Challenges and Opportunities of Artificial Intelligence and Machine Learning in Circular Economy

Miroslav Despotovic[1] , Matthias Glatschke[2]

[1] University of Applied Sciences Kufstein, Tyrol, Austria; miroslav.despotovic@fh-kufstein.ac.at

[2] Psoido GmbH, Erfurt, Germany; matthias.glatschke@psoido.com

1 INTRODUCTION

Cities and regions play a key role as promoters, facilitators and, above all, enablers of the circular economy in terms of innovation, data and assessment, capacity building, financing and regulation as part of the overall transition process to optimize the current linear system, use green and clean techniques for production and change the relationships between value chains, as well as identify synergies and optimize processes across sectors. The inherent "take - make - waste" nature of the present linear economy is a major contributor to resource limits being overshot. The transition to a circular economy and the associated challenges and opportunities have been controversially discussed and defined. Artificial Intelligence (AI) and Machine Learning (ML) can significantly drive the transition to a circular economy paradigm and help to overcome current challenges and create a much more environmentally sustainable future. Roberts al al. concludes that AI can be a key enabler in the transition from a linear to a circular economy. It can assist in the design of durable and sustainable products, drive new circular business models, and support the infrastructure needed to scale the circular economy [2].

This article provides an overview of the opportunities and challenges associated with the transition to a circular economy. It addresses the application of AI and ML from several essential perspectives, such as fostering circular business, infrastructural challenges, providing AI-based dynamic pricing, but also in regard to implications and risks of AI deployment within circular economy, privacy breach or algorithmic presetting. The EU-Taxonomy [1] provides clear definitions and criteria for environmentally sustainable business activities, and AI can play a pivotal role in designing durable and sustainable products and promoting new circular economy models.

2 CONCEPTS & LIMITATIONS OF A CIRCULAR ECONOMY

Since the 1970s, various approaches have been developed to make the circular economy (CE) a reality [3, p. 97]. At that time, awareness of the limited resources and environmental impacts of the linear economy model began to emerge, resulting in a new mindset and accompanying novel concepts, such as:

- "Limits to Growth" by [4] regarding the long-term effects of unlimited economic growth and warned of the limits imposed by natural resources and the environment.
- "Cradle-to-Cradle" by [5] emphasizes on creating products and sys-tems that are designed to be fully recycled or biodegraded at the end of their life cycle without leaving harmful waste.
- "Performance Economy" by [6] underscores the importance of maximizing value creation through the usage of products and services rather than the mere ownership of materials.
- Lyle's "regenerative design" model forces the design of products and systems that regenerate natural resources and minimize environmental impact [7].

According to Korhonen et al., the concept and implementation of the circular economy (CE) have been driven mainly by practitioners, including policymakers, companies, management consultants, industry associations, and corporate foundations. [8].

The rebound effect assumes that an increase in efficiency leads to a decrease in production costs, usually resulting in reduced consumer prices. Consequently, consumer behavior changes, leading to increased demand. This increased demand can partially or even entirely compensate for the initial savings. For the sustainable management of resources, it is necessary to allocate resources efficiently to reduce resource consumption, which is desirable both ecologically and economically. The rebound effect is becoming increasingly important for the challenges of transitioning to a circular economy, as observed by Castro et al. [9]. The Circularity Gap Reporting Initiative (CGRI) periodically reports a circularity rate for the circular economy, assessing global economic conditions. In recent years, the global circular economy has experienced a declining trend. In 2018, the circularity rate was 9.1%, decreasing to 8.6% in 2020 and 7.2% in 2023. This decline mainly results from an increase in absolute resource consumption [10].

3 ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING IN CIRCULAR ECONOMY

In the context of a modern economic system, there is a constant need for innovative solutions that can enhance the overall quality and sustainability of production while reducing costs. AI technologies are capable of introducing new industrial paradigms [11]. Recognized as one of the fathers of AI McCarthy [12] defined AI in 1990 as the scientific and technological field focused on developing intelligent machines, with a specific emphasis on intelligent computer programs. AI encompasses various domains including data mining, ML, and deep learning. It is a synthesis of mathematical reasoning and error-reduction operations [13]. Primarily, AI techniques learn from extensive datasets, comprising numerical inputs, audio, video, or image data, and iteratively refine their learning function to minimize errors. The objective is to achieve the highest possible accuracy in modeling and prediction [14]. AI has demonstrated a significant impact on driving progress towards a sustainable global society [15]. As a result, AI has the potential to play a central role in addressing the crucial challenges associated with a smarter circular economy, including sustainable manufacturing [5], waste management [16] reverse logistics [17], energy optimization [18], and supply chain management [13]. By harnessing AI technologies, solutions can be developed to optimize these areas, enabling more efficient and environmentally friendly practices within the circular economy context.

3.1 Shaping the circular economy through AI and ML

Noman at al. referred to AI as intelligent systems that aim to replicate human-like cognitive abilities, including reasoning, understanding, generalization, and learning from past experiences. Major industries in today's economy have shown great interest in AI, which encompasses the thinking, acting, and performing capabilities of machines. Concurrently, the Circular Economy (CE) has gained the attention of academia, governments, and businesses. The sustainability of an organization is now closely linked to digital innovations. At the core of the circular economy lies the integration of digitization and innovation, enabling long-term sustainability. Through digital innovation, a circular economy maximizes the utilization of limited resources by leveraging digital platforms, smart devices, and AI [14, p. 16].

3.2 Designing and maintaining circular products

AI can support the design, development, and maintenance of circular products. This is performed in two ways. First, a product must be designed and created in accordance with the so-called 3Rs (Reduce, Reuse, Recycle). In particular, products must be designed to ensure a prolonged lifespan and separate the components of the biological cycle from those of the technical cycle, which enhances their recycling potential [19]. AI can support design professionals by generating initial eco-friendly product design proposals, adapting designs based on environmental parameters, and/or considering other actors in a circular value chain [20]. For example, product design criteria could be based on regional or recycled materials, which, in turn, would reduce resource extraction and emissions caused by transporting materials. In addition, AI can assist in the development of new materials that can substitute for unsustainable resources, such as harmful chemicals.

AI can be employed to review products and make data-driven decisions to maintain circular products. For example, AI-powered digital twins that mimic physical objects can help analyze performance over time and formulate recommendations for improvement [21]. The resulting insights can be used to make informed decisions regarding a given product, including determining necessary interventions, optimizing performance, and extending the life of the product [22].

3.2 Fostering circular business

AI could also favor circular business models. In this regard, these three areas are likely to be promising.

First, AI can be utilized to develop innovative circular business models such as AI-based dynamic pricing. When products are marketed as services or recycled products are distributed, it is unlikely that standardized pricing will apply, given the multitude of variables that influence the price of a product. Similarly, matching algorithms can contribute to matching buyers and sellers more effectively [23].

Second, AI can support the circular economy by upgrading the required recycling infrastructure for a functioning circular economy. Efficient sorting is necessary because circular economy intends to reuse, repair, and recycle items. AI-powered image recognition can identify and differentiate waste, thereby minimizing resource consumption [6]. In the e-waste sector, robots are embedded in disassembly lines to capture and recycle high-value or hazardous materials at the end of a product's lifecycle [24].

Third, AI can help with the infrastructural challenges required to ensure that the resources serving the circular economy are, in turn, sustainable. The energy consumption of data storage and processing is an example worth highlighting. If data-intensive circular economy models require high electricity consumption, much of the environmental ambitions of the circular economy could be undermined [25].

4 IMPLICATIONS AND RISKS OF AI DEPLOYMENT IN A CIRCULAR ECONOMY

The deployment of AI in the development of products and businesses offers multiple potential gains. However, without proper consideration of the associated dangers, the use of AI could undermine its beneficial value by being harmful and disfavored by society [26].

4.1 Privacy breach

CE depends on collaborative partnerships and processes between various players. Given the interconnected nature of supply chains, a single economic stakeholder is unable to "close the chain"; circular economies practically fail to materialize without collaboration. Data are the foundation for these intra and inter-organizational links, as they provide stakeholders with information on the various parameters of the underlying factors, such as location, quality, and availability. However, data gathering and analysis pose privacy risks. In terms of data collection, the distribution of tracking and measurement equipment, such as IoT, in the personal realms is, in many cases, a precondition for AI-powered CE products. This poses a significant risk to privacy [22].

4.2 Algorithmic presetting

In the existing literature, the adoption of algorithm-based business models such as automated dynamic pricing and matching is generally regarded positively. AI can be employed to scale circular business operations by automatically setting prices for reused products and matching them with potential consumers, based on factors such as recent market demand, product conditions, or consumer profiles. However, the implementation of automatic dynamic pricing and algorithmic profiling has encountered challenges, leading to unfair or potentially discriminatory outcomes [2]. Recently, instances of unfair practices in automated dynamic pricing have emerged. For example, a provider of online Scholastic Assessment Test preparation courses employed zip codes as a proxy for ethnic origin, resulting in discriminatory treatment where Asians were offered higher fees than non-Asians at nearly twice the rate

[27]. Similarly, the pricing algorithm of the dating app Tinder was found to discriminate against users over the age of 30 [28].

DISCUSSION & CONCLUSION

AI 's ability to replicate human-like cognitive abilities and its application in various industries make it a valuable tool in achieving circular economy goals. By supporting the design, development, and maintenance of circular products, AI facilitates the implementation of the 3Rs (reduce, reuse, recycle) principles and the creation of eco-friendly designs. It can generate initial design proposals, adapt existing designs based on environmental parameters, and contribute to the development of sustainable materials. AI-powered digital twins play a crucial role in analyzing product performance over time and provide insights for improvement, thereby extending product lifespans. Additionally, AI fosters circular business models through dynamic pricing, improved recycling infrastructure, and addressing infrastructural challenges to ensure resource sustainability. AI and ML play an increasingly vital part in achieving and improving the principles of the circular economy, such as resource optimization, waste management, supply chain management, product design and lifecycle assessment, and predictive maintenance.

In summary, although algorithm-based business models utilizing AI for automated dynamic pricing and matching are generally favored in the literature, there have been cases in which these practices have led to unfair outcomes. Awareness of these challenges is crucial to ensuring that AI-driven circular business operations uphold fairness and avoid discriminatory practices.

Overall, AI and ML provide valuable tools and techniques for optimizing resource management, improving waste management systems, streamlining supply chains, developing sustainable product designs, and engaging consumers in ways that encourage a circular economy to evolve. To enable AI-driven circular economy solutions, it is essential to address privacy concerns associated with data gathering and analysis, especially when deploying IoT devices in personal settings. Striking a balance between data utilization and privacy protection is vital for the successful and ethical implementation of circular economic practices.

[1] Regulation 2020/852 of the european parliament and of the council of 8. Juni 2020 on the establishment of a framework to facilitate sustainable investment, and amending Regulation (EU) 2019/2088 [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32020R0852 (accessed Jun. 14, 2023).

[2] H. Roberts et al., Artificial intelligence in support of the circular economy: ethical considerations and a path forward, AI Soc., Nov. 2022, doi: 10.1007/s00146-022-01596-8.

[3] M. von Hauff, Grundwissen Circular Economy: vom internationalen Nachhaltigkeitskonzept zur politischen Umsetzung. in utb Wirtschafts- und Sozialwissenschaften, no. 5988. München: UVK Verlag, doi: 10.36198/9783838559889.

[4] D. H. Meadows and Club of Rome, Eds., The Limits to growth: a report for the Club of Rome's project on the predicament of mankind. New York: Universe Books, 1972.

[5] W. McDonough and M. Braungart, Cradle to cradle: remaking the way we make things, 1st ed. New York: North Point Press, 2002.

[6] W. R. Stahel, The Performance Economy. London: Palgrave Macmillan UK, 2010. doi:10.1057/9780230274907.

[7] J. T. Lyle, Regenerative design for sustainable development. in Wiley series in sustainable design. New York, NY: Wiley, 1994.

[8] J. Korhonen, A. Honkasalo, and J. Seppälä, Circular Economy: The Concept and its Limitations, Econ., vol. 143, pp. 37–46, Jan. 2018, doi: 10.1016/j.ecolecon.2017.06.041.

[9] C. G. Castro, A. H. Trevisan, D. C. A. Pigosso, and J. Mascarenhas, The rebound effect of circular economy: Definitions, mechanisms and a research agenda, J. Clean. Prod., vol. 345, p. 131136, Apr. 2022, doi: 10.1016/j.jclepro.2022.131136.

[10] Circularity Gap Reporting Initiative (CGRI), CGR_Circularity Gap Report 2023. [Online]. Available: https://www.circularity-gap.world/2023#download

[11] N. Gupta, A Literature Survey on Artificial Intelligence, Int. J. Eng. Res. Technol., vol. 5, no. 19, Apr. 2018, doi: 10.17577/IJERTCONV5IS19015.

[12] J. McCarthy, M. L. Minsky, N. Rochester, and C. E. Shannon, A Proposal for the Dartmouth Summer Research Project on Artificial Intelligence, August 31, 1955, AI Mag., vol. 27, no. 4, Art. no. 4,Dec. 2006, doi: 10.1609/aimag.v27i4.1904.

[13] U. Awan, N. Kanwal, S. Alawi, J. Huiskonen, and A. Dahanayake, Artificial Intelligence for Supply Chain Success in the Era of Data Analytics, in The Fourth Industrial Revolution: Implementation of Artificial Intelligence for Growing Business Success, A. Hamdan, A. E. Hassanien, A. Razzaque, and B. Alareeni, Eds., in Studies in Computational Intelligence, vol. 935. Cham: Springer International Publishing, 2021, pp. 3–21. doi:10.1007/978-3-030-62796-6_1.

[14] A. A. Noman, U. H. Akter, T. H. Pranto, and A. B. Haque, Machine Learning and Artificial Intelligence in Circular Economy: A Bibliometric Analysis and Systematic Literature Review, Ann. Emerg.Technol. Comput., vol. 6, no. 2, pp. 13–40, Apr. 2022, doi: 10.33166/AETiC.2022.02.002.

[15] H. Wilts, B. R. Garcia, R. G. Garlito, L. S. Gómez, and E. G. Prieto, Artificial Intelligence in the Sorting of Municipal Waste as an Enabler of the Circular Economy, Resources, vol. 10, no. 4, p. 28,Mar. 2021, doi: 10.3390/resources10040028.

[16] S. L. Nañez Alonso, R. F. Reier Forradellas, O. Pi Morell, and J. Jorge-Vazquez, Digitalization,Circular Economy and Environmental Sustainability: The Application of Artificial Intelligence in the Efficient Self-Management of Waste, Sustainability, vol. 13, no. 4, p. 2092, Feb. 2021, doi:10.3390/su13042092.

[17] M. Schlüter et al., AI-enhanced Identification, Inspection and Sorting for Reverse Logistics in Remanufacturing, Procedia CIRP, vol. 98, pp. 300–305, 2021, doi: 10.1016/j.procir.2021.01.107.

[18] G. Lechner and M. Reimann, Integrated decision-making in reverse logistics: an optimisation of interacting acquisition, grading and disposition processes, Int. J. Prod. Res., vol. 58, no. 19, pp.786–5805, Oct. 2020, doi: 10.1080/00207543.2019.1659518.

[19] Ellen MacArthur Foundation, Circular economy introduction. [Online]. Available: https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview (accessed Jun. 22, 2023).

[20] F. Acerbi, D. A. Forterre, and M. Taisch, Role of Artificial Intelligence in Circular Manufacturing:A Systematic Literature Review, IFAC-Pap., vol. 54, no. 1, pp. 367–372, Jan. 2021, doi:0.1016/j.ifacol.2021.08.040.

[21] Siemens AG, Digital Twin. https://www.plm.automation.siemens.com/global/en/our-story/glossary/digital-twin/24465 (accessed Jun. 22, 2023).

[22] G. Bressanelli, F. Adrodegari, M. Perona, and N. Saccani, Exploring How Usage-Focused Business Models Enable Circular Economy through Digital Technologies, Sustainability, vol. 10, no. 3, Art.no. 3, Mar. 2018, doi: 10.3390/su10030639.

[23] P. Gailhofer et al., The role of Artificial Intelligence in the European Green Deal. Policy Department for Economic, Scientific and Quality of Life Policies Directorate-General for Internal Policies.

[24] A. Renteria and E. Alvarez-de-los-Mozos, Human-Robot Collaboration as a new paradigm in circular economy for WEEE management, Procedia Manuf., vol. 38, pp. 375–382, Jan. 2019, doi:0.1016/j.promfg.2020.01.048.

[25] N. Jones, How to stop data centres from gobbling up the world's electricity, Nature, vol. 561, no. 7722, pp. 163–166, Sep. 2018, doi: 10.1038/d41586-018-06610-y.

[26] L. Floridi, J. Cowls, T. C. King, and M. Taddeo, How to Design AI for Social Good: Seven Essential Factors, Sci. Eng. Ethics, vol. 26, no. 3, pp. 1771–1796, Jun. 2020, doi: 10.1007/s11948-020-0213-5.

[38] J. A. Larson Surya Mattu,Jeff, The Tiger Mom Tax: Asians Are Nearly Twice as Likely to Get a Higher Price from Princeton Review, ProPublica, [Online]. Available: https://www.propublica.org/article/asians-nearly-twice-as-likely-to-get-higher-price-from-princeton-review?token=UnpQVP7I8tJbGlMfvfYJisVdJ7aaZ7jl (accessed Jun. 22, 2023).

[39] M. Heikkilä, UK consumer group: Tinder's pricing algorithm discriminates against over-30s, POLITICO, [Online]. Available: https://www.politico.eu/article/uk-consumer-group-tinders-pricing-algorithm-discriminates-against-gay-users-and-over-30s/ (accessed Jun. 22, 2023).