predictive analytics on data from sensors, BAM can predict energy usage patterns in buildings and identify the areas where energy consumption can be reduced. This helps to lower the environmental impacts and energy costs of buildings. Secondly, BAM uses Building Information Modelling (BIM) and ML to create a digital representation of a project which enables them to optimize the construction process and identify the points of waste in the projects. Hence, through the use of AI and digital technologies, BAM has reduced its carbon emissions and energy usage, and has identified patterns within projects enabling it to identify sources of waste in the supply chain.
   Summary: Construction and demolition waste makes up a significant fraction of the waste produced globally, i.e, 25% to 40% of the total waste generated. (https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/construction-and-demolition-waste-challenges-and-opportunities-circular-economy, accessed on 13 March 2023) Implementing sustainability in construction is very important in terms of economic and environmental aspects. BAM Ireland uses AI and digital technologies to make construction more safe and sustainable. The data insights gathered from digital technologies such as BIM combined with AI in construction help BAM to identify sources of waste, reduce energy and water consumption, reduce greenhouse gas emissions, and lower operating costs over the life cycle of the building.
4. **Sensi:** Sensi (https://sensi.ie/) is an Irish start-up that specializes in developing a range of Reverse Vending Machines (RVM)s for the CE. RVMs are automated machines that accept empty containers, such as aluminium cans, and provide users with a refund or other types of compensations. Sensi-based smart RVMs are designed to accept different types of recyclables, such as plastic PET (polyethylene terephthalate) bottles, aluminium cans, and paper cups. They reward users with a digital voucher in the form of a QR code for recycling. The machines use IoT and Computer Vision algorithms to solve the recycling problem. When a user inserts a used bottle or can into the RVM, the machine then makes use of IoT sensors and visual AI techniques such as Computer Vision algorithms to identify the type and material of the container before sorting it into the appropriate recycling bin. Unlike other machines that recognize items based on their barcodes, Sensi machines use advanced digital techniques to identify items based on their appearance. The advantage of Sensi's RVM is that their AI technology allows their machines to learn and adapt over time based on a large dataset of typically recycled items for improving overall identification accuracy. The machine can also

be configured to work for other items such as reusable coffee cups and reusable food containers. These RVMs have been installed in several locations in Ireland.

Summary: Retail waste, which includes a wide range of materials including plastic, paper, metal, and food waste, is a serious environmental issue due to its large quantity and the associated environmental impacts. Recycling of retail waste is essential for sustainable development since it protects the environment, boosts the economy, and helps preserve natural resources. Sensi Ireland is encouraging and facilitating efficient and effective recycling by its smart RVMs equipped with IoT and AI. By promoting recycling and reducing waste, Sensi Ireland is helping to create a more circular economy where resources are used more efficiently and waste is minimized.

6. Challenges Moving forward for AI in CE

In the previous sections, we have outlined some motivations for CE approaches to be adopted (Section 1) followed by carefully outlining the role that AI can play in the CE (Section 3). We described some specific government-led initiatives to encourage AI usage in CE activities with a short discussion of initiatives from Ireland (Section 4). AI is a very broad term and can be somewhat inaccessible to those outside the AI domain. Consequently, we described in general detail some of the most popular techniques (Section 3.1) from AI. We then provided some examples of companies using AI in their CE approaches in Section 5. At this point in our work, it is clearly understood that AI can be a crucial factor in enabling a CE. However, there are some challenges that need to be addressed in order to utilise AI with its full potential within CE. We now outline what we consider to be three of the most pressing challenges facing companies and practitioners around using AI in CE processes. Indeed, the challenges below are not necessarily unique to the implementation of AI within CE processes. These challenges are present in many applications of AI in real-world processes, tasks, and systems.

- **Lack of training data**: The efficiency of AI-based systems to be trained and tailored for various CE approaches offers great potential. The major challenge is that in order to train and build intelligent AI models for CE, very large amounts of training data is usually required [77]. The lack of high-quality training data can be a potential hurdle in the effective utilisation of AI For CE. Training datasets may be difficult to generate and indeed to do so can be expensive. Collection and curation of training data can also take a great deal of time. In the absence of appropriate volumes of training data, one possible solution is to consider the usage of transfer learning. Transfer learning is a popular approach within deep learning applications. Transfer learning is a method where an already pre-trained existing AI model working for a particular task is reused and *transferred* for a new problem [78]. AI-gathered knowledge from a high-quality existing dataset is then *transferred* to a new target application which is lacking in data, using the pre-trained existing AI model [79].
- **Addressing privacy and ethics considerations**: To design efficient AI models for CE, an amount of data from various platforms is required to train and test the models in order to achieve circularity at a higher level. However, collection and analysis of such data could also pose various privacy, ethical, and legal risks [4,80]. In many CE applications, particularly those related to consumer or customer behaviour, one finds that AI models are trained on the data generated by humans interacting with systems such as Internet applications, social media applications, and so on. These are heavily reliant on knowledge of the user's location (and associated geospatial data) and other personal characteristics. The use of these types of data streams introduces privacy considerations that are not easily solved [81]. For example, geospatial data about people makes it possible to connect or link those people to other types of user information including work, social, political affiliation, and other behavioural patterns, all of which represent highly confidential information [82]. Furthermore, in terms of the analysis of such data, the inferences AI could make about an individual or group could also raise ethical issues. For example, when using data from smart

meters to improve energy consumption and lower waste, AI models could make some inferences regarding individuals' private life patterns [83]. Such data could possibly be misused for fraudulent purposes. Hence, when developing AI-based systems for CE, the societal impact of the systems [84] should be addressed properly and also incorporate privacy, ethical, and legal considerations for governing the use of training and testing data.

- **Collaborative Infrastructure**: CE is concerned with the interactions and procedures among multiple parties [85]. Given the connectedness of various technological factors to support CE, the smooth transition to a CE can hardly be achieved without collaboration among stakeholders. CE transition requires an entire network and ecosystem of stakeholders in order to build trust and the platforms to collaborate. Collaborative AI Ecosystems [86], can lead to more streamlined, optimized, and sustainable processes [87]. Thus, the creation of environments enabling collaboration between research centres, businesses, and public bodies on AI innovation for CE should become a strategic priority for governments.

Table 4. This table summarises the examples we described in Section 5, including their CE goals and the AI techniques employed for implementing these goals.

Example	CE Activities	AI Used
Vision AI	Reduce Reuse Recycle	Computer Vision Machine Learning Pattern Detection
Positive Carbon	Reduce Prevention	Computer Vision Food Detection AI Weight Sensors
BAM	Reduce	Machine Learning AI in Construction Building Information Modelling
Sensi	Reduce Reuse Recycle	Visual AI Machine Learning Pattern Recognition

7. Conclusions and Future Work

This paper has provided a discussion of the intersection between AI and CE, terms often referred to as *megatrends* by some authors [88]. Our paper has given a general overview of how AI can be used to enable circular ambitions in practice. The initial part of this work focused briefly on the CE model and how it differs from the LE model and offers a more sustainable and resilient approach to economic development. In Section 3, we reviewed how AI techniques can be readily applied to advance three key aspects of a CE: design of new circular products, operating circular business models, and the overall optimisation of circular infrastructure. In Section 3, we also discussed the role of some popular AI techniques in enabling circular practices. We discussed some initiatives in Ireland, the home country of this research work, regarding the adoption of CE and the role AI has to play, and presented some examples from Ireland where AI has been practically used in CE processes. These examples, while explained at a high level, can serve as inspiration to other stakeholders to encourage them to explore pertinent and relevant opportunities of how AI techniques can be used in their area of interest or industry. Finally, in Section 6, we discussed some challenges that need to be considered in order to utilise AI with its full potential for CE. A transformation from a linear to a circular economy is more important than ever and digitalisation can play a very critical role in this transformation. Over the past decade, the world has seen a significant industrial development using digital technologies. Stakeholders are considering incorporating AI into their businesses to attain economic growth along with substantial environmental benefits. AI can positively influence the development and the adoption of CEs worldwide. However, gaps exist in the knowledge around how AI techniques can be practically applied in order to implement more circular business models and achieve CE ambitions across organisations. It is now of high importance to raise awareness about how AI can support CE so that governments, organisations, and sectors benefit from CE opportunities driven by AI. The range of tools available to develop AI software is expanding and becoming more user-friendly. This is an important step towards more widespread consideration and adoption of AI as a digitalisation tool in practical real-world situations.

There are a number of immediate focus areas for our future work efforts. We shall undertake a series of stakeholder interactions and interviews with a focus on specific sectors such as construction, waste, and the bio-economy in order to explore the vision of circularity in these sectors and the role AI can play in order to achieve these visions. An important outcome of these stakeholder interactions will be developing a practical understanding of the issues and obstacles faced by companies, practitioners, governments, and so on around the implementation of AI in CE processes. Several authors [89–91] argue that the potential barriers to the practical adaption of the CE can be solved by deploying emerging digital technologies such as IOT, Big Data, Cloud Computing, and especially, AI. However, such deployments must be first carefully designed, tested, and validated. This can take significant time and resources which can be a barrier to the eventual adoption of AI approaches.

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