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Industry 4.0 technologies in support of circular Economy: A 10R-based integration framework☆

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ABSTRACT

The urgency of addressing global challenges such as climate change, resource scarcity, and environmental degradation has positioned the Circular Economy (CE) as a crucial strategy for sustainable development. Industry 4.0 (I4.0) technologies have been recognized as key enablers of CE. However, a significant knowledge gap exists regarding how organizations can effectively integrate these technologies with CE strategies. Existing integration frameworks often focus narrowly on specific industries, technologies, or the traditional 3R model, neglecting the broader 10R framework and, hence, offering limited guidance. This paper addresses these gaps by developing a comprehensive 10R-based integration framework, providing practical guidance on how I4.0 technologies can support the full range of CE strategies. Using a literature review based on keywords' clusters analysis, this study explores how I4.0 can support both implementation and decision-making in the CE 10Rs, providing a practical guide for businesses and supporting a broader shift towards sustainable business models. The results show that IoT, Big Data, and Digital Twins effectively support Rs related to smarter product use and manufacturing processes. Additive Manufacturing, Augmented/Virtual Reality, and Cognitive Twins are crucial in extending the lifespan of products or components. IoT, Artificial Intelligence, Blockchain, and human-robot collaboration can improve recycling practices and material recovery. The study reveals that while 'Reduce' and 'Recycle' dominate the literature, integrating I4.0 technologies with lesser-explored strategies like 'Reuse,' 'Repurpose,' 'Refurbish,' and 'Remanufacture' offers significant potential for future research. It also stresses the need to assess the energy and environmental impacts of I4.0 technologies themselves in the CE context.

1. Introduction

As reported by several international agencies and organizations, the last years have been characterized by an increasing number of natural disasters deriving from global warming, which are expected to further increase (IPCC, 2023; WMO, 2024). In this perspective, aiming to avert the most catastrophic impacts of climate change, it is crucial to reduce greenhouse gas emissions to limit global temperature rise to well below 2 °C, and preferably to 1.5 °C, above pre-industrial levels, as set in the Paris Agreement (UN, 2015). In line with this, governmental bodies commit to achieving net-zero greenhouse gas emissions. For example, the European Union has set a goal to become the first climate-neutral economy and society by 2050 (European Commission, 2020).

However, as suggested by the Intergovernmental Panel on Climate Change (IPCC), achieving net-zero emissions requires transformative changes across all sectors of the economy (IPCC, 2022). Specifically, the IPPC suggests that the circular economy (CE) represents a crucial strategy for reducing greenhouse gas emissions and achieving net-zero emission goals. This is further corroborated by other international agencies, governmental bodies, and researchers (Acerbi et al., 2024; European Commission, 2020; IEA, 2022; Saccani et al., 2023; Sassanelli et al., 2023). Indeed, the European Commission specifically stated that *"The EU's transition to a circular economy [...] is a prerequisite to achieve the EU's 2050 climate neutrality target"* (European Commission 2023). According to Bocken et al. (2016), this is possible thanks to the three main strategies that characterize CE, i.e. (i) slowing resource loops, (ii)

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closing resource loops, and (iii) narrowing resource flows. Over the years, different CE frameworks have encompassed these three main strategies. Indeed, aiming to expand the possibilities for businesses to implement a CE, we have now moved from the initial 3Rs framework, where only three strategies were considered (i.e., *Reduce*, *Reuse*, and *Recycle*), to a more complete CE framework like the 10R where ten strategies are now considered (i.e., *Refuse*, *Rethink*, *Reduce*, *Reuse*, *Repair*, *Refurbish*, *Remanufacture*, *Repurpose*, *Recycle*, and *Recover*) (Cramer, 2017; Morseletto, 2020; Potting et al., 2017).

Nevertheless, despite the development of more complete CE frameworks to support and encourage businesses to expand their CE implementations and despite the clear benefits that CE provides in terms of reducing the environmental impacts of products (and also in terms of decoupling the use of the planet's resources from the population consumption), CE adoption is still very limited. According to CIRLE Economy (2023), in 2022, just 7.3 % of the 100 billion tons of materials used to feed our economy came from CE business models. Researchers have hence investigated how to boost the adoption of CE, and Industry 4.0 (I4.0) technologies have rapidly emerged as enabling factors for the adoption of CE. Indeed, in the last decade, I4.0 technologies have been widely recognized as enablers of integrated value chains (Awan et al., 2022; Basile et al., 2023; Sassanelli et al., 2021; Schmidt et al., 2023), and hence their adoption to boost CE adoption has been considered “natural” (Moktadir & Ren, 2023). As an example, the Internet of Things (IoT) and Big Data Analytics (BDA) enable the establishment of closed-loop supply chains, which are crucial for enabling CE adoption (Patil et al., 2023). Indeed, they allow, for example, to optimize reserve logistic flows by enhancing visibility, efficiency, and decision-making (Pratap et al., 2024). Then, IoT and BDA can also support the *Reduce* CE strategy enabling an efficient exploitation of natural resources (Esmaeilian et al., 2018; Romero & Noran, 2017; Song et al., 2017). Other examples of I4.0 technologies supporting CE strategies are machine learning and artificial intelligence (Ahmed et al., 2023), which, for example, can automate sorting in recycling processes, hence supporting the *Recycle* strategy (Chen, 2022; Namoun et al., 2022), or Additive Manufacturing, similarly supporting the *Recycle* strategy since it enables to use recycled products as new raw materials (Urbinati et al., 2024; Clemon & Zohdi, 2018; Mandil et al., 2016). Many other studies on the enabling role of I4.0 technologies can be found in the literature (Bressanelli et al., 2018; Lopes de Sousa Jabbour et al., 2018; Rosa et al., 2020).

All this evidence on the potentialities of I4.0 technologies to support CE has then led researchers to focus on the development of frameworks that could support the integration of I4.0 technologies and CE: indeed, researchers highlighted the existence of knowledge gaps on how organizations can integrate CE strategies and I4.0 technologies and distance between theory and practice (Taddei et al., 2022; Taddei et al., 2024). Bressanelli et al. (2018), Lopes de Sousa Jabbour et al. (2018), and Rosa et al. (2020) suggested that frameworks guiding companies in such integration could be the solution. Hence, following Lopes de Sousa Jabbour et al.'s (2018) first integration framework, several others can be found in the literature (Lopes de Sousa Jabbour et al., 2023; Lu, Zhao, & Liu, 2022; Kazancoglu et al., 2021); nevertheless these are all characterized by different types of limitations. Indeed, as better described in Section 2.3, the existing frameworks either have a limited scope, addressing specific sectors, or focus on specific circular business models or practices, overlooking the full range of CE strategies, or focus on a specific I4.0 technology or a subset of I4.0 technologies.

Considering this and considering the still high practical need for an integration framework that could close the knowledge gaps on how organizations can integrate CE strategies and I4.0 technologies, this work aims to develop an integration framework that is expected to successfully support the spread of CE adoption since it overcomes the just-mentioned limitations of the existing frameworks. Therefore, the research objective (RO) of this work is the following:

RO: the development of a comprehensive and exhaustive research framework to close the knowledge gaps on how organizations can integrate CE strategies and I4.0 technologies.

To develop such a framework, it is clear the necessity to understand which I4.0 technologies can support CE, and how they can do so. Indeed, only by knowing which I4.0 technologies can support and boost the adoption of CE strategies and how they can do so, we will have all the information required to develop such an integration framework and ensure its correctness. Therefore, the research question (RQ) related to our RO is the following:

RQ: Which I4.0 technologies can support the adoption of CE strategies, and how do they do so?

To answer this RQ, we have carried out a literature review. Indeed, literature reviews allow a thorough theoretical exploration of the available literature on a topic. This, in turn, ensures that the developed integration framework will be grounded on the literature. Moreover, when carrying out the literature review, we have adopted a comprehensive perspective. This will ensure that the integration framework developed will overcome the limitations of the current integration frameworks (limited scope, specific sectors addressed, etc.) given the comprehensive perspective adopted. Notably, given the remarkable amount of scientific research concerning the integration of CE and I4.0 technologies, this work adopts quantitative tools to carry out the literature review, which ensures an impartial and precise categorization. More in detail, this study employs a quantitative bibliometric approach, specifically the keyword co-occurrence network method (Waltman, van Eck, & Noyons, 2010). It is important to note that the need for a new literature review is justified by the gaps in the current literature, which are discussed in detail in Section 2.4. In fact, existing reviews often miss direct links between I4.0 technologies and CE strategies, focus narrowly on the 3Rs overlooking advanced Rs like remanufacturing, or rely on outdated and limited data. Thus, there is a clear need for a more comprehensive review that covers the full range of I4.0 technologies, explores all 10Rs strategies, and incorporates the latest developments to guide effective CE implementation.

The remainder of the paper is structured as follows. Section 2 provides the theoretical background needed for a better understanding of this work, describing the CE strategies and I4.0 technologies considered (Sections 2.1 and 2.2., respectively), as well as a critical summary of the existing frameworks to better define the need for this work. Section 3 describes the methodology adopted, and then Section 4 reports the main results. Here, first, the different research clusters identified from the bibliometric analysis are described (Section 4.1) and then analyzed under the perspective of the 10R framework categorization proposed by Potting et al. (2017), which presents the 10Rs and organizes them into three main strategy groups, namely (i) smarter product use and manufacture, (ii) extended lifespan of product and its parts and (iii) useful application of materials (Section 4.2). This allowed us to derive the integration framework describing how I4.0 technologies can support CE, presented in Section 4.3. Finally, Section 5 discusses the findings, and Section 6 concludes the work.

2. Theoretical background

This Section provides key notions on CE and I4.0 technologies (Sections 2.1 and 2.2, respectively). Then, Section 2.3 discusses the literature on the integration of CE and I4.0, with a particular focus on the existing frameworks and their limitations. Section 2.4 indicates that literature reviews on this topic generally share the same limitations, highlighting the need for a new, more comprehensive review.

2.1. Circular economy

At its core, the CE focuses on preserving products, components, and materials in the economy for as long as possible by establishing *circular value chains* (Ren et al. 2023). The application of CE principles in manufacturing, often referred to as *circular manufacturing* (Liu et al., 2023), is recognized as a key strategy for achieving sustainable manufacturing (Jawahir & Bradley, 2016), as it enables the decoupling of economic growth from environmental impacts (Ren et al., 2023). In this context, *waste management* activities and *reverse logistics* become an integral part of the *circular supply chain* to reach the desired condition of "*end of waste*" and, thus, the entire value chain system needs to be reconfigured (Salmenperä et al., 2021).

Historically, the CE has been rooted in the fundamental principles of the 3Rs: *Reduce*, *Reuse*, and *Recycle*, known as the 3R framework. The latter aims to enhance production efficiency by reducing the consumption of natural resources and mitigating pollution, emissions, and waste. Since then, additional frameworks have been developed based on the 3R framework. The 3R framework served as the cornerstone for the development of green manufacturing concepts that began to emerge in the 1990 s, built upon the foundation of the lean manufacturing paradigm introduced in the 1980 s, which initially concentrated on one R strategy only, i.e., *Reduce*. Already in the last decade, a transformation from green to sustainable manufacturing has been recognized as needed to deliver sustainable value to society. To this end, the 6R framework emerged, encompassing strategies such as *Redesign*, *Remanufacturing*, and *Recovery* (Jawahir & Bradley, 2016). Such a framework has evolved over the years to broaden the set of strategies considered and expand the possibilities for businesses to implement a CE. For instance, strategies like *Refuse* and *Rethink* took the place of the broader concept of Redesign, and the Remanufacturing strategy integrated new strategies like *Repair*, *Refurbish*, and *Repurpose*. This gave rise to a more complete framework, known as the 10R framework (Potting et al., 2017), defined in Table 1.

The 10Rframework is nowadays widely adopted by scholars because of its completeness and comprehensiveness (Morseletto, 2020). However, other approaches can also be found in the literature. A remarkable example is the ReSOLVE framework proposed by the Ellen MacArthur Foundation in 2015 (Ellen MacArthur Foundation, 2017). It comprises six key elements: Regenerate, Share, Optimize Loop, Virtualize, and Exchange. Anyway, the ReSOLVE framework loses specificity if compared to the 10R framework (Helena et al., 2022). The study by Modgil et al. (2021) mapped the relationships between the 10R framework and the ReSOLVE framework; according to their findings, firms are prone to adopt the 10R framework for developing circular business models due to its effectiveness. In fact, by including a broader set of strategies, the 10R framework considers each aspect of a product's value, aiming to maximize the resources' values throughout the entire lifecycle, and it is adaptable to a wide range of industries and product types. It recognizes that different products may require different strategies for optimal resource management, addressing the diversity of products in the modern world.

Moreover, the categorization of the 10Rs into the "Smarter product use and manufacture," "Extend lifespan of product and its parts," and "Useful application of materials" strategies (Morseletto, 2020; Potting et al., 2017) aligns conceptually with the three core principles of the circular economy outlined by the Ellen MacArthur Foundation: (i) eliminate waste and pollution, (ii) circulate products and materials at their highest value, and (iii) regenerate natural systems (Ellen MacArthur Foundation, 2024). However, this categorization provides distinct advantages when aligning CE with I4.0. Unlike the broader systemic principles of the Ellen MacArthur Foundation, these categories map directly to specific stages of the product life cycle, offering actionable insights for supply chain actors. In fact, "Smarter product use and manufacture" addresses the design, manufacturing, and operational efficiencies; "Extend lifespan of product and its parts" emphasizes maintenance, reuse, and remanufacturing, directly linking to reverse logistics and smart monitoring systems; and "Useful application of materials" concentrates on waste processing and recycling (Morseletto, 2020). These operationally grounded strategy groups facilitate the integration of CE concepts into 4.0 production systems and supply chains (de Mattos Nascimento et al., 2024). In contrast, while the Ellen MacArthur Foundation's principles focus on desirable systemic outcomes, they are less explicitly tied to distinct operational stages,

Table 1
Summary of the 10R framework.

CE Strategy Group	CE strategy	Description	Reference
Smarter product use and manufacture	Refuse (R0)	Rendering a product redundant by either abandoning its function or replacing it with a radically different product offering the same function. Additionally, refuse can be extended to encompass the rejection of certain materials or production processes, aiming to foster a more circular economy.	(Kirchherr, Reike, & Hekkert, 2017; Potting et al., 2017)
	Rethink (R1)	Re-elaboration and reconceptualization of ideas, dynamics, processes, concepts, uses, and post-uses related to a product to make it use-intensive.	(Linder, 2017; Potting et al., 2017)
	Reduce (R2)	Using fewer natural resources results in reduced energy, raw materials, and waste inputs. This concept can also be extended to reducing the overall number of products, such as decreasing car ownership, thereby promoting reuse.	(Morseletto, 2020; Reike, Vermeulen, & Witjes, 2018)
Extend lifespan of product and its parts	Reuse (R3)	Utilizing a product still in good condition for a second or subsequent time, either by another user or owner. In this process, the product continues to serve its original function effectively. A reused product retains both its function and identity intact.	(Jayaraman, 2006; Potting et al., 2017)
	Repair (R4)	Repair involves restoring the original function of a defective product and making a broken product operational again by fixing or replacing failed parts. Corrective maintenance is often considered synonymous with repair.	(den Hollander, Bakker, & Hultink, 2017; Jayaraman, 2006)
	Refurbish (R5)	Refurbishing involves restoring an old product and updating it to meet modern standards. It aims to upgrade or modernize the product's functionality. Unlike remanufacturing, refurbishing usually does not entail disassembly; instead, it focuses on replacing parts. Refurbished products are generally improved and restored to meet specific quality standards.	(Morseletto, 2020; Potting et al., 2017)
	Remanufacture (R6)	Incorporating parts of discarded products into a new product with the same function. The process ensures that the remanufactured product attains the quality equivalent to a brand-new one, even when utilizing components retrieved or reclaimed from other products.	(Morseletto, 2020; Yuksek et al., 2023)
	Repurpose (R7)	Utilizing discarded products or their components to create a new product with a different function. It also refers to reusing a product for an alternative purpose, termed open-loop reuse.	(Morseletto, 2020; Potting et al., 2017)
Useful application of materials	Recycle (R8)	Extracting secondary materials from discarded products. Secondary materials may undergo upcycling, a transformation that converts them into materials of higher quality, or in the opposite direction, i.e., downcycling, which occurs in most cases. While upcycling is intuitively the preferable solution due to its higher value, it is not always a feasible solution.	(Ashby, 2020; Morseletto, 2020)
	Recover (R9)	Incineration of materials with energy recovery. In a broader context, it refers to waste that is not recycled but used as a source of energy or valuable biochemical compounds. Recovery encompasses various conversion processes, primarily focused on organic waste.	(Demirbas, 2009; Morseletto, 2020)

requiring further interpretation to align with the specifics of a value chain.

Given this research's objective to develop an integration framework leveraging existing literature to identify how I4.0 technologies can support CE principles, the 10R- structured into the three practical strategy groups proposed by Potting et al. (2017) – emerge as an ideal choice. Their operational focus and applicability closely align with the research goals, offering a robust basis for integrating CE strategies with I4.0 technologies.

2.2. Industry 4.0 technologies

Industry 4.0 (I4.0), often referred to as the *fourth industrial revolution*, marks a transformative era in manufacturing (Dalenogare et al., 2018; Zheng et al., 2021). The concept of I4.0 is very complex, and the existing literature lacks a single, universally accepted definition (Ciano et al., 2021). However, regarding the manufacturing field, the core idea of I4.0 is to act as a *digital transformation* to achieve not only *smart manufacturing* systems but *smart factories* throughout the value chain.

I4.0 leverages *digitalization* to support various phases of a value chain. Since the design and development phase of a technology, businesses can develop *digital twins* to simulate and optimize designs before physical production, reducing errors and costs (Faveto et al., 2022; Lu et al., 2020). During the sourcing phase, most primary materials are derived from extraction processes known for their significant environmental impacts and potential risks to human health. The use of *Cyber-Physical Systems* (CPSs) in this phase can effectively automate these operations, resulting in reduced environmental footprints and enhanced safety measures for individuals (Ahmed, Nazzal, & Darras, 2022; Panza, Bruno, & Lombardi, 2023). During the production phase, then, the efficient transformation of raw materials into finished products can rely on several I4.0 technologies, like *Autonomous Robots* to increase automation and *Digital Twin* and *CPSs* to simulate and optimize processes (Lee et al., 2020; Zheng et al., 2021). Moreover, *Additive Manufacturing* (AM), a key technology of I4.0, enables on-demand and customized production, reducing the need for extensive inventories and tooling (Kunovjanek, Knofius, & Reiner, 2022; Peron & Sgarbossa, 2021). I4.0 can also optimize logistics operations through *Data analytics* and *RFID* technology because they enable real-time inventory tracking and optimization (Casella, Bigliardi, & Bottani, 2022; Popova et al., 2021). *Internet of Things* (IoT) and *data analytics* provide real-time traceability of the entire supply chain, helping companies monitor inventory levels, track shipments, and make informed procurement decisions (Dalenogare et al., 2018; Zheng et al., 2021).

I4.0 also provides the opportunity to enhance stakeholder engagement throughout the value chain. For example, Big data helps understand customer preferences and behavior, enabling businesses to offer personalized products and services (Jiang et al., 2016; Panza et al., 2022). This phenomenon, also known as *Social Manufacturing*, i.e., a context characterized by increased stakeholders' involvement in the product creation (Panza et al., 2022; Yao et al., 2022), paves the way for the broader concept of *Wisdom Manufacturing*. The latter aims to optimize the use of human and computer-based knowledge to enable an efficient and effective delivery of value into society (Qin & Lu, 2021; Yao et al., 2022).

Industry 4.0 technologies hold great potential to revolutionize the entire manufacturing value chain; their main definitions are presented in Table 2.

2.3. Integration frameworks of circular economy & Industry 4.0 technologies

The integration of CE and I4.0 technologies has increasingly attracted researchers' attention (Dantas et al., 2021; Lopes de Sousa Jabbour et al., 2018). Indeed, existing literature highlights strong links between CE and I4.0, reporting several examples of how their integration can

Table 2
Summary of the main I4.0 technologies.

I4.0 technology	Description	Reference
Additive Manufacturing	Manufacturing process that involves building three-dimensional objects by adding material layer by layer, guided by a digital model or 3D computer-aided design (CAD) data.	(Peron et al., 2022; Pilagatti, Atzeni, & Salmi, 2023)
Artificial Intelligence	Replicating human intelligence in machines, allowing them to learn, perform decisions, and execute tasks automatically. Machine learning, deep learning, neural networks, and others are considered sub-sets of artificial intelligence (AI).	(Biggio & Kastanis, 2020; Panza, De Maddis, & Russo Spena, 2022)
Autonomous Robots	Robotic systems capable of operating and performing tasks without direct human control or intervention. It can independently navigate its environment, make decisions based on sensory input or pre-programmed algorithms, and execute actions to achieve specific objectives.	(Cherubini et al., 2016; Zheng et al., 2021)
Big Data & Analytics	Big Data refers to large amounts of data, structured or unstructured, generated from various sources at a high velocity and varying degrees of complexity. Big Analytics involves extracting valuable insights from large, complex datasets. Advanced statistical, mathematical, and computational techniques are applied to analyze and interpret data and detect correlations, trends, and anomalies.	(Fosso Wamba et al., 2015; Vera-Baquero, Colomo-Palacios, & Molloy, 2014)
Blockchain	Distributed and decentralized digital ledger technology that allows multiple parties to maintain a secure, transparent, and immutable record of transactions or data in a tamper-resistant manner.	(Kouhizadeh, Zhu, & Sarkis, 2020; Treiblmaier, 2018)
Cloud Computing	Paradigms in which computing resources, including servers, storage, databases, networking, software, and analytics, are delivered over the Internet. Instead of owning and maintaining physical infrastructure, organizations can access and utilize these resources on-demand through a cloud service provider's remote data center.	(Fisher et al., 2018; Tao et al., 2011)
Cyber-Physical Systems	A system that integrates physical components, like products and machines, with a digital environment through sensors and communication networks creates a seamless interaction between the physical and virtual worlds.	(Lee, Bagheri, & Kao, 2015; Panza, Bruno, & Lombardi, 2023)
Digital Twin	Virtual representation of a physical object, system, or process that exists in the digital realm. It is a computer-generated model that mirrors	(Ciano, Pozzi, et al., 2021; Lee et al., 2020)

(continued on next page)

Table 2 (*continued*)

I4.0 technology	Description	Reference
	its real-world counterpart's characteristics, behavior, and attributes.	
Horizontal & Vertical Integration	Horizontal integration in I4.0 focuses on integrating processes within an organization. In contrast, vertical integration extends integration across the entire value chain, connecting various stakeholders and stages of production to create a more cohesive and data-driven ecosystem.	(Dalenogare et al., 2018; Pérez-Lara et al., 2020)
Internet of Things	Network of physical devices, objects, and systems embedded with sensors, software, and connectivity capabilities, allowing them to collect and exchange data over the Internet. These "smart" devices can communicate with each other and central systems, enabling data sharing, analysis, and decision-making without requiring direct human intervention.	(Oztemel & Gursev, 2020; Wolfartsberger, Zenisek, & Wild, 2020)
Simulation	Method of creating a virtual representation or imitating a real-world system, process, or situation. It involves using computer-based models and algorithms to mimic the behavior and dynamics of the real system over time.	(Higashino, Capretz, & Bittencourt, 2016; Zheng et al., 2021)
Virtual & Augmented Reality	Virtual Reality is a technology that creates a simulated, computer-generated environment or experience that a person can explore and interact with. Augmented Reality enhances a user's real-world environment by overlaying computer-generated content, such as images, videos, text, or 3D objects, onto the physical world in real-time.	(Wang, Ong, & Nee, 2016; Yew, Ong, & Nee, 2016)

have positive effects in terms of, e.g., lifecycle management of products, material and energy consumption, recycling, development of innovative products and services and the achievement of sustainable development goals (SDGs) (Dantas et al., 2021; Findik, Tirgil, & Özbuğday, 2023; Laskurain-Iturbe et al., 2021; Lei et al., 2023; Lopes de Sousa Jabbour et al., 2018; Massaro et al., 2021; Patyal et al., 2022; Rosa et al., 2020). For example, IoT connects devices and systems, enabling real-time monitoring of material flows and production processes, which supports resource optimization and waste reduction (Bag et al., 2021; Rosa et al., 2019). BDA processes the vast amount of information these interconnected devices generate, identifying patterns that lead to reduced emissions and operational efficiencies (Bag & Pretorius, 2020; Rajput & Singh, 2020). AM also contributes by allowing on-demand production and reducing material waste, particularly by using recycled materials to create new components (Rosa et al., 2019).

Moved by these links and potentialities, literature has followed Bressanelli et al. (2018) suggestion to describe how to integrate CE efficiently and effectively and I4.0 technologies to reduce the distance between theory and practice, also identified by Rosa et al. (2020). Several works have been developed since the one by Lopes de Sousa Jabbour et al. (2018) proposing a roadmap to fill the identified knowledge gap related to how organizations can integrate CE strategies and I4.0 technologies; however, several limitations that warrant attention and pose challenges to the developed frameworks can be highlighted. Indeed, several frameworks (e.g., the ones proposed by Bag and Pretorius (2022), Dantas et al. (2021), de Oliveira Neto, da Conceição Silva, and Filho (2023), Elghaish et al. (2022), Kazancoglu et al. (2021), Khan, Piprani, and Yu (2022), Lopes de Sousa Jabbour et al. (2023), Lu, Zhao, and Liu (2022), Patyal et al. (2022), Romero et al. (2021)) are limited in scope, addressing specific industries or the achievement of SDGs. Other frameworks address specific circular business models or practices, overlooking the full range of CE strategies (e.g., the ones proposed by Atif et al. (2021), Atif (2023a), Bressanelli et al. (2018), Kim, Lim, and Hsuan (2023), Nascimento et al. (2019)), or a specific I4.0 technology or a subset of the I4.0 technologies (such as Khan et al. (2021), Lopes de Sousa Jabbour et al. (2018), Liu et al. (2022), Rosa et al. (2020), Tang et al. (2022)). Among the frameworks not limited in scope and involving the majority of I4.0 technologies and CE strategies (e.g., the ones developed by Agrawal et al. (2022), Cagno et al. (2021), Lei et al. (2023), Sahu, Agrawal, and Kumar (2022)), the main limitation is represented by the number of contributions they are grounded on.

Considering the frameworks that are limited in scope, among the others, Elghaish et al. (2022) study the relationships between blockchain (BC), IoT, digital twins, AI, and CE to address the specific needs of the construction industry, while Lu, Zhao, and Liu (2022) aim to integrate the 3Rs and I4.0 technologies in sustainable SC practices, studying five categories of dynamic capabilities.

Considering the studies that address the specific circular business models or practices, overlooking the full range of CE strategies, Bressanelli et al. (2018) propose a framework linking IoT and BDA to specific usage-focused serviced business models functionalities, while Nascimento et al. (2019) combine cyber-physical systems and AM with specific practices, such as selective waste collection, waste sorting, waste treatment, product printing and product assembly, to address Reuse and Recycle.

Referring to the ones considering a specific I4.0 technology or a subset of the I4.0 technologies, limiting their applicability, Khan et al. (2021) and Tang et al. (2022) develop frameworks that focus on BC technology, which the authors consider the most promising among the recent technologies. Considering the frameworks based on a set of technologies, for example, the recent framework by Liu et al. (2022) considers three categories of digital functions, namely automation, data analysis, and data collection and integration, related to IoT, BDA, and AI, overlooking other I4.0 technologies, such as AM and virtual reality (VR).

Among the works limited by the number of contributions considered as the foundation of the framework, Cagno et al. (2021) analyze the literature to understand the role of I4.0 technologies in operationalizing the CE transition, based on the ReSOLVE framework, covers the majority of I4.0 technologies while excluding works considering the integration of other I4.0 technologies, such as AM and synonyms CE, limiting the number of contributions analyzed to 66.

The work by Agrawal et al. (2022) develops a framework based on 165 articles combining I4.0 and CE based on the clustering of leading articles obtained through a co-citation network. Even though the set of considered articles is wider and justifies the use of social network analyses, again, the search criteria adopted by this work overlook the literature considering specific I4.0 technologies and the studies regarding CE activities. Moreover, the proposed framework does not explore in detail the interaction between single I4.0 technologies and CE strategies, limiting its practical applicability.

Similarly, Sahu, Agrawal, and Kumar (2022), proposing a transition framework based on a systematic literature review of 204 articles from 2000 to 2020, fails to include literature considering specific CE strategies and I4.0 technologies or adopting synonymous terms. Moreover, while considering challenges and drivers, the proposed framework does not thoroughly explore the interaction between single I4.0 technologies and CE strategies.

The work by Lei et al. (2023) mines 266 articles for their content on I4.0 technologies and CE practices, applying systematic literature review and social network analysis. Also in this case, the search criteria exclude works on specific technologies or strategies, and the proposed framework does not explore in detail the interaction between single I4.0 technologies and CE strategies, limiting its practical relevance.

Gupta et al.'s (2021) work develops a framework based on the practices of the circular economy, cleaner production, and Industry 4.0. However, the aim is to assess ethical and sustainable business performance rather than show the link between these practices and guide their implementation.

As companies struggle to achieve the CE paradigm and the integration between I4.0 and CE is still undeveloped (Lei et al., 2023; Liu et al., 2022; Massaro et al., 2021), the need for frameworks supporting companies, first claimed by Lopes de Sousa Jabbour et al. (2018), is still relevant. Despite literature having proposed several frameworks in the last years, several limitations threatening them are highlighted. Hence, an integration framework grounded on the deep exploration of the relationships between I4.0 technologies and CE strategies from a comprehensive perspective is urgently required and represents the goal of this work. To develop a framework that addresses these limitations, a thorough literature review is essential. As we will demonstrate in Section 2.4, existing reviews on the link between CE and Industry 4.0 lack the necessary scope to overcome these challenges, underscoring the need for a new, more comprehensive review.

2.4. *Other reviews on the link between circular economy & Industry 4.0 technologies*

The previous section demonstrated that existing integration frameworks between CE and I4.0 have notable limitations, preventing them from serving as complete guides. While a comprehensive literature review could help fill these gaps, many of the frameworks discussed are already grounded in existing reviews, which themselves share similar shortcomings. In this section, we will critically examine additional literature reviews on the intersection of CE and I4.0, showing that these, too, are inadequate for constructing a more complete framework. This analysis underscores the need for a new, more comprehensive review to overcome the persistent limitations in the current body of research.

Several reviews have been conducted in this field, each offering valuable insights, but significant gaps remain. Notably, many reviews explore the integration of I4.0 and the CE but lack in-depth analysis of how specific I4.0 technologies connect with particular CE strategies. For instance, Agrawal et al. (2023) focus on identifying drivers and barriers in the supply chain but do not deeply investigate the interactions between I4.0 technologies and CE practices. Similarly, Awan et al. (2022a) emphasize value chain redesign and strategic initiatives without linking technologies like IoT or blockchain to specific CE strategies. Awan et al. (2022b) offer a global value chain perspective but also fall short in exploring the direct relationships between I4.0 tools and CE applications. Atif (2023b) highlights the transition to Industry 5.0 but lacks a detailed exploration of how I4.0 supports CE strategies like reuse or remanufacture. Furthermore, Duong et al. (2024) focus on integrating I4.0 with supply chain quality management, and Gatell and Avella (2024) examine its impact on lean culture and leadership. However, both reviews limit their scope to organizational perspectives rather than exploring specific technology-strategy links. Thus, while these reviews offer valuable insights, they generally do not provide the detailed technological guidance needed for implementing CE strategies with I4.0.

Several studies focus primarily on one or a limited subset of I4.0 technologies, thus limiting their broader applicability across CE strategies. For instance, Awan et al. (2021) center on IoT applications in CE without delving into other significant technologies. Liu et al. (2023) investigate AI, BDA, blockchain, and IoT but overlook other technologies like AM or digital twins, which are critical for certain CE practices such as reuse and remanufacturing.

Another major gap in existing literature reviews is the incomplete coverage of CE strategies, particularly the full 10Rs framework. Most reviews focus on only a subset of these strategies, limiting their utility for comprehensively guiding CE transitions. Das et al. (2024) offer a detailed bibliometric analysis of 1002 articles but fail to address certain CE strategies and technologies. Specifically, they omit Rethink and fail to explore digital twins and virtual reality—increasingly crucial technologies for smart manufacturing and product lifecycle management. Liu et al. (2023) similarly focus only on the 3Rs (Reduce, Reuse, and Recycle), leaving out more complex strategies such as Refurbish, Remanufacture, and Repurpose, which are vital for extending product lifecycles. Others explore the general CE concept but do not explicitly address the specific R strategies (e.g., Hennemann & Sehnem, 2022). The review by de Mattos Nascimento et al. (2024) is one of the more comprehensive in attempting to link specific I4.0 technologies with the 10Rs framework. However, it falls short in covering the most recent technological advances.

Many of the literature reviews, just like de Mattos Nascimento's (2024) work, fail to capture the rapid advancements in CE-I4.0 integration by limiting their scope to articles published up to 2021 or earlier. For instance, Awan et al. (2021), Cwiklicki and Wojnarowska (2020), Teixeira and Teixeira (2022), and Upadhyay et al. (2023) all review articles up to 2020 or 2021. With the rapid technological advancements in I4.0, such as the development of digital twins, AM, and blockchain, this omission limits the relevance of their conclusions.

Several reviews are constrained by the number of articles reviewed, which limits their comprehensiveness. For example, Cwiklicki and Wojnarowska (2020) analyze only 32 papers, Teixeira and Teixeira (2022) similarly assess only 41 papers, and Hennemann & Sehnem (2022) review 63, which are relatively small samples for a rapidly evolving field (Agrawal et al., 2023; Das et al., 2024; Liu et al., 2023).

Several other reviews further narrow the scope by focusing on specific industry sectors or application areas, limiting their generalizability. Cheah et al. (2022) and Afshari et al. (2024) focus on solid waste management, while Abdul-Hamid et al. (2022) explore the palm oil industry. Daneshmand et al. (2023) narrowed their review to robotic assembly and disassembly. While these studies contribute to understanding specific areas, they do not offer a holistic view of how I4.0 can support CE across different industries.

While these reviews contribute valuable insights into the integration of CE and I4.0, they face significant limitations regarding their technological scope, coverage of CE strategies, sectoral focus, and sample size. Therefore, to develop a framework that can guide industries in effectively implementing CE through digital technologies, a more comprehensive review is needed to cover the full spectrum of I4.0 technologies, thoroughly explore all 10Rs strategies, and incorporate the most recent studies to ensure relevance and practical applicability.

3. Methodology

To develop a CE-I4.0 technologies integration framework overcoming the limitations of the existing ones, this work is grounded on a wide body of literature covering the studies that have related any technology of I4.0 to any CE strategy. The dataset of articles was obtained through a search conducted on Scopus. Scopus was chosen since it is the largest and most comprehensive citation and abstract database of peer-reviewed scientific literature to date (Zhang et al., 2020; Pozzi et al., 2022). Additionally, Zhang et al. (2020) found that most sustainability-related studies in the Web of Science database coincide with those in Scopus, indicating significant overlap between the two sources. The search utilized keywords derived from the literature analyzed in the theoretical background. The first group of keywords (group A) pertains to CE, while the second group (group B) concentrates on I4.0, as detailed in Table 3. The keywords for this study were drawn from key works on CE and I4.0. Rosa et al. (2020), who systematically

Table 3
Keywords groups.

Group A: CE-related keywords	Group B: I4.0-related keywords
circular economy; circular value chain; circular supply chain; circular manufacturing; waste management; end of waste; reverse logistics; sustainable manufacturing; green manufacturing	industry 4.0; fourth industrial revolution; 4th industrial revolution; industrial internet; smart manufacturing, smart factory; smart production; cyber manufacturing; digital transformation; cyber-physical system; cyber-physical production system; cyber-physical system; cyber-physical production system; cloud; cloud computing; cloud manufacturing; cloud-based design and manufacturing; software-defined manufacturing; factory of things; wisdom manufacturing; self-organizing manufacturing; social manufacturing; smart city production system; internet of things; industrial internet; big data; digitalization; digitization; autonomous robot; autonomous mobile robot; collaborative robot; cobot; co-bot; automated guided vehicles; simulation; digital twin; horizontal integration; vertical integration; rfid; sensor; smart bin; additive manufacturing; 3d print*; augmented reality; virtual reality; artificial intelligence; machine learning; blockchain; 5 g; deep learning; data analytics

reviewed the relationship between CE and I4.0, provided the foundation for selecting keywords for both groups. Additional keywords related to CE were taken from Battini et al. (2017), who explored closed-loop supply chains. For I4.0, the study by Ciano et al. (2021) was also a crucial source, as it investigated the specific I4.0 technologies. The logical operators ‘AND’ and ‘OR’ were used to generate the search strings within TITLE and AUTHKEY (author keywords) (e.g., ‘[keyword of Group A OR another keyword of Group A] AND [keyword of Group B OR another keyword of Group B]). The search was limited to articles, reviews, and conference papers in English. The ever-expanding body of research reflects the rapid evolution of the relationship between CE and I4.0 technologies (Liu et al., 2023). Conference papers often precede journal publications, offering early insights into trends and innovations that will later appear in peer-reviewed journals. Including conference papers in this study ensures that emerging concepts are considered. The documents considered were published after 2011, the year the term ’Industry 4.0′ was coined, and fell the subject areas of ‘engineering,’ ‘computer science,’ ‘business, management and accounting,’ ‘decision science,’ and ‘economics, econometrics, and finance,’ resulting in 1787 documents (April 2023).

To classify such a large dataset, the utilization of bibliometric tools based on clustering became necessary. Specifically, the VOS method for keyword co-occurrence network analysis, implemented within the VOSViewer software (Waltman, van Eck, & Noyons, 2010), was used. This method is grounded in modularity-based clustering, a weighted and parameterized iteration of the clustering algorithm originally conceived by Newman and Girvan (2004). It aims to pinpoint communities or clusters within a keyword network. These clusters comprise keywords frequently used in conjunction, signifying a shared thematic focus.

This tool for literature reviews is valued for its objectivity. It classifies and represents topics based on quantitative rationales, setting it apart from traditional literature reviews that rely solely on content analysis (Kim, Colicchia, & Menachof, 2018; Pozzi, Cannas, & Ciano, 2022; Strozzi et al., 2017).

The effectiveness of this bibliometric tool is demonstrated by its recent use in several studies (e.g., Ciano, Pozzi, et al., 2021; Ivanov et al., 2023; Naz et al., 2023; Pozzi et al., 2022), particularly in defining the characteristic themes of topics with extensive literature, as is the case in this study. Reviewing these papers helps uncover the subjects identified by the clusters, each assigned descriptive names based on its content to enhance readability and understanding. After analyzing the clusters, this study identifies in the results the specific links between the I4.0 technologies presented in Section 2.2 and the strategies and their relevant Rs (of the 10R framework) that these technologies can support. This makes formalizing an integration framework between the two paradigms possible, as presented in section 4.3.

Fig. 1 provides a concise summary of the core stages of the methodology and the previously explained search string.

4. Results

This section will present the results. First, the cluster analysis results will be described in Section 4.1, reporting the different clusters identified and describing them through some relevant works belonging to each cluster. Then, the clusters will be analyzed according to the 10R framework (Section 4.2), which will then allow us to derive the main contribution of this work, i.e., the integration framework (Section 4.3).

4.1. Cluster analysis

Using the standard VOSViewer co-occurrence threshold and a resolution of 1.3 (Ciano, Pozzi et al., 2021), the author keyword co-occurrence network included 226 keywords distributed across 13 distinct clusters. These are defined and illustrated in Table A1 in the Appendix, arranged in descending order by the number of keywords in each cluster, and they are discussed below.

1. IoT-based waste management in smart cities

A *smart city* is “not just about smart infrastructure but the extent to which such infrastructure assists in achieving sustainable development objectives” (Esmaeilian et al., 2018). *Waste management* is a crucial problem that *smart cities* must face (Burnes & Towers, 2016; Esmaeilian et al., 2018), and the literature points to *IoT* as a potential solution. The use of *IoT* in *waste management* facilitates real-time monitoring and optimization of *waste collection*, leading to an efficient allocation of resources and fostering a cleaner urban environment. As suggested by Esmaeilian et al. (2018), the literature on this topic can be classified into four categories: (i) data acquisition and *sensor*-based technologies; (ii) communication technologies and data transmission infrastructure; (iii) testing the capabilities of IoT systems in field experiments; and (iv) truck routing and scheduling for *waste collection* operations.

The studies falling within the first category have extensively focused on *smart bins,* i.e., bins equipped with *RFID* tags for identification, capacity *sensors* for waste level detection, actuators to lock the *bin* lids when full, and *wireless* antennas to transmit sensor data for *waste collection* operations have received (Pardini et al., 2020). Anagnostopoulos et al. (2015) integrated this architecture with a transportation system that included *GPS* technologies for real-time monitoring of waste levels in bins and efficient *waste collection.*

The literature has classified *waste management* technologies into spatial technologies (e.g., *GIS, GPS*), identification technologies (e.g., *RFID,* barcodes), data acquisition technologies (e.g., *sensors*, imaging), and data communication technologies (e.g., GSM, *Wi-Fi,* Bluetooth). The emphasis has been predominantly on the last three groups (Esmaeilian et al., 2018). Consequently, this suggests potential for further research and exploration in spatial technologies.

Regarding data acquisition and communication technology, Lata and Singh (2016) developed a web interface for monitoring trash bins using data from a wireless sensor network. Misra et al. (2018) proposed an integrated sensing system for automating solid waste management composed of *sensors*, an *Arduino* microcontroller, a *Wi-Fi* module, a cloud server, and a dedicated app. The system utilizes a smart bin equipped

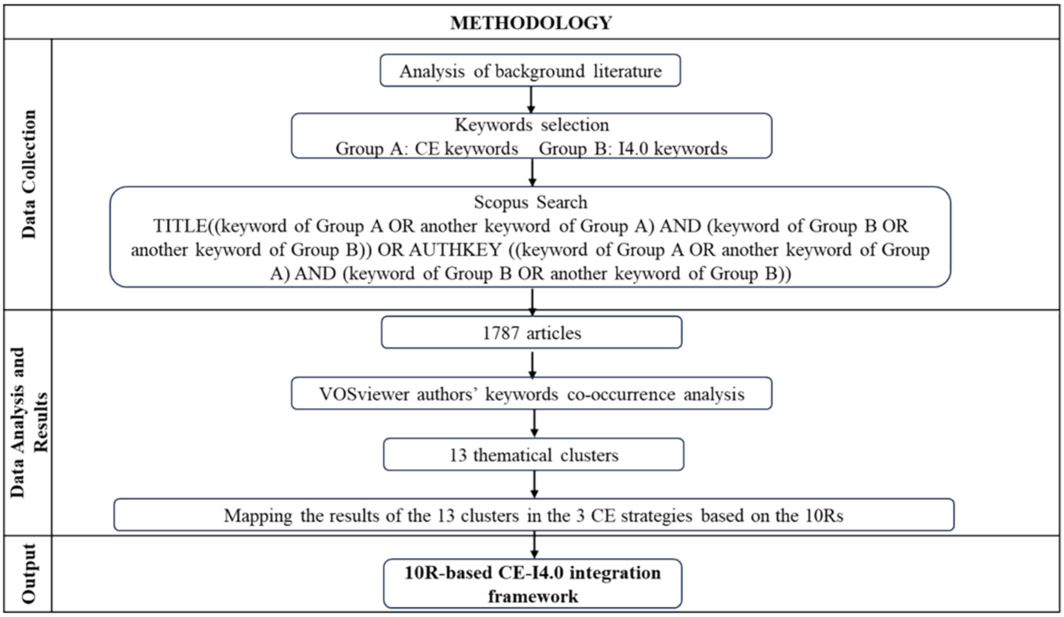


Fig. 1. Schematic representation of the methodology adopted.

with level sensors and *gas sensors* to detect both waste levels and hazardous gases/odors. The information can be monitored through an app and is transmitted to the responsible authority through a cloud server, which offers advantages in terms of usability, accessibility, and disaster recovery.

Regarding identification and spatial technologies, examples include enhancing construction waste logistics with *RFID* (Zhang & Atkins, 2015), designing a *food waste* management system with RFID-based bins (Wen et al., 2018) and testing smart systems for *waste collection* using *GIS* simulation environments (Gutierrez et al., 2015).

Efforts have also focused on dynamic routing and scheduling optimization for waste collection in supply chains. These models aim to maximize on-time collection and minimize waste depletion costs (Anagnostopoulos et al., 2015).

Recent studies focus on the use of AI, specifically learning techniques, for waste management in smart cities (e.g., Chen, 2022; Namoun et al., 2022). *Machine learning* can assist in automatically recycling by classifying and separating materials in mixed recycling applications, enhancing the separation of complex waste. *IoT* devices can be installed in waste bins, including recycling bins, to gather real-time data on waste producers' behavior, while *image processing* can calculate a landfill index, offering insights into waste and recycling patterns and recommendations for improved productivity (Chen, 2022).

2. Circular economy transformation for sustainable development

As society is facing main concerns in ensuring social, environmental, and economic *sustainability* while meeting the continuously growing worldwide demand for capital and consumer goods (Stock & Seliger, 2016), *Sustainable Development Goals* are a global initiative supporting sustainable practices and solutions, constituted of 17 points developed by the United Nations 2030 Agenda (Dantas et al., 2021).

Research on the links between *Industry 4.0* and *circular economy* strategies burst in 2018 when seminal papers by Lopes de Sousa Jabbour et al. (2018) and de Sousa Jabbour et al. (2018) proposed innovative research agenda and roadmap that meant to exploit the technologies of the *fourth industrial revolution* towards *circular economy* and *sustainable operations*. *Digital technologies* are reported to support *circular business models*, leading to *sustainable development*. *Circular business models* exploit *innovation* to improve the dimensions of business models, i.e., create, capture, and deliver, to improve resource efficiency by extending the duration of products and parts. Among them, the product-service system is acknowledged as an important business model *innovation* enabled by big data, IoT, and cloud computing (Chauhan et al., 2022; Bressanelli et al., 2018). *Case studies* empirically confirm that integrating I4.0 and CE leads to many positive effects, such as reductions in material and energy consumption and waste and emissions generation, towards *sustainability* (Laskurain-Iturbe et al., 2021). In the *construction* industry, BC, IoT, AI, and digital twins are reported to play a prominent role in leveraging CE (Elghaish et al., 2022). As well, direct impacts on SDGs are reported in the literature. IoT *technology* integrated into waste management contributes to clean water and sanitation (SDG 6) and climate action (SDG 13) (Fatimah et al., 2020). IIoT, BDA, and CPPS improve efficiency and increase the capacity of clean energy use and production, contributing to affordable and clean energy (SDG 7), while IIoT, CPPS, BDA, and AM help build the structure necessary to foster inclusive and sustainable industrialization (SDG 9), and automatization, CC, BD and Cybersecurity contribute to cities and communities systems like transport, lighting, logistics and security (SDG 11) (Dantas et al., 2021).

As the achievement of SDGs involves complex systems and dynamic changes, the perspective of *dynamic capabilities* is considered by several studies. For example, Lu, Zhao, and Liu (2022) demonstrate how the link between I4.0 and CE can enhance *dynamic capabilities* for sustainable supply chain *management* implementations, and Bag and Pretorius (2022) prove that the degree of I4.0 adoption and 10R advanced manufacturing capabilities improve *sustainable development* outcomes. Other research focuses on the factors influencing the integration of I4.0 and CE to achieve sustainable development. Through the application of *DEMATEL* technique, AI, service and policy framework, and CE are reported as significant enablers, while interface design and automated synergy model emerge to be the main challenges (Rajput and Singh, 2019). Considering BC implementation, knowledge training and data security are reported as critical factors in achieving sustainable development (Huang et al., 2022).

3. Simulation and optimization models for reverse logistics performance evaluation

Reverse logistics represents a crucial step for achieving *sustainable supply chains*, as it represents a *reverse supply chain* that starts from the end users, where used products are collected, and it attempts to manage End-of-Life (EoL) products by either recycling them, remanufacturing or repairing them (Govindan, Soleimani, & Kannan, 2015). However, despite the clear environmental benefits of *reverse logistics*, its implementation is not straightforward. The literature has identified some main *barriers* to its adoption (e.g., low commitment from managers, heterogeneous quality of returned products, …), whose impact can be mitigated by adopting some main *enablers* (Mishra et al., 2023). Particularly, Govindan and Bouzon (2018) referred to the development of *decision-support* tools to support practitioners willing to implement such *business models* in their decision-making process as one of the key enablers.

In this perspective, *optimization* (or optimisation) and *simulation* lead the way, with several studies sufficiently numerous to provide enough material for developing *systematic literature reviews* (Abid & Mhada, 2021). These studies are often combined with multi-criteria decision-making (*MCDM*) models to identify the most relevant input/output parameters (Ilgin, 2017). More in detail, *optimization* methods are equally divided between single-objective and multi-objective models, solved with many algorithms, e.g., Branch and Bound, Genetic Algorithm, etc. (Pinto et al., 2023). Examples of these studies are those of Wang et al. (2018) and Tosarkani, Amin, and Zolfagharinia (2020), where Wang et al. (2018) developed a single objective *optimization model* that focused on maximizing the profit of an e-recycling *reverse logistics* node, while Tosarkani, Amin, and Zolfagharinia (2020) developed a multi-objective *optimization model* aiming to maximize the environmental compliance and economic profits of third parties in electronic reverse logistics networks. Regarding *simulation*, the most used models are Monte Carlo *simulations*, discrete event *simulations*, agent-based *simulations* and *system dynamics* (Pinto et al., 2023). For example, Yang and Chen (2020) adopted a Monte Carlo simulation to perform a trade-off investigation between robustness against uncertain situations and the price of such robustness in a *reverse logistics* network, while Buyvol, Makarova, and Boyko (2022) adopted *system dynamics* to support the organization of the reverse logistics network within the service system of an automotive company. More recent papers focus on closed-loop supply chains adopting advanced technologies such as sensors (e.g., *RFID*), internet of things, BC, cyber-physical systems, etc. (Dutta et al., 2023; Hrouga, Sbihi, & Chavallard, 2022).

In addition to the common *performance evaluations* (e.g., profit, CO_2 emission, etc.), a niche research stream focuses on the *bullwhip effect* and supply chain *resilience*. Dealing with the former, the literature results are quite contrasting, with some studies affirming that *reverse logistics* limits the *bullwhip effect* stabilizing the supply chain inventories and other studies reporting that *reverse logistics* renders supply chains more prone to the bullwhip effect (Corum, Vayvay, & Bayraktar, 2014; Turrisi, Bruccoleri, & Cannella, 2013). On the contrary, when dealing with supply chain *resilience*, the literature agrees on the beneficial implications of adopting *reverse logistics,* stating that it will support face materials and product shortages in case of supply chain disruption (Kazancoglu et al. 2023).

4. Adoption of blockchain technology for circular supply chain management

Rejeb et al. (2022) reported that BC has the potential to enable a *circular supply chain*. More in detail, BC provides transparency and *traceability* within supply chain operations, thanks to seamless information sharing, efficient exchange of life cycle inventory data, and real-time monitoring of product conditions (Rusch, et al., 2023). The enhanced *traceability*, together with the heightened levels of trust, increase cooperation and coordination within the business ecosystem, which are fundamental enablers of *circular supply chains* (Erol et al., 2022). Kayikci et al. (2022) reinforce these findings, highlighting network collaboration as the *critical success factor* for developing BC-based *circular supply chains*. Furthermore, BC can play a pivotal role in optimizing recycling facilities and practices, establishing clear CE processes, making informed choices on raw materials, and optimizing manufacturing processes (Chaudhuri, Subramanian, & Dora, 2022).

BC can enable a CE in many different sectors and contexts. For example, Elghaish et al. (2023) focus on the construction sector, showing how BC can promote a wider implementation of *circular supply chains* by enabling the creation of *BIM* families for existing elements, which can be shared with both local and international designers. Nandi et al. (2021) focus on the potentialities of BC as an enabler of CE in the context of the *COVID-19* pandemic. According to their findings, by jointly using IoT, BC, AI, and tracking tools, the post-COVID-19 pandemic recovery can be accelerated, improving the resilience and sustainability of supply chains and promoting their circularity.

In fact, BC can be used in combination with IoT to enhance the efficiency of reverse supply chain systems, streamline the collection and analysis of data related to end-of-life products, and enable more accurate *traceability* (Hrouga, Sbihi, & Chavallard, 2022) favoring an efficient *circular supply chain management*. Therefore, stakeholders in the *circular supply chain* can enhance *eco-efficiency* and strengthen the resilience of the entire supply chain (Paul et al., 2022). For instance, Magrini et al. (2021) investigated the utilization of IoT and BC technologies in the field of *e-waste*. Their research revealed that the integration of IoT and BC offers significant benefits, including the ability to monitor products throughout their lifecycle, support CE strategies, and facilitate informed decision-making processes. Indeed, organizations can effectively track the usage, maintenance, and *e-waste management*, thereby enhancing their sustainability efforts and optimizing resource utilization. An example of e-waste management system based on *smart contracts* and leveraging *Ethereum* BC can be found in (Gupta & Bedi, 2018).

5. Big data enabling lifecycle and waste management in the construction industry

Despite the importance, according to Patil et al. (2023), literature still needs to establish clear links between *big data*, the broader I4.0 paradigm, and sustainable supply chains in the CE era. However, the research stream on *big data, data mining* techniques*,* and *sensor* technology in the *construction* industry clearly shows how their utilization enables cognitive buildings to leverage real-time information collected during operations, informing stakeholders about building and occupant behavior. In addition, by establishing a connection between virtual models and physical assets, integrating Building Information Modelling (BIM) practices, and implementing data-driven asset management, the construction industry can enrich building information throughout the *life cycle,* providing valuable services to users (Pasini et al., 2016). Moreover, *big data* retrieved from tracking technologies, such as *RFID* integrated with GPS, support environmental management in monitoring and controlling adverse impacts of construction waste and carbon dioxide emissions, offering a way to uniquely identify and track materials, components, and equipment with minimal or no worker input (Sardroud & Limbachiya, 2010).

It is indeed in *waste management* that *big data* provides its highest contribution. Until recently, the routing problem of *construction* and demolition *waste* collection has been primarily addressed using deterministic models, overlooking the inherent uncertainty. However, studies like the one by Yazdani et al. (2021) have emerged utilizing integrated simulation and optimization methods, specifically hybrid *genetic algorithms*, to optimize waste collection vehicle routing from construction sites to recycling facilities, resulting in a highly effective semi-heuristic algorithm. These algorithms have also proven to be efficient for general *municipal solid waste* (Aliahmadi, Barzinpour, & Pishvaee, 2020).

Although not present in this cluster, BIM seems to be a central topic in many papers connecting *big data* and *construction waste management* (Wong & Zhou, 2015). Also, a rapidly growing interest in developing approaches for the integration between BIM and Life cycle assessment (*LCA*) has become a trend in 2022, which implies that this topic will continue to be a hot research interest in future (Tam et al., 2022). Some articles on *construction waste management* focus on developing a comprehensive BIM platform for environmental sustainability monitoring and management throughout a building's *life cycle* including the reduce, reuse and *recycle* concepts (e.g., Huang et al., 2018).

Many articles on the subject have a specific geographical context, namely *Hong Kong* (e.g., Lu et al., 2015; Xi Chen & Lu, 2017). Among them, recent articles focus also on the transportation aspects. For example, the study by Lu et al. (2022) utilizes a combination of quantitative and qualitative data to gain a comprehensive understanding of the loading patterns of *construction waste* hauling trucks, contributing to knowledge of *waste management* practices and potential efficiency improvements. Wei et al. (2022) used *big data analytics* to analyze the freight characteristics and carbon emissions of trucks *transporting construction waste.* The study by Bi et al. (2022) presents an optimization model for *construction waste* collection and *transportation*, resulting in improved *performance,* including reduced costs, improved efficiency, and minimized environmental impacts.

6. From smart manufacturing to Industry 5.0 for human-centric and sustainable manufacturing

Smart manufacturing is a fully integrated and collaborative manufacturing system grounded on *cyber-physical systems*, *industrial internet of things*, *cloud* computing and *manufacturing*, control, simulation, service-oriented computing, AI, and data science, embodying the concept of Industry 4.0 (Kusiak, 2018). In this context, sustainability was mainly fostered through *energy efficiency* (Meng et al., 2018). Among the others, the *digital twin,* i.e. the system integrating virtual and physical systems that, due to *iiot*, is profoundly impacting manufacturing systems (Saporiti et al., 2023), supports sustainable manufacturing employing real-time monitoring and *process simulation* (He & Bai, 2021), and an example of *service-oriented architecture* for *energy efficiency* grounded on the *digital twin* of a dyeing and finishing department is reported by Park et al. (2019). Despite Industry 4.0 playing a role in sustainability, such as supporting *sustainable waste management* through the *IoT-based* real-time collection of data (Zhang et al., 2021) and reducing *food waste* (Lopes de Sousa Jabbour et al., 2023), its main objective is to improve the efficiency of the process (Nahavandi, 2019).

Industry 5.0 is an industrial evolution that aims to overcome the limitations of *smart manufacturing* and increase environmental sustainability and synergy between humans and machines in *cyber–physical* production systems, enabling customized autonomous manufacturing through enterprise social networks (Nahavandi, 2019; Maddikunta et al., 2022). Human centricity and environmental sustainability issues are the focus of the Industry 5.0 agenda (Turner et al., 2022).

Grounded on the concept of *operator 4.0* as a smart and skilled operator participating in job roles due to robots, machines, and *cyber-physical* systems (Romero et al., 2016), *Industry 5.0* pursues the human-automation symbiosis and the development of human-centric manufacturing (Romero and Stahre, 2021). *Collaborative robots* play a crucial role in *Industry 5.0*, as they are designed to cooperate with humans in the completion of tasks (Turner et al., 2022). Examples of human-robot collaboration applied to disassembly processes are reported by literature, such as a safe robot system for wheel disassembly made of a vision-based control system equipped with a force sensor and customized unscrewing tool (Turner et al., 2022). Other Industry 4.0 technologies, such as *virtual reality*, can extend their implementations from supporting, for example, the design of ergonomic workstations (Peruzzini et al., 2017), to improving operators' resilience using a safe (virtual) environment for training for risk and crisis management (Romero & Stahre, 2021).

Regarding environmental sustainability, *Industry 5.0* is characterized by greater awareness especially related to carbon emissions throughout manufactured products lifecycle (Turner et al., 2022). In this context, the traditional *Life Cycle Assessment (LCA)* method is combined with intelligent products holding and communicating information, e.g., carbon emissions, material content, geographical origin of materials, and disassembly instructions, supporting the disassembly activities conducted by *collaborative robots* and humans together (Turner et al., 2022).

7. Simulation and lean manufacturing to support green manufacturing

Green manufacturing has gained wide interest in the last years as it focuses on reducing the negative *environmental* impact of production. This implies emissions reduction, improved *energy* management, and the use of fewer natural resources through the *optimization* of *production* processes and the adoption of *reverse logistic* practices, where products are either *reused*, *remanufactured* or *recycled* (Chuang & Yang, 2014; Kannan, Shankar, & Gholipour, 2022) approaches can be found.

The first one is represented by the *digitization* of manufacturing companies, where industry 4.0 technologies are adopted to *optimize production* processes and to enable *reverse logistic* practices (Bag et al., 2023; Ghobakhloo, 2020). This is the case with several I4.0 technological pillars (e.g., *artificial intelligence*, collaborative robots, automated guided vehicles, AM and simulations) (Liu and De Giovanni, 2019; Umar et al., 2022). *Simulations* are extensively studied (Vrchota et al., 2020). For example, Machado, Winroth, and Ribeiro da Silva (2020) reported that *modelling and simulation* (e.g., *discrete event simulation*, *Monte Carlo simulation*, agent-based simulation, etc.) are relevant in the context of *green manufacturing* since they can support improvements in the factory to reduce *energy* consumption and to *optimize* operations by either validating or testing new methods, tools and/or systems. Moreover, as demonstrated by Bottani, Montanari, and Rinaldi (2019) when studying waste electrical and electronic equipment (*weee*) supply chains, they can also be adopted to design supply chains for reverse logistics, even under *uncertainties* (e.g., incomplete information, uncertain return quantities, etc.). *Reverse logistic* practices are also favored by the adoption of simulation during the product development phase since, especially when considering the entire *product life cycle*, they facilitate product *remanufacture* and *reuse* (Ching et al., 2022).

The second approach for *green manufacturing* is its combination with *lean manufacturing* (Choudhary et al., 2019). Among the lean strategies playing an essential role in *green manufacturing,* it is worth mentioning total quality management practices (Hassan & Jaaron, 2021) and Kanban (Baumer-Cardoso et al., 2020). Other strategies like just-in-time delivery, instead, may require increased transportation, packaging, and handling, which contradicts the green approach (Paksoy, Weber, & Huber, 2019). Also, here, *simulations* have been used, aiming to support and enable this integration. This leads to the third approach to achieving *green manufacturing,* represented by its integration with *lean manufacturing* and *digitization* (and, more generally, I4.0 technologies), also called smart lean-green manufacturing.

The third approach is the most recent and is predominated by the use of *modelling and simulation* for testing and validation purposes. An example is the work of (Baumer-Cardoso et al., 2020), who adopted *discrete event simulation* to validate the integration of *lean manufacturing* practices and *green manufacturing* in the case of an injection molding company. This approach is characterized by the adoption of other I4.0 technologies. Specifically, the main focus is on IoT, BDA and *artificial intelligence* that can be used to empower managers to make precise decisions since they allow to convert collected data into useful data information (Bonilla et al., 2018; Franciosi et al., 2018).

8. Use of AI and Additive manufacturing to increase recycling efficiency

One of the key challenges in *recycling* is the sorting and *classification* of materials (Ashby, 2020). Traditional methods rely on manual labor, which can be time-consuming, labor-intensive, and prone to errors (Nonso, Nnamoko Barrowclough & Procter, 2022). Researchers have applied *Artificial intelligence* techniques to address such challenges. Specifically, different *intelligent systems*, mainly based on *computer vision* technologies, have been used in the literature to automatically identify and sort different classes of materials, such as municipal *solid waste*, electric batteries, textiles, and plastics. For example, Ba Alawi et al. (2021) evaluated three pre-trained convolutional neural networks (CNNs) on a public dataset of 22,564 images (SEKAR 2019) for solid waste identification. The images were categorized as recyclable or organic, and the algorithm DenseNet-121 outperformed, achieving a 94 % classification accuracy (Ba Alawi et al., 2021).

Johnson, Khatoon, and Fitzpatrick (2022) focused on the use of AI for battery recovery. They designed an automated system for battery detection combining deep learning with *robotics*. This system was able to detect devices containing batteries on the E-waste conveyor belt feed, and batteries were then extracted and designated for separate processing and *disassembly*.

In the textile sector, Luo, Xie, and Fan (2014) integrated Near Infrared (NIR) and Raman spectroscopy to enhance textile recycling. They created a decision tree to identify cotton purity, facilitating the selection of appropriate recycling channels for cotton textiles. More recent studies have been focusing on *neural network*-based classifiers to detect different types of textile materials employing multi-spectral analysis tools (Rudisch et al., 2021).

In *plastic recycling*, Chin, Varbanov, and Klemes (2021) developed decision rules to detect various plastic origins, enabling the identification of appropriate recycling plans based on contamination levels. They applied a decision tree and a random forest algorithm to a dataset containing the concentration of 15 metals in 82 samples of *plastic wastes*. The classification accuracy ranged from 83.1 % to 100 %.

In addition to *AI*, researchers have also investigated AM to support recycling. Specifically, AM has been reported to support the recycling of *plastic waste* converting it into additively manufactured products through *distributed recycling* and *distributed manufacturing* paradigms. Indeed, once *plastic wastes* have been properly detected for recycling, they can be used to create filaments that feed *3d printing* machines. Different materials have been already tested in the automotive industry, such as ABS, PC, PLA (Ruiz, Pinho, & Resende, 2022) and in the maritime industry (Silva et al., 2023), obtaining promising results from a technical standpoint. Sanchez et al. analyzed the literature on the recycling process of thermoplastic materials via AM technologies. The results confirmed the existence of economic and environmental suitability, as well as technical feasibility. However, considering the large variability of *plastic waste* characteristics, it is still unclear how to systematically extrude recycled filaments with adequate properties for *3d printing* from *plastic waste* (Cruz Sanchez et al., 2020; Oyinlola et al., 2023).

9. Digital technologies for sustainable energy and textile

The adoption of *cleaner production* methods, combined with *Industry 4.0 technologies*, is crucial for industries moving toward *environmental sustainability* (Rusch et al., 2023; Agrawal et al., 2022). For instance, in decentralized energy systems such as Electric Vehicle charging systems, renewable energy grids, or microgrids, one of the key aspects is *energy management*. *Blockchain technology* allows energy consumption and generation data to be securely stored and verified across multiple nodes. This ensures that energy flows are accurately monitored, and any excess energy produced can be traded or stored efficiently, improving overall energy management. Additionally, BC can support the integration of *renewable energy* sources by enabling smart contracts, which automatically can manage energy flow, balance supply and demand, and optimize energy use based on predefined rules (Rana et al., 2024). Moreover, BC can implement incentive mechanisms and tokenization to encourage environmentally friendly consumer behavior (Esmaeilian et al., 2020).

These technological advancements, when integrated with *circular economy* principles, lead to the development of systems that are resilient to the challenges posed by *climate change* (Lu, Zhao, & Liu, 2022). In this context, it is interesting to note that many studies have focused on the *textile sector* (Kusi-Sarpong et al., 2023; Alves et al., 2022). Indeed, this industry is known for its environmental impact through resource extraction, energy consumption, waste generation, and chemical use (de Oliveira Neto et al., 2022). For example, Shou and Domenech (2022) 's work demonstrates, through a case study on leather handbags, how *digitalization* can facilitate *zero-waste* strategies and *resource recovery*, thereby contributing to a cleaner and more sustainable industrial landscape.

Driven by the 2030 sustainable development agenda, the textile industry has embraced cleaner production practices aligned with the circular economy to address environmental challenges and promote sustainable resilience (de Oliveira Neto et al., 2022).

10. Digitally supported circular business models

Circular *business models*, such as *industrial symbiosis* and *product-service systems*, are based on a network of actors working together towards slowing, closing, and narrowing the loop (Antikainen, Uusitalo, & Kivikytö-Reponen, 2018). *Industrial symbiosis* associates two or more industrial facilities or companies where wastes and by-products of one become resources for another (Chertow, 2000), promoting *resource efficiency* (Fraccascia et al., 2020). Internet-based collaborative platforms help match consumers' products designed to be *repair*ed or refurbished with service providers, and collectors can become *logistic service* providers for companies connected on a collaborative platform (Kerdlap, Low, & Ramakrishna, 2019). AM processes supported by permissioned BC promote the direct use of by-products as material input for production, encouraging *repair* and refurbishment operations and reducing *logistics* needs (Ferreira et al., 2023). E-*commerce* platforms grounded on BC and IoT develop a multi-echelon virtual closed-loop supply chain (Prajapati et al., 2022). *Game theory* and *agent-based simulation* models support scenario-based analyses on cost-sharing policies (Yazan & Fraccascia, 2020), while machine learning helps backflow *forecasting* (El Hachimi, Oubrich, & Souissi, 2018).

The *Product-Service System* (PSS) is a special case of *servitization* combining the offer of both products and services for extending the product lifetime and closing materials loops (Baines et al., 2007). IoT, BD, and analytics are reported to support its functionalities, ensuring monitoring and tracking product activity, providing preventive and predictive maintenance, and optimizing product usage (Bressanelli et al., 2018). The 5G mobile network is expected to increase the reliability of data-heavy applications and services that require data exchange in real-time required by the access-based PSS (Tunn et al., 2020).

11. Additive manufacturing for sustainable manufacturing

Thanks to its intrinsic characteristics of producing parts layer-by-layer, *Additive manufacturing* (*AM*) enables high design flexibility with tremendous benefits in terms of product customization (Kunovjanek, Knofius, & Reiner, 2022). Moreover, it allows to produce near net-shape products, hence with minimal material waste (Wiese et al., 2022). Consequently, AM is recognized for contributing substantially to *sustainable manufacturing* by employing economically viable, safe processes that minimize environmental impact and reduce energy consumption and resource usage (Jia, Gunasekera, & Glancey, 2023). Considering this, many researchers have focused on evaluating the environmental implications of adopting AM, often comparing it with traditional subtractive manufacturing such as *machining* (e.g., Cozzolino et al., 2022). For example, in a lifecycle analysis, Ingarao and Priarone (2020) found that AM is more energy-efficient than traditional subtractive manufacturing for producing Ti-6Al-4 V components, mainly due to better raw material efficiency. Moreover, some of these works also provided *decision-making* support for sustainable process selection.

AM is also studied in the light of *sustainable manufacturing* as part of *digital manufacturing* and *smart factories,* where AM is used in combination with other Industry 4.0 technologies (e.g., digital twin, cyber-physical production system, BDA, machine learning, etc.) (Ngu, Lee, & Bin Osman, 2020). In this way, data-driven, connected, resilient, and *sustainable manufacturing* is achievable, where fewer resources are used since they are shared in the light of a sharing economy, and processes are optimized through the use of data and advanced technologies (Kusiak, 2018).

12. Literature analysis on Industry 4.0 and sustainable manufacturing

The investigation of how I4.0 technologies can support sustainability in *manufacturing* has been extensively studied, resulting in numerous *literature reviews*. They primarily examine the connection between these technologies and sustainable manufacturing, detailing how each one contributes (e.g., Machado, Winroth, & Ribeiro da Silva, 2020; Sartal et al., 2020).

Among the results, it was observed that employing *simulation modelling*, such as virtual simulations of new procedures and maintenance activities, holds significant potential for reducing energy consumption and improving processes (Bahrin et al., 2016). Modeling techniques can optimize factors such as personnel allocation, energy requirements, and material demands. Furthermore, by enabling preventive and early detection of defects, the *predictive maintenance* paradigm can be fostered (Müller, Kiel, & Voigt, 2018).

AM technologies have emerged as a key support for *circular manufacturing* by reducing material waste and inventory needs while also enabling the production of customized product batches for flexible customer demands. Additionally, AM facilitates cost-effective and rapid prototyping, which reduces the time to market (Yang, Liu, & Yu, 2018). For example, the utilization of 3D printing for producing spare parts, particularly for repair purposes, is experiencing rapid growth (Ponis et al., 2021).

Moreover, systems' horizontal and vertical integration (H&VI) has become crucial in promoting communication across various organizational levels and manufacturing plants, contributing to the development and reinforcement of company values. By integrating information from all organizational areas, manufacturing waste and energy consumption can be optimized. Moreover, it enables a *closed-loop supply chain* and facilitates better alignment with customer demand in terms of quantity and product specifications (Kamble, Gunasekaran, & Gawankar, 2018; Machado, Winroth, & Ribeiro da Silva, 2020). H&VI are considered pivotal since supplier and customer involvement are crucial for achieving sustainability (Dwivedi et al., 2022). Also, the work of (Behl et al., 2023) identifies H&VI as one of the most important enablers towards sustainability.

13. Digital twin for a sustainable production

Digital twins (DTs) have emerged as a key technology for *sustainable production* or *manufacturing* (e.g., Kamble et al., 2022; He & Bai, 2021). *DTs'* ability to enable real-time monitoring, simulation, and optimization of manufacturing processes leads to improved energy efficiency, reduced waste, and enhanced resource utilization. *DTs* aid designers in identifying all the design parameters necessary for achieving optimal process performance while minimizing energy consumption (Yu et al., 2022). Also, using *DTs* for virtual prototyping significantly reduces waste by thoroughly examining designs across scenarios and refining product designs before production. This cuts material waste reduces development costs and accelerates time to market (Singh et al., 2021). Moreover, *DTs* can also contribute to overall sustainability and support the transition toward *sustainable* and smart *manufacturing* since they facilitate predictive maintenance, intelligent decision-making, and collaboration across the supply chain (He & Bai, 2021; Park, Lee, & Noh, 2020). Furthermore, recent literature has shown that *DTs* can also support circular value networks (Blomqvist et al., 2022; Mangers, Amne Elahi, & Plapper, 2023). Data collected through value stream mapping is processed into a *DT*, accounting for regional variations to aid product designers. This informs a decision-support tool aligning designs with CE criteria, promoting efficient recycling and recycled material demand in beginning-of-life products influenced by customer demand or policy mandates (Mangers, Amne Elahi, & Plapper, 2023).

The effectiveness of *DTs* depends on implementing open standards for seamless semantic data exchange. This necessitates a shared *ontology* network for data documentation and creating a secure, decentralized digital platform for collaborative efforts (Blomqvist et al., 2022). This has sparked a growing interest in combining *DTs* with advanced semantic modeling technologies like *ontology* and knowledge graphs to bolster circular value networks effectively. The integration, known as Cognitive DT or Cognitive Twin, aligns with Product Lifecycle Management strategies in *manufacturing* sectors, ensuring sustainable and competitive advantages (Zheng, Lu, & Kiritsis, 2022) by supporting digital model integration throughout the entire lifecycle, including the *value stream.*

4.2. From the cluster analysis to the 10R-based CE strategies

In this section, the analysis focuses on the findings of various clusters concerning CE strategies within the 10R framework, answering the study's RQ. As already mentioned, drawing on the works of Potting et al. (2017) and Morseletto (2020), the different strategies are divided into three main groups, i.e. (i) smarter product use and manufacture, which groups the Refuse, Rethink and Reduce strategies, (ii) extend lifespan of products and its part, which groups the Reuse, Repair, Refurbish, Remanufacture, and Repurpose strategies, and (iii) useful application of materials, which groups Recycle and Recovery strategies. This enables the development of a theoretically derived implementation framework for how I4.0 technologies can support CE. A summary of the main findings is also available in Table A2 in the Appendix.

Smarter product use and manufacture: Refuse – Rethink – Reduce.

Examples of all I4.0 technologies supporting either the implementation of specific strategies or general smarter product use and manufacture are found in the cluster analysis. Concerning the latter, IoT, CPS, BDA, AI, BC and simulation are reported to empower decision-making to achieve the general objectives (Clusters 3, 4 and 7), and BC encourages environmentally friendly consumer behavior through incentive mechanisms and tokenization (Cluster 9). Focusing on the implementation of specific strategies, the lack of examples of I4.0 technologies supporting the effort to make product redundant, i.e. "Refuse" strategy, is highlighted. On the contrary, considering the "Rethink" strategy, VR, simulation, and integration are found to support manufacturing companies in making products use more intensive, investigating different design options to be adaptable to further uses (Clusters 6 and 12), and IoT, BDA and 5G networks to sustain the implementation of product-service systems with data sharing and transparency along the value chain (Cluster 10). While focusing on the "Reduce" strategy, several I4.0 technologies are found to play a role in lowering resource consumption and improving efficiency. In logistics and SC activities, BDA, simulation, and AI optimize waste collection and vehicle routing (Clusters 5 and 6), while BC helps with monitoring and reporting, enhancing efficiency (Cluster 9). The digital SC twin can sustain the cold logistics, reducing product losses (Cluster 6). Considering manufacturing, examples mainly deal with resource waste and carbon emissions reduction supported by cobots, AGVs, AM, and the decision enabled by AI and ML (Cluster 7). AM is reported to also reduce the consumption of energy and natural resources (Clusters 11 and 12). IoT, simulation and DT support energy efficiency (Clusters 6, 12 and 13).

Extend lifespan of products and its part: Reuse – Repair – Refurbish – Remanufacture – Repurpose.

The cluster analysis reveals instances of I4.0 technologies that support either the implementation of specific strategies or the decision-making in extending the lifespan of products and its parts.

Only one R is found to be directly supported by I4.0 technologies, i.e. Repair. The two discussed I4.0 technologies for supporting Repair are AM (Cluster 12) and Augmented Reality (AR) and VR (Cluster 12).

Instead, the selection of the most suitable R strategy among Reuse, Repair, Refurbish, Remanufacture and Repurpose, is supported by multiple I4.0 technologies that can be adopted individually or in combination. For example, Simulation models are frequently employed as I4.0 technology to explore various scenarios and aid practitioners in making informed decisions (Clusters 3 and 10). Similarly, BC technology has appeared to support the decision-making process of the most suitable R strategy in several clusters (Clusters 3, 4, 9, and 10). IoT, BDA, CPSs, and AI (Clusters 3, 6, and 7) can be leveraged in combination to collect and analyze data that enable managers and practitioners to make predictions regarding the most suitable R strategies. Finally, the utilization of cognitive twins (Cluster 13), in synergy with the Product Life Cycle Management strategies, is found to ensure sustainable advantages for enterprises, especially in manufacturing sectors and, hence, it can support the selection of the most suitable R strategy.

Useful application of materials: Recycle – Recovery.

Useful applications of materials are supported by several technologies. In the realm of recycling, IoT devices can be installed in waste bins, including recycling bins, to gather real-time data on waste producers' behavior (cluster 1). ML can assist in automated recycling by classifying and separating materials in mixed recycling applications, enhancing the separation of complex waste (cluster 1). ML techniques can also be utilized for backflow forecasting (cluster 10). Image processing can calculate a landfill index, offering insights into waste and recycling patterns and recommendations for improved productivity (cluster 1). BC enables effective monitoring of waste flow and promotes greater integration within recycling chains, providing a secure and transparent platform for tracking and verifying the movement of recycled materials (cluster 4). Human-robot collaboration plays a role in the recycling process, with tasks assigned depending on the condition of the discarded device (cluster 6). Computer vision technologies are employed to automatically identify and sort different types of materials, thereby improving the recycling process (cluster 8). AM can be crucial in closing the recycling chain by converting recycled filaments or powders into products (cluster 8). Additionally, combining an e-commerce platform with BC and IoT creates a multi-echelon virtual closed-loop supply chain, involving manufacturers, distributors, retailers, recycling and disposal centers, and logistics providers, fostering collaboration and considering return flows. Internet-based collaborative platforms facilitate the connection between waste generators and companies in the context of industrial symbiosis. Agent-based simulation aids in overcoming the quantity mismatch in industrial symbiosis (cluster 10).

In the field of recovery, the analysis did not uncover specific I4.0 technologies providing support.

Transversal support.

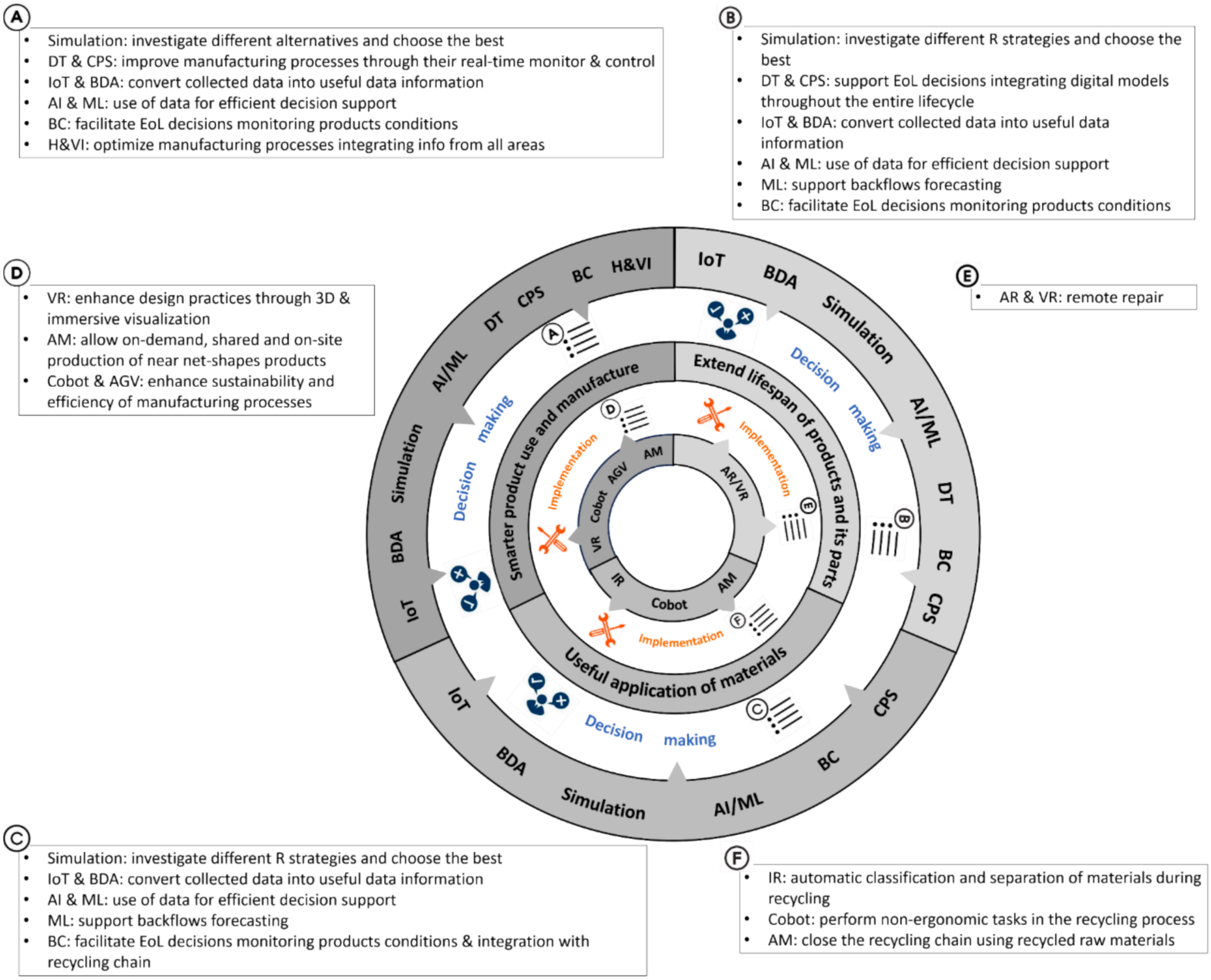
Although not explicitly attributed to a specific 'R', different technologies can empower various strategies (Cluster 3). IoT, CPS, BDA, and AI assist managers in making precise decisions regarding which 'R' to adopt. Simulation, BC, and other technologies provide support for this decision-making process (Cluster 3). The combination of IoT and BC allows for product condition monitoring, aiding in end-of-life decision-making and CE strategy selection (Cluster 4). IIoT contributes to renewing and improving the traditional LCA method (Cluster 6). IoT, BDA, and AI convert collected data into useful information for making precise 'R' adoption decisions (Cluster 7). BC can implement incentive mechanisms and tokenization to encourage environmentally friendly consumer behavior (Cluster 9). These strategies and technologies collectively shape the landscape of material applications and sustainable practices.

4.3. Integration framework

As can be discerned from the previous sections (section 4.1 and section 4.2), I4.0 technologies play a role in supporting CE strategies in two primary ways. Indeed, from the analysis of the different clusters, it is possible to identify how I4.0 technologies support CE strategies (i) by acting on the managerial level to improve the decision-making process associated with CE and (ii) by acting on the operational level, improving the implementation of CE. Dealing with the former, abundant literature has been found on the capabilities of I4.0 technologies to support the decision-making process associated with CE. Particularly, the decision-making process can be associated with the decision of which R strategy is best to adopt at the EoL. Indeed, plenty of literature can be found on how simulation, IoT, CPS, BDA, and AI can empower managers to make informed decisions about the adoption of specific "R" strategies (Govindan & Bouzon, 2018; Lin & Chen, 2015). Additionally, the focus of the decision-making process can also be on a specific R strategy. As an example, with a focus on the R strategies *Reduce* and *Recycle*, AI is reported to aid decision-makers in optimizing waste collection vehicle routes to minimize fuel consumption (Yazdani et al., 2021). Concerning the enabling role of I4.0 technologies for implementing CE strategies, the analysis of the different clusters shows how I4.0 technologies can facilitate and improve the direct implementation and adoption of specific "R" strategies. As an example, AR&VR facilitate the implementation of the *Repair* strategies and associated activities by offering remote assistance to technicians (Keller et al., 2014; Bahrin et al., 2016). Similarly, AM plays a role in facilitating the implementation of *Recycle* strategy by transforming recycled filaments or powders into products (Cruz Sanchez et al., 2020; Colorado, Velásquez, & Monteiro, 2020). Interestingly, from the analysis of the different clusters it clearly emerges how certain technologies such as BDA, IoT, CPS, Simulation, AI, DT, H&VI, and BC primarily support CE strategies by acting and improving the decision-making process. In contrast, other technologies such as AR&VR, cobot, AGV, AM, and image recognition (IR) predominantly support CE strategies by facilitating and improving the direct implementation of specific "R" strategies.

In light of these findings, a theoretically derived integration framework was developed and is presented in Fig. 2. Specifically, the framework contains three layers. The central one corresponds to the different CE strategies, divided into the three main groups identified by Potting et al. (2017) and Morseletto (2020). Then, the outer and the inner layers contain the I4.0 technologies supporting CE strategies. Specifically, the outer layer contains the I4.0 technologies that support CE strategies by acting on the managerial level, while the inner layer contains the I4.0 technologies that support CE strategies by acting on the operational level. Indeed, as described in the previous paragraph, from the literature, it was possible to see how a certain technology mainly impacts only one level.

The areas between the different layers, then, contain different lists (A, B, C, …E) that synthetize how I4.0 technologies support a certain group of CE strategies from a managerial and operational level (more external and internal area, respectively). As an example, list A synthetizes the literature findings on how IoT, BDA, Simulation, AI/ML, DT, CPS, BC, and H&VI can support the decision-making process related to the CE strategies falling within the group "smarter product use and manufacture". Notably, many similarities can be found within the lists, synthesizing how the I4.0 technologies of the outer layer can support the three groups of CE strategies (i.e., lists A, B, and C). The reason behind this is that the I4.0 technologies belonging to the outer layer focus on data collection and/or analysis, which are, hence, transversal for many CE strategies. This, hence, implies that the same I4.0 technologies can be used to support more than one group of CE strategies. This, in turn, represents a great benefit for managers as they can get support in their decision-making process with the same technologies for more than one CE strategy. On the contrary, focusing on the lists synthetizing how the I4.0 technologies of the inner layer can support the three groups of CE



Ⓐ
- Simulation: investigate different alternatives and choose the best
- DT & CPS: improve manufacturing processes through their real-time monitor & control
- IoT & BDA: convert collected data into useful data information
- AI & ML: use of data for efficient decision support
- BC: facilitate EoL decisions monitoring products conditions
- H&VI: optimize manufacturing processes integrating info from all areas

Ⓑ
- Simulation: investigate different R strategies and choose the best
- DT & CPS: support EoL decisions integrating digital models throughout the entire lifecycle
- IoT & BDA: convert collected data into useful data information
- AI & ML: use of data for efficient decision support
- ML: support backflows forecasting
- BC: facilitate EoL decisions monitoring products conditions

Ⓓ
- VR: enhance design practices through 3D & immersive visualization
- AM: allow on-demand, shared and on-site production of near net-shapes products
- Cobot & AGV: enhance sustainability and efficiency of manufacturing processes

Ⓔ
- AR & VR: remote repair

Ⓒ
- Simulation: investigate different R strategies and choose the best
- IoT & BDA: convert collected data into useful data information
- AI & ML: use of data for efficient decision support
- ML: support backflows forecasting
- BC: facilitate EoL decisions monitoring products conditions & integration with recycling chain

Ⓕ
- IR: automatic classification and separation of materials during recycling
- Cobot: perform non-ergonomic tasks in the recycling process
- AM: close the recycling chain using recycled raw materials

Fig. 2. Theoretically derived CE – I4.0 technologies integration framework.

strategies (i.e., list D, E, and F), we can see how a certain I4.0 technology either supports only one specific group of CE strategies, or it can support more than one group but in different ways, so their use cannot be considered transversal. This implies that separate investments must be made for different groups of CE strategies.

To the best of our knowledge, this is the first time such a theoretical framework has been developed. Not only does our framework overcome the limitations of those available in literature as it does not focus on a specific sector or specific I4.0 technologies/CE strategies, but it also provides clear indications on which technologies should be adopted given a certain interest and how these can be of help. For example, if one is interested in getting support in the decision-making process for CE strategies belonging to the group “smarter product use and manufacture,” then he/she should refer to list A to understand which technologies can be used and how. If, instead, one is still interested in the CE strategies belonging to the group “smarter product use and manufacture” but from an operational perspective, then he/she should refer to list D to understand which technologies can be used and how.

5. Discussion

The discussion will explore how the findings and the developed framework either confirm, integrate, or surpass those of previous studies while also identifying potential avenues for future research.

5.1. Comparison with previous literature

Smarter product use and manufacture: Refuse – Rethink – Reduce. Considering the use of Industry 4.0 technologies to design smarter product use and manufacture, in contrast with previous works that found the use of BDA to support CE design activities in rare cases (e.g., Rosa et al., 2020), this study finds examples of I4.0 technologies that support these strategies. Among them, most examples concern lowering resource consumption and improving manufacturing efficiency, i.e. “Reduce” strategy. This result supports the findings of Lei et al. (2023) that report “Reduce” to be among the top four CE strategies, together with recycling, maintenance, and waste management. This study also reports the DT as a technology leading to improved energy efficiency, reduced waste, and enhanced resource utilization, and the digital supply chain twin as improving logistics and refrigeration processes to reduce product losses. This result extends the findings from Lei et al. (2023) and other previous studies, such as Rosa et al. (2020), which mainly report on IIoT, BDA, and AM, and it contrasts with the findings of Lei et al. (2023), that found no application of DT in CE. Considering the opportunities offered by lean manufacturing to green manufacturing to implement the Reduce strategy, the synergy between lean manufacturing, I4.0, and CE represents an interesting further research path.

In contrast with recent research by Lei et al. (2023), this study reports several I4.0 technologies supporting manufacturing companies making products use more intensively, i.e., "Rethink" practice, such as VR, simulation, integration, and AM. Considering PSS, future studies should verify the opportunities offered by 5G applications in access-based PSS.

***Extend lifespan of products and its parts: Reuse – Repair – Refurbish – Remanufacture – Repurpose*.**

Differently from the previous frameworks available in the literature, in this study the Repair strategy is directly supported by specific I4.0 technologies, i.e., AM and AR&VR. The former enables the possibility of repairing the parts on-site, thereby reducing the demand for logistics services (Rahito, Wahab, & Azman, 2019; Ponis et al., 2021), while the latter provides the benefits of remote maintenance, repair, and training, eliminating the necessity for technicians to be physically present on-site and, thus, leading to cost savings and environmental advantages (Keller et al., 2014; Bahrin et al., 2016).

Regarding the selection of the most suitable R strategy, the developed framework confirms and extends the results found in the previous frameworks. It confirms that simulation and optimization models play a key role in providing adequate support to decision-makers, as asserted in the framework by Rosa et al. (2020). Indeed, simulation models can be employed to analyze material flows, energy consumption, and waste generation, while optimization models can reduce transportation-related emissions, minimize inventory, and ensure responsible sourcing (Lin & Chen, 2015; Govindan & Bouzon, 2018).

This study confirms what was discussed in the recent work by Liu et al. (2022) on the combination of IoT, BDA, and AI. IoT devices can gather real-time data on product condition and performance, and by leveraging BDA and AI techniques, they can provide actionable information into potential Reuse, Repair, Refurbish, Remanufacture, or Repurpose strategies (Bonilla et al., 2018; Franciosi et al., 2018; Hrouga, Sbihi, & Chavallard, 2022). Moreover, IoT data can be utilized with BC technologies to make efficient and trustworthy choices related to the preferable R strategy (Paul et al., 2022). In fact, BC incentives mechanisms and tokenization encourage eco-friendly consumer behavior (Esmaeilian et al., 2020), essential for the diffusion of reused, repaired, refurbished, remanufactured, or repurposed products in the market. This finding extends the results of Khan et al. (2021). While they focus on the potential benefits of incorporating BC technology into CE strategies, their scope is limited to recycling and remanufacturing strategies only. AI and ML are often considered in the previous frameworks, although they have some limitations, as explained in section 2.3. This study confirms and extends the discussion on the importance of ML in the decision-making process for CE. For instance, decision-makers face complexity in selecting the most suitable R strategy because of the diverse quality of returned products and the uncertainty of returned flows. ML aids in this process by predicting various characteristics of returned products, offering valuable support (El Hachimi, Oubrich, & Souissi, 2018).

Finally, the study explains that using cognitive twins complements the other I4.0 technologies across diverse industrial sectors, especially in manufacturing, as it enables enterprises to achieve sustainable and competitive advantages (Zheng, Lu, & Kiritsis, 2022). Similar considerations related to the DT were drawn in the work by (Elghaish et al., 2022), although with a focus on the construction sector.

Useful application of materials: Recycle – Recovery.

Our findings indicate a significant focus on the "recycle" category, aligning with Agrawal et al.'s (2021) study, which identified it as one of the most common keywords in CE literature. Moreover, IoT proves to be a core technology, confirming the findings by Lai et al. (2023). For example, the smart-bin concept, integrating IoT into waste bins, offers real-time waste data, aiding informed decisions (Chen, 2022). Moreover, Ziouzios and Dasygenis (2023) highlight that the concept of recycling can also be extended to the bins themselves, as there are examples of IoT-based smart bins made from recycled materials.

AI proves to be another key technology, confirming the study by Lai et al. (2023). In fact, Image processing identifies and sorts materials (Lu & Chen, 2022). Convolutional neural networks classify waste images (Zhang et al., 2021). Machine learning enhances material classification and separation (Guo et al., 2021) and aids backflow forecasting (El Hachimi et al., 2018).

The results confirm the importance of BC technology, as highlighted by Cagno et al. (2021). Moreover, our results offer a more detailed perspective on what other studies broadly label as BC platforms (e.g., Lai et al., 2023), explaining that omnichannel and e-commerce platforms can be integrated with BC and IoT. This creates a virtual closed-loop supply chain supporting reverse logistics (De Giovanni, 2022; Dutta et al., 2020; Prajapati et al., 2022).

The results confirm the importance of AM converting recycled materials into new products (Lai et al., 2023). Sanchez (2020) explores distributed recycling through six stages in AM, suggesting a need for further research in the recovery and preparation stages.

5.2. Implications for future research

Although I4.0 technologies show promise or established links in supporting CE practices, this study highlights several key areas where their potential remains underutilized or underexplored. Addressing these gaps through future research could pave the way for more innovative solutions and broader implementation.

In alignment with previous studies, regarding smarter product use and manufacture, no examples of Industry 4.0 (I4.0) technologies directly supporting the "Refuse" practice—where products are made redundant by abandoning their function or by offering the same function through radically different products—were found. This research gap suggests the need for exploration to harness the potential of 4.0 technologies in the context of Refuse initiatives.

When considering the extension of the lifespan of products and their parts, future research should prioritize exploring the direct support of I4.0 technologies for various "R" strategies beyond the current emphasis on Repair. Notably, Reuse, Refurbish, Remanufacture, and Repurpose currently lack direct technological support, representing a promising area for further exploration. However, it is important to highlight the absence of empirical evidence regarding the efficacy of adopting I4.0 technologies to promote CE adoption by companies. This gap underscores the need for a deeper understanding of how I4.0 technologies can effectively assist stakeholders engaged in practical circular business models.

Furthermore, since I4.0 technologies are closely tied to digitalization, which demands substantial energy consumption, future research should also focus on evaluating digital technologies' energy and environmental impacts while assessing their contributions to CE.

The analysis shows that in the context of useful application of material, literature extensively covers the role of I4.0 technologies in the "Recycle" category. However, there is a notable lack of discussion on their application in supporting "Recovery" initiatives, suggesting an area for further research. Additionally, while Agrawal et al. (2022) discuss human-robot collaboration in recycling, this topic remains underexplored in other reviews and frameworks. This represents a promising research direction, particularly in the study of e-waste management (Axenopoulos et al., 2019; Renteria & Alvarez-de-los-Mozos, 2019).

Future research could investigate the use of advanced AI and ML technologies to enhance CE strategies. For example, generative AI can facilitate the development of modular product designs that are easier to assemble, disassemble, and repair, thereby improving product durability and recyclability in line with CE principles. Additionally, generative AI can aid in selecting more recyclable or environmentally friendly materials, reducing waste and dependency on non-recyclable resources. By analyzing product lifecycle data, generative AI can also tailor refurbishment strategies to extend product lifespans and reduce downtime (Li et al., 2024).

ML techniques, on the other hand, can accelerate the identification of sustainable and recyclable materials, offering industries eco-friendly alternatives and lowering reliance on non-renewable resources. For instance, ML has already been applied to design composites with optimal performance, ensuring that materials can be effectively reused or repurposed, thereby contributing to the CE objective of extending product lifecycles (Saha et al., 2024).

These advancements suggest significant potential for future developments, where AI and ML could further revolutionize the implementation of CE strategies by driving smarter resource utilization, achieving near-zero waste, and advancing innovative approaches to lifecycle management.

6. Conclusion

To promote the adoption of the CE and assist countries in achieving their net-zero goals, this study provides a comprehensive analysis and introduces a novel integration framework illustrating how I4.0 technologies can support CE strategies, with a specific focus on the 10R model. While prior research has proposed several frameworks, these efforts have been limited in scope, often focusing on specific sectors, circular business models, practices, or subsets of I4.0 technologies, leaving significant knowledge gaps. Recognizing these limitations and the practical need for a more holistic approach, this research develops a comprehensive framework designed to support the widespread adoption of CE by leveraging the full potential of I4.0 technologies.

The proposed integration framework is grounded on an extensive literature review. It utilizes bibliometric tools and keyword clustering techniques to identify specific research domains and map their associated literature. Additionally, it presents a novel perspective on the synergy between I4.0 technologies and CE strategies.

This research answers the RQ, identifying the I4.0 technologies that can support the adoption of CE strategies and how they do so. Its main findings can be summarized as follows: I4.0 technologies play a pivotal role in supporting CE strategies through two distinct pathways: (i) at the managerial level, by enhancing decision-making processes, and (ii) at the operational level, by improving the practical implementation of CE strategies. At the managerial level, I4.0 technologies assist decision-makers in selecting the most suitable "R" strategy (e.g., Reuse, Repair, or Recycle) for end-of-life (EoL) products. This is achieved through data-driven insights facilitated by tools such as Simulation, the IoT, CPS, BDA, and AI, enabling businesses to make informed and strategic choices. At the operational level, instead, I4.0 technologies directly support the adoption and execution of specific "R" strategies. For example, AR and VR facilitate the "Repair" strategy by providing technicians with remote assistance. At the same time, AM strengthens the "Recycle" strategy by transforming recycled materials into new products. Another key finding of this research is that I4.0 technologies are not confined to supporting a single CE strategy but can often contribute to multiple strategies simultaneously. For instance, AI and BDA can enhance "Reduce" by optimizing resource usage while also improving "Recycle" through more efficient sorting and recycling processes. Similarly, BC technology facilitates transparency and traceability throughout the supply chain, a critical enabler for several CE strategies.

This study also identifies under-researched areas within the intersection of I4.0 technologies and CE. While much of the existing literature has focused on the "Reduce" and "Recycle" strategies, there is significant potential for innovation in integrating I4.0 technologies with less-explored strategies such as "Reuse," "Repurpose," "Refurbish," and "Remanufacture." These strategies present opportunities for further research and development to enhance their implementation through advanced digital solutions. Moreover, the integration of I4.0 technologies into the CE framework requires a careful assessment of the energy consumption and environmental impacts associated with the digital technologies themselves, ensuring that their adoption aligns with overall sustainability goals.

In conclusion, this work not only offers a practical roadmap for practitioners aiming to utilize I4.0 technologies to achieve more sustainable and efficient CE strategies but also provides new perspectives and research opportunities for academics exploring the intersection of I4.0 and CE.

CRediT authorship contribution statement

Maria Pia Ciano: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Mirco Peron:** Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Luigi Panza:** Writing – original draft, Formal analysis, Data curation, Conceptualization. **Rossella Pozzi:** Writing – original draft, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

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Table A1

1	2	3	4	5	6	7	8	9	10	11	12	13
waste management	circular economy	reverse logistics	blockchain	big data	smart manufacturing	green manufacturing	artificial intelligence	digitalization	industrial symbiosis	sustainable manufacturing	literature review	sustainable production
internet of things	industry 4.0	simulation	supply chain	life cycle assessment	energy efficiency	remanufacturing	recycling	blockchain technology	logistics	additive manufacturing	manufacturing	digital twins
machine learning	sustainability	systematic literature review	supply chain management	big data analytics	digital twin	optimization	3d printing	cleaner production	resource efficiency	energy consumption	circular manufacturing	ontology
iot	sustainable development	system dynamics	e-waste	construction waste management	cloud manufacturing	discrete event simulation	computer vision	industry 4.0 technologies	business models	smart factory	closed-loop supply chains	sustainable manufacturing capability
smart city	digital transformation	barriers	circular supply chain	sensor	cyber-physical systems	monte carlo simulation	classification	energy management	e-commerce	decision-making	predictive maintenance	value stream mapping
deep learning	case study	business model	covid-19	closed-loop supply chain	industrial internet of things	environment	solid waste	renewable energy	forecasting	digital manufacturing	simulation modelling	
internet of things (iot)	digital technologies	sustainable supply chain	smart contract	data mining	internet-of-things	digitization	distributed manufacturing	environmental sustainability	game theory	sharing economy		
solid waste management	digitalisation	resilience	e-waste management	lca	sustainable waste management	artificial intelligence (ai)	neural networks	circular economy practices	repair	cyber-physical production system		
smart bin	sustainable operations	cyber-physical system	circular supply chain management	genetic algorithm	virtual reality	lean manufacturing	plastic recycling	climate change	agent-based simulation	machining		
smart cities	dematel	decision making	smes	mobile application	process simulation	reuse	ai	resource recovery	product-service systems	modelling and simulation		
rfid	digital technology	mcdm	smart contracts	municipal solid waste management	life cycle assessment (lca)	weee	distributed recycling	textile industry	servitization			
sensors	sustainable development goals	modeling	traceability	digital circular economy	operator 4.0	product life cycle	disassembly	zero-waste				
ultrasonic sensor	waste	reverse supply chain	eco-efficiency	performance	collaborative robots	production	intelligent systems					
smart waste management	circular business models	radio frequency identification (rfid)	bim	transportation	food waste	energy	plastic waste					
cloud computing	circular economy (ce)	simulation model	critical success factors	hong kong	iiot	modeling and simulation	robotics					
arduino	innovation	agent-based modeling	distributed ledger	rfid technology	industry 5.0	reverse logistic						
image processing	management	bullwhip effect	ethereum	waste recycling	service-oriented architecture	uncertainty						
waste management system	dynamic capabilities	enablers	information technology									
cloud	technology	modelling										
data analytics	construction	optimisation										
lora	circularity	performance evaluation										
waste segregation	fourth industrial revolution											
lorawan												
raspberry pi												
object detection												
cnn												

(*continued on next page*)

Table A1 (*continued*)

1	2	3	4	5	6	7	8	9	10	11	12	13
convolutional neural network												
garbage collection												
waste collection												
wireless sensor networks												
convolutional neural networks												
gsm												
image classification												
smart bins												
arduino uno												
smart waste management system												
waste classification												
wireless sensor network												
food supply chain												
gis												
gps												
internet of things (iot)												
microcontroller												
sensor technology												
wi-fi												
artificial neural network												
cloud server												
decision support system												
edge computing												
fog computing												
food waste management												
gas sensor												
lpwan												
remote monitoring												
segregation												

Table A2

CE Strategy	R	Cluster	I4.0 technology	Description of how I4.0 technologies support the R strategy
Smarter product use and manufacture	Refuse	**C11**	AM	Refuse to buy new AM machines. AM machines can be shared in the context of digital manufacturing and smart factories
	Rethink	**C6**	VR	VR in building information modelling Design towards Adaptability allows visualization of the modular construction elements, and design of existing buildings to be adaptable to further uses before working on the envelope itself.
		C10	Data sharing and transparency (vertical integration)	IoT, Big Data and analytics improve data sharing and transparency along the value chain and support the *product-service system*
		C12	Simulation	Simulation offers the opportunity to enhance processes by investigating different design options through virtual simulations of their behaviour.
		C5	*big data analytics*	*Big data analytics* for the analyses of the freight characteristics and carbon emissions of trucks *transporting construction waste*
	Reduce	**C5**	AI, simulation, and optimisation methods	Fuel reduction with simulation and AI: integrated simulation and optimisation methods, specifically hybrid *genetic algorithms*, to optimize waste collection vehicle routing from construction sites to recycling facilities, resulting in a highly effective semi-heuristic algorithm
		C6	*Digital twin*	*Digital twin* replicating the requirements of the production system in *service-oriented architecture* supports process and *energy efficiency*
		C6	digital supply chain twin	Digital supply chain twin to reduce product losses in logistics and refrigeration process
		C7	Cobot & AGV	Cobot & AGV reduce the number of resources wasted and carbon emissions
		C7	AM	AM reduces the number of resources wasted and carbon emissions.
		C9	Blockchain (BC)	BC can enhance system efficiency while reducing costs and promote sustainability monitoring and reporting across supply chain networks
		C11	AM	AM allows to produce near net-shapes products, hence reducing energy consumption and natural resources
		C11	AM	AM enables digital manufacturing and smart factories where fewer resources are used since they are shared.
		C12	AM	AM can support CE by minimizing material usage and waste generation.
		C12	IoT	IoT enables seamless data collection and analysis of various industrial processes, facilitating the optimisation of manufacturing activities, energy consumption, and the reduction of waste.
		C12	Simulation	Simulation offers the potential to decrease the energy consumption of processes through virtual simulations of their behaviour.
		C12	horizontal and vertical integration	By integrating information from all organizational areas with horizontal and vertical integration, manufacturing waste and energy consumption can be optimized.
		C13	digital twin	digital twins can enable real-time monitoring, simulation, and optimisation of manufacturing processes, leading to improved energy efficiency, reduced waste, and enhanced resource utilization.
	General	**C3**	IoT, CPS, BDA, and AI	IoT, CPS, BDA, and AI can be used to empower managers to make precise decisions related to which R to adopt
		C3	Simulation	Simulation can be used to empower managers to make precise decisions related to which R to adopt
		C3	BC	BC can be used to empower managers to make precise decisions related to which R to adopt
		C4	IoT and BC	The combination of IoT and BC offers the ability to monitor product conditions, facilitating end-of-life decision-making and supporting the selection of CE strategies.
		C7	AI and ML	AI & ML enable efficient decision support which reduces waste and carbon emission
		C7	IoT, BDA and AI	IoT, BDA and AI can be used to empower managers to make precise decisions related to which R to adopt since they allow to convert collected data into useful data information
		C9	BC	BC can implement incentive mechanisms and tokenization to encourage environmentally-friendly consumer behaviour
Extend lifespan of product and its part	Reuse	–		–
	Repair	**C12**	Augmented and Virtual Reality	Augmented and Virtual Reality can provide the advantage of remote repair, eliminating the need for technicians to physically visit the location.
	Refurbish	–		–
	Remanufacture	–		
	Repurpose	–		–
	General	**C3**	Simulation	Simulation can be used to empower managers to make precise decisions related to which R to adopt
		C3	BC	BC can be used to empower managers to make precise decisions related to which R to adopt
		C4	IoT and BC	The combination of IoT and BC offers the ability to monitor product conditions, facilitating end-of-life decision-making and supporting the selection of CE strategies.
		C6	*iiot*	*iiot* can contribute to renew and improve the traditional *Life Cycle Assessment (LCA)* method
		C7	IoT, BDA and AI	IoT, BDA and AI can be used to empower managers to make precise decisions related to which R to adopt since they allow to convert collected data into useful data information
		C9	BC	BC can (i) implement incentive mechanisms and tokenization to encourage environmentally-friendly consumer behaviour; BC can (ii) improve visibility throughout the product lifecycle
		C10	ML	Machine learning techniques can help backflow *forecasting*
		C10	AM	AM processes supported by BC promote the direct use of by-products enabling industrial symbiosis
		C10	E-*commerce* platform, BC and IoT	E-*commerce* platforms combined with BC and IoT develop a multi-echelon virtual closed-loop supply chain where manufacturers, distributors, retailers, recycling and disposal

(*continued on next page*)

Table A2 (*continued*)

CE Strategy	R	Cluster	I4.0 technology	Description of how I4.0 technologies support the R strategy
				centres and logistics providers are entities that collaborate also considering the return flows;
		C10	Internet-based collaborative platforms	Internet-based collaborative platforms for *industrial symbiosis* to facilitate the link between waste generators and companies
		C10	*Agent-based simulation*	*Agent-based simulation* to overcome the quantity mismatch in *industrial symbiosis*
		C13	cognitive twin	The application of cognitive twins aligns with the use of Product Lifecycle Management strategies in various industrial sectors, particularly in *manufacturing*, to ensure *sustainable* and competitive advantages for enterprises
Useful application of materials	Recycle	**C1**	IoT	*Machine learning* can assist in automatically recycling by classifying and separating materials in mixed recycling applications, enhancing the separation of complex waste
		C1	*ML*	IoT devices can be installed in waste bins, including recycling bins, to gather real-time data on waste producers' behaviour
		C1	*image processing*	*image processing* can calculate a landfill index, offering insights into waste and recycling patterns and recommendations for improved productivity
		C4	BC	BC enables effective monitoring of waste flow and promotes greater integration within recycling chains. BC technology provides a secure and transparent platform for tracking and verifying the movement of recycled materials
		C6	Human-robot collaboration	Human-robot collaboration in the recycling process where tasks are assigned depending on the condition of the discarded device
		C8	Computer vision technologies	Computer vision technologies can be used to automatically identify and sort different types of materials, thus, improving the recycling process.
		C8	AM	AM can play a crucial role in closing the recycling chain by converting recycled filaments or powders into products.
		C10	ML	Machine learning techniques can help backflow *forecasting*
		C10	E-*commerce* platform, BC and IoT	E-*commerce* platforms combined with BC and IoT develop a multi-echelon virtual closed-loop supply chain where manufacturers, distributors, retailers, recycling and disposal centres and logistics providers are entities that collaborate also considering the return flows;
		C10	Internet-based collaborative platforms	Internet-based collaborative platforms for *industrial symbiosis* to facilitate the link between waste generators and companies
		C10	*Agent-based simulation*	*Agent-based simulation* to overcome the quantity mismatch in *industrial symbiosis*
	Recovery			
	General	**C3**	IoT, CPS, BDA and AI	IoT, CPS, BDA and AI can be used to empower managers to make precise decisions related to which R to adopt.
		C3	Simulation	Simulation can be used to empower managers to make precise decisions related to which R to adopt
		C3	BC	BC can be used to empower managers to make precise decisions related to which R to adopt
		C4	IoT and BC	The combination of IoT and BC offers the ability to monitor products conditions, facilitating end of life decision-making and supporting the selection of CE strategies.
		C6	*iiot*	*iiot* can contribute to renew and improve the traditional *Life Cycle Assessment (LCA)* method
		C7	IoT, BDA and AI	IoT, BDA and AI can be used to empower managers to make precise decisions related to which R to adopt since they allow to convert collected data into useful data information
		C9	BC	BC can implement incentive mechanisms and tokenization to encourage environmentally friendly consumer behaviour

Data availability

Data will be made available on request.

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