Guest editorial: The role of Industry 4.0 in enabling circular economy

1. Introduction

Research on circular economy (CE) has been of interest to academics and practitioners, referring to industrial economies that aim to enrich sustainability through complementary objects and design (Ghisellini *et al.*, 2016). In the last two decades, manufacturing has undergone a major shift from factory-based operations to internationally decentralised networks, vertical collaboration between supply chain partners and business ecosystems (Shi *et al.*, 2021). The global industrialisation process is now more subject to the requirements and constraints of environmental protection. However, issues such as pollution management brought about by intense industrialisation make the balance between industrialisation and ecology insoluble (Shi *et al.*, 2021). The idea of reducing waste and increasing efficiency has been of interest since the early days of the industrial economy, and CE currently aims to achieve this by means of recovering value from tangible goods. This closed loop of recycling and recovery can improve economic and environmental performance, for example, through recycling and energy recovery (Ashby, 2018).

CE can address broader issues to address socio-environmental challenges (Ghisellini *et al.*, 2016). The circular supply chain (CSC) is a complex system that provides infinite recycling, remanufacturing and recirculation of materials and resources (Genovese *et al.*, 2017; Webster and MacArthur, 2017). The implementation of a CE programme involves company implementing strategies to develop the circularity of its production system and collaborating with other companies throughout the supply chain to achieve a more efficient circular production model (Genovese *et al.*, 2017; Nasir *et al.*, 2017; Wrinkler, 2011). In this context, engaging companies' supply chains in their CE initiatives is a promising and worthwhile endeavour (Jiang and Zhou, 2012; Nasir *et al.*, 2017). The benefits of CE are enhanced by the acceleration of global challenges, particularly its approach to maximising benefits and value across the biological and technological cycles of products, components and materials. This can be achieved by deliberately considering how resources are used and reused throughout a product's lifecycle, from design to disposal.

Scientists and experts agree that technology can contribute to more reliable and sustainable CE outcomes (e.g. Kumar *et al.*, 2018; Massaro *et al.*, 2021). With the launch of the German policy initiative "Industry 4.0" (I4.0), digital technologies have received much attention from academics and practitioners, and this new approach is creating value (Ceipek *et al.*, 2020; Roblek *et al.*, 2016). I4.0, AI, robotics, big data and the Internet of Things (IoT) have accelerated industrialisation by increasing efficiency and effectiveness (Kiel *et al.*, 2017; Sung, 2018; Lanzolla *et al.*, 2020). Today, companies are using a variety of technologies driven by I4.0 to optimise their resource use, improve operational efficiency and achieve higher levels of sustainability across all environmental, social and economic dimensions (Nikolaou *et al.*, 2021). This transformation requires companies' research and development (R&D), design and production departments to respond quickly to the changing needs of external factors such as the market and the natural environment, for example, Alibaba's use of digital technologies, including resource allocation at the organisational and business ecosystem level. This is consistent with the nature of CE, which refers to regenerative or restorative industrial

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economies whose designs, processes, intentions and behaviours reflect CE (Geissdoerfer *et al.*, 2017).

2. The relevance of the CE literature

To address the growing tension between economic development and environmental protection, the CE has become the focus of researchers' attention (MacArthur, 2013). The environmental and ecological crisis has become one of the greatest challenges to the world's sustainable development. New approaches are needed to achieve a more balanced development between industrialisation, environmental protection and resource efficiency (Shi *et al.*, 2021). We have presented the following information on CE descriptions below:

> Circular economy refers to regenerative systems that reduce resource inputs and waste as well as emissions by slowing, closing and limiting material and energy cycles (Yuan *et al.*, 2008; Murray *et al.*, 2017; Schroeder *et al.*, 2019; Patwa *et al.*, 2021).

The CE can theoretically improve financial performance while also ensuring that natural resources are consumed sustainably, many scholars and practitioners argue that it offers a viable way for companies to achieve harmony between economic growth and environmental protection (Kristoffersen *et al.*, 2021). CE can be considered as a shift from a traditional linear life cycle to four recycling cycles' paradigm shift, namely reduction, remediation, remanufacturing and recycling (Urbinati *et al.*, 2017; Fernández and Kekäle, 2005). In addition to its widely depicted environmental benefits, as a new economic model, CE may create new business opportunities for SMEs in emerging markets, such as reducing material costs (Rizos *et al.*, 2016) and extending product life (Agyemang *et al.*, 2019; Geng and Doberstein, 2008).

Furthermore, information processing theory emphasises that matching information processing needs with capabilities can enhance competitive advantage (Premkumar *et al.*, 2005). Information processing needs depend on uncertain environmental factors that are undoubtedly consistent with the environmental resources highlighted by the natural resource perspective. Information processing capabilities emphasise the range of capabilities acquired through resource allocation to enhance the collection, processing and application of information (Premkumar *et al.*, 2005). Thus, in the implementation of a CE using environmental resources, information processing capabilities can influence the use and arrangement of resources by providing a wider range of information sources and information sharing (Büyüközkan and Göçer, 2018). In recent years, China has proposed a number of policies to promote a CE (McDowall *et al.*, 2017; The State Council, 2021a, b), such as the 2021 peak carbon and carbon neutrality targets. These targets point to the establishment of a green, low-carbon and CE system that promotes a comprehensive green transformation of the country's economic and social development (The State Council, 2021a). Indeed, China has arguably elevated the positioning of the CE to a new strategic level (McDowall *et al.*, 2017). The CE has become central to Chinese policy (McDowall *et al.*, 2017), and Chinese companies are vigorously pursuing it (Zhu *et al.*, 2019). China is now faced with how to achieve sustainable and digital development, and Chinese companies are responding well by combining the digital economy with the CE (Tseng *et al.*, 2018; Chen *et al.*, 2021).

3. The role of I4.0 in fostering CE

I4.0 is known as the "Fourth Industrial Revolution" – originated with the German Federal Government in 2011. I4.0 is defined as "a strategic initiative in Germany that aims to play a pioneering role in an industry that is currently revolutionising manufacturing" (Xu *et al.*, 2018). I4.0 emphasises the enhancement of industrial capabilities through the application of technology and digital enhancement of industry (Luthra *et al.*, 2020). There is no consensus in the literature on how to classify the technologies associated with I4.0 (Laskurain-Iturbe *et al.*, 2021). I4.0 and CE are understood as two sides of the same coin (Garcia-Muiña *et al.*, 2018). The concept of CE is widely considered to be an important tool for sustainable development, which attempts to bring environmental protection and economic growth into balance. Its role is increasingly valued in the context of I4.0, which has created and adopted a variety of new technologies (Zhou *et al.*, 2020).

Dantas *et al.* (2021) indicate that technologies associated with I4.0 include CPS, IoT, Big Data and Analytics (BD(A)), Additive Manufacturing (AM), Internet of Services (IoS), Cloud Computing (ClC), Augmented Reality (AR), Systems Integration (SI), Simulation (SIM), Cyber Security (CS) and Autonomous Robotics. In addition, digitisation (Dig) and intelligent robotics (Rob) are also considered new I4.0 approaches that have been used to develop waste management toward CE (Sarc *et al.*, 2019). Gubbi *et al.* (2013) state that the IoT consists of radio frequency identification (RFID) systems and wireless sensor networks (WSN). Wortmann and Flüchter (2015) highlight the IoT as a subset of I4.0, as IoT-based solutions are often applied by smart industries, which is widely discussed in the context of I4.0. The IoT is further subdivided into the industrial Internet of Things (IIoT) and the consumer Internet of things (CIoT) (Sarc *et al.*, 2019). Rajput and Singh (2019) argue that I4.0 is a combination of cyber-physical systems (CPS), IoT and cognitive computing (CoC). Blömeke *et al.* (2020) state that CPS constitutes I4.0 a technological core, a network of digital physical systems that enables new forms of manufacturing, value chains and strategic planning by providing advanced data management solutions (Ceipek *et al.*, 2020). Furthermore, these technologies have the potential to redefine value creation. Productivity is also increased, while traceability is improved through the supply chain, thus creating new service-oriented economic models (Mittal *et al.*, 2018; Reinhard *et al.*, 2016). Technology facilitates coordination across the supply chain in achieving CE goals, maximising profits while conserving natural resources and minimising energy expenditure and pollution (Aminoff and Kettunen, 2016; Nasir *et al.*, 2017).

Industrialisation and emerging challenges industrialisation have more implications for the process of transformation of a country's industrial structure, for example, from an agrarian to an industrial society (Chang, 1949; Kiely, 1998; Pomeranz, 2001). The focus is on the process of formation and development of the transition from zero or small industries to mature industries, an example being the current commercialisation of digital technologies to emerging industries (Rogers *et al.*, 2004; Datta *et al.*, 2013). Industrialisation implies the design, construction, operation and improvement of industrial systems (Slack *et al.*, 2016). Cezarino *et al.* (2021) investigate how I4.0 and CE are interconnected. Rosa *et al.* (2020) develop a framework for interconnecting I4.0 and CE. Zhou *et al.* (2020) assessed the joint impact of I4.0 and CE in terms of technological advances and structural changes. Dantas *et al.* (2021) showed in their systematic literature review that combining CE practices and I4.0 technologies can achieve sustainable development goals. Spaltini *et al.* (2021) proposed a framework to analyse the impact of different CE strategies and I4.0 technologies and identified CM and AM as the most important enabling technologies for CE strategies, including reduction, redesign, recycling and remanufacturing. Ertz *et al.* (2022) published a literature review that explored how I4.0 technologies can extend product life (which is considered a way to save CE resources) and found that AM, AI, IoT and BD(a) are four key I4.0 technologies. An empirical study by Tang *et al.* (2022) of private companies involved in supply chain operations showed that blockchain had a significant impact on all components of CE. Bai *et al.* (2022) explored the impact of I4.0 technologies on the Sustainable Development Goals (SDGs), noting that CE plays a key role in connecting I4.0 and the SDGs.

In recent years, I4.0 infusion of remanufacturing, recycling and reusing resources appears to have contributed to the adoption of CE approaches in organisations' global operations

(Rosa *et al.*, 2020). There has been a large body of conceptual and empirical research demonstrating how I4.0 can contribute to the adoption of innovative circular business models, resource efficient intra- and inter-organisational processes, and the delivery of products and services that meet CE objectives (Chauhan *et al.*, 2022; Schuh *et al.*, 2014; Fisher *et al.*, 2017). According to information processing theory (Premkumar *et al.*, 2005), every firm must process complex environmental information and in order to gain a sustained competitive advantage, firms must match their information processing capabilities with their information processing needs. Digital supply chain platforms are digitally driven infrastructures that are built for the continuous high speed transfer of supply chains (Rai *et al.*, 2006). These platforms need to integrate a variety of advanced technologies such as big data, artificial intelligence, blockchain, the IoT and cloud computing. Digital supply chain platforms can greatly improve the information processing capabilities of enterprises (Gunasekaran *et al.*, 2017; Frank *et al.*, 2019), and they are drivers of CE implementation. Environmental orientation and digital supply chain platforms are important for companies to implement a CE. Digital technologies are changing the industrial landscape and disrupting traditional business models. New business opportunities associated with I4.0 are emerging (Rubio *et al.*, 2021). I4.0 is an important driver of the CE, with the potential to decouple economic growth from resource consumption. Both in terms of global green trends and strategies to combat climate change and in terms of resource demand and utilisation levels, countries must vigorously develop a CE to achieve efficient resource use and recycling and promote high-quality economic and social development (Development and Commission, 2021).

Although research on the integration of I4.0 technologies into CE is at an early stage, several examples illustrate the great potential of technologies to realise the CE vision (Choi, 2019; Verdouw *et al.*, 2016). While some of these illustrations are summarised in Table 1,

Technologies	Technologies used in enabling effective CE
Internet of things (IoTs)	IoT technologies can help reduce waste and improve food safety, as well as increase the overall efficiency and sustainability of the food supply chain (Ben Daya *et al.*, 2019)
Machine learning	Machine learning has been used to help reduce greenhouse gas emissions and to promote environmental and social concerns (Liu *et al.*, 2020)
Circular integrated waste management systems (CIWMS)	CIWMS have been used to promote sustainability by increasing the link between resource disposal and recycling (Cobo *et al.*, 2018)
3D printing	To produce high-quality consumer goods such as camera tripods, SD card holders and camera covers, plastic waste from computer debris is transformed into 3D printed filaments, thus shortening the CE cycle (Zhong and Pearce, 2018)
Waste electrical and electronic equipment (WEEE)	WEEE can be used to integrate waste and product lifecycle management, making cities more sustainable and smarter by using the internet of Things (Esmaeilian *et al.*, 2018). To improve the WEEE recycling process, collaborative robots could be introduced into a processing line that would work alongside humans to increase the number of valuable parts recycled (Alvarez-de-los-Mozos and Renteria, 2017)
Radio frequency identification (RFID)	RFID technology is an effective way to improve product quality assurance and safety by identifying batch dates and times as well as identifying individual products (Verdouw *et al.*, 2016). Environmental factors such as weather, humidity and nutritional parameters can be assessed using this tool

Table 1.
Technologies used in enabling effective CE

the interested reader is referred to the literature review by Farooque *et al.* (2019), which provides further details.

4. Toward a research agenda for CE

This editorial notes that I4.0 for CE is still an emerging area of research. There are many relevant publications dealing with conceptual work and case studies, which are typical of research areas that are still in their infancy. Many topics in I4.0 and CE are receiving more attention, including information processing and digital technologies. A number of technical, process and motivational challenges still need to be overcome before CE can become a reality.

The seven papers in this special issue are based on innovative and valuable empirical findings that provide novel perspectives and contribute to the development of effective CE practices through the use of I4.0. Each of the seven papers in this issue provides relevant insights into an emerging area of research. While we believe that these papers focus on the current state of the intersection between I4.0 and CE, we also believe that they provide a strong basis for future research. We hope that this particular issue will further the research agenda around the intersection between I4.0 and CE.

Ding, Xia, Zhao and Li's "The impact of government subsidies on build-operate-transfer contract design for charging piles in CE" develops a typical game model to investigate optimal BOT contracts between government and charging pile operators and their preferences for both types of subsidies. This study builds a first analytical model to study both subsidies in the construction and operation of charging piles and to study optimal BOT contracts and subsidy preferences. These insights will appeal not only to charging post operators but also to policymakers from a CE perspective.

Liu, Song, Zheng, Ma and Li's "Remanufacturing production decisions considering the product life cycle and green consumers" scale in the CE" aims to investigate the optimal strategies of original equipment manufacturers (OEMs) while considering consumer segmentation and upward substitution of remanufactured products in the product life cycle. In this paper, the authors develop two remanufacturing models: the OEM remanufacturing model and the licensed remanufacturing model. The impact of green consumer size and product life cycle expressed as market growth rate on the OEM's optimal decision is then investigated. The authors used game theory to derive optimal solutions for both models. This study fills a gap in existing research by discussing both product lifecycle and green consumer scale, providing manufacturers with a new basis for remanufacturing decisions.

Zheng, Wang, Lin and Liu's "Understanding CE adoption by SMEs: a case study on organizational legitimacy and I4.0" explores how I4.0 can facilitate small and medium-sized enterprises (SMEs) in emerging markets to gain and maintain organisational legitimacy from governments and markets and to derive value from the adoption of CE by enterprises. The authors conducted an in-depth, multi-stakeholder case study of an SME in the hazardous waste recycling and reuse industry in China, using a qualitative analysis approach. The paper validates the beneficial role of I4.0 in CE applications in SMEs and generates legitimisation processes and strategies to facilitate SMEs to capture value from CE applications.

Li, Hu, Zheng, Yin and Fu's "Drivers and outcomes of CE implementation: evidence from China" draws on a natural resource-based perspective and information processing theory to explore how environmental orientation and digital supply chain platforms can facilitate CE implementation and improve the impact of CE implementation on financial performance. The authors surveyed 249 Chinese firms and used hierarchical regression analysis to test the hypotheses. This article contributes to the literature on the CE by revealing new drivers and outcomes of different implementation models of the CE. Furthermore, the findings have implications for how companies should develop their CE initiatives in the context of the digital revolution.

Dai, Wen, Zhou, Tong and Xu's "Enhancing online to offline delivery efficiency facilitated by I4.0: a personnel configuration perspective" focuses on improving delivery efficiency in an online-to-offline (O2O) context from the perspective of individual configuration facilitated by I4.0 technologies, i.e. comparing the efficiency of in-house and crowdsourced delivery in the context of O2O on-demand food delivery in China. The authors collected 128,152 orders from 38 restaurants of an online restaurant chain in China and used multiple regression analysis to investigate the delivery efficiency gap between in-house and crowdsourced deliverers and the determinants of this efficiency gap. The results of this study contribute to the online fulfilment literature by focussing on delivery efficiency in the context of O2O from the perspective of staffing facilitated by I4.0 technologies. The authors examine how internal and external factors moderate the performance efficiency between these two types of delivery agents.

Lei, Cai, Cui, Wu and Liu's "How do different I4.0 technologies support certain CE practices?" aims to quantitatively explore the impact of various I4.0 technologies on CE practices. A mixed-method approach including systematic literature review, content analysis and social network analysis was used in this study. This study uses a comprehensive, quantitative and visual analysis to reveal the current level of implementation of I4.0 technologies and CE practices. It further explores how different I4.0 technologies affect various aspects of CE, how different I4.0 technologies are integrated to facilitate CE implementation and how various CE practices are implemented simultaneously through I4.0 technologies.

Shi, Hu, Shang and Liu's "Industrialisation, Ecologicalisation and Digitalisation (IED): Building a theoretical framework for sustainable development" aims to develop a holistic view that integrates the three bodies of knowledge (industrialisation, ecologicalisation and digitalisation (IED)). The authors conduct a critical literature review of the three bodies of knowledge. Key themes were summarised by identifying research gaps. A theoretical framework is synthesised and developed that aims to achieve synergies between IEDs and modules, integrated architectures, mechanisms and dynamic pathways. This research helps to address the limited literature on IED linkages by integrating different perspectives to develop theory in a novel way. In effect, it provides an important tool for organisations to consider resource cascading and digitisation in the industrial system design process.

5. Conclusion

This position paper aims to summarise some of the main themes of recent research on the I4.0 facilitation of CE. It starts with a definition of CE and then describes the contribution of I4.0 to CE practices, as well as the barriers that are often mentioned when discussing CE practices. The relationship between I4.0 technologies and CE practices is revealed to be crucial not only for implementing CE but also for using I4.0 to achieve sustainable development goals. In addition, we explore the development of I4.0 technologies and propose future research directions and paradigms on I4.0 and CE practices.

As illustrated by the papers in this special issue, the importance of I4.0 for CE and technological advances offer a wealth of research opportunities. With this particular issue, we aim to enhance the understanding of I4.0 and CE practices, while providing a basis for future research in the field. As I4.0 technologies are increasingly updated to support CE practice, the potential for academics and researchers to generate new knowledge and advance this value agenda is evident.

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