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How do digital technologies trigger sustainability and circularity in operations management processes? The role of environmental drivers

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Abstract

Purpose – This study aims to identify the main environmental drivers and impact areas activated by digital technologies (DTs) when adopted in different operations management processes for fostering circularity and environmental sustainability.

Design/methodology/approach – This paper carries out a systematic literature review of 195 articles. Content-based analysis is employed to code the three constructs of digital technologies, operations management processes and environmental drivers. Frequency and contingency analyses are conducted to identify 21 statistically significant relationships among the constructs. A research framework and research directions are then derived.

Findings – The findings highlight consolidated, emerging and specific relevant relationships between digital technologies and operations management processes, as well as the nature of the environmental drivers triggered by their interplay. Literature has so far placed particular emphasis on the resource efficiency environmental driver to exploit the sustainability potential of digital technologies. The potential of activating the most circular environmental drivers (i.e. lifetime extension, intensified asset usage and closing the loop) deserves deeper investigation.

Practical implications – The identified relationships and their impact mechanisms can serve as practical guidelines for managers seeking to deploy digital technologies within operations management processes to foster circularity and sustainability. Specifically, managers can draw indications into where (i.e. which operations management process) and how (i.e. through which impact domains) digital technologies can be applied to activate specific environmental drivers.

Originality/value – While digital technologies have been widely recognized as enablers of circularity and sustainability in manufacturing, their detailed operative mechanisms within different operations management processes are still under-investigated. The identified mechanisms, their discussion and the developed research framework contribute to fill this gap.

Keywords Digital technologies, Operations management processes, Contingency analysis,
Environmental drivers, Circular economy, Sustainability

Paper type Literature review

1. Introduction

Digital technologies (DTs), such as the Internet of Things (IoT) and artificial intelligence (AI), are driving the evolution of manufacturing and supply chains (Frank *et al.*, 2019). The integration of DTs with operations management (OM) processes – such as product development (PD), supply chain management, production, distribution, maintenance and reverse logistics (REVLOG) – also holds significant potential for enabling environmentally sustainable and circular operations by enhancing energy efficiency, minimizing waste, promoting resource reuse, and facilitating closed-loop material cycles (Barteková and Börkey, 2022, Aldrighetti *et al.*, 2023; Neri *et al.*, 2023). For example, Johnson and Johnson leveraged the Industrial IoT by using real-time sensors to collect data, leading to a 43% reduction in

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material waste. Similarly, Schneider Electric achieved a 17% reduction in material waste through the use of IoT and AI (World Economic Forum, 2022).

However, companies face obstacles to achieve sustainability outcomes, such as economic barriers, compatibility, scalability, interoperability between existing and new systems, cultural and skills gaps (Cannas *et al.*, 2024; Rajput and Singh, 2021). At a scientific level, a comprehensive understanding of the adoption of DTs in OM processes for environmental sustainability outcomes is still lacking. From one side, when analysing the role of DTs for environmental sustainability and circularity, the literature provides a quite fragmented picture (Alcayaga *et al.*, 2019; Birkel and Müller, 2021; Bressanelli *et al.*, 2022; Taddei *et al.*, 2022). On the other hand, while general claims about the environmental potential of DTs abound, the detailed mechanisms of such interplay – in terms of specific impacted areas and triggered environmental sustainability drivers – have not been adequately investigated to date (Das *et al.*, 2024; Schilling and Seuring, 2024). To fill this gap, this study addresses the following research question:

RQ1. How digital technologies acting on operations management processes contribute to foster environmental sustainability and circularity?

The paper carries out a systematic review of the literature dealing with DTs acting on OM processes, and their environmental implications. Descriptive, frequency, content-based and contingency analyses are carried out, based on an original research framework. The findings uncover that the adoption of DTs in different OM processes activates diverse environmental drivers to increase sustainability and circularity, with resource efficiency as the dominant driver. Moreover, consolidated, niche, and emerging relationships between DTs and OM process are highlighted.

The remaining of the paper is structured as follows. Section 2 provides the background and develops the research framework. Section 3 describes the methodology. Section 4 details the literature review findings. Section 5 engages in a discussion and conceptualization of the results. Lastly, Section 6 concludes summarizing the theoretical contributions, managerial implications and limitations of this study.

2. Background and research framework development

This section provides a background on the key concepts of DTs, OM processes, and environmental sustainability drivers. It also elucidates the research gap and presents the developed research framework.

2.1 Digital technologies and their environmental sustainability potential

DTs are changing production systems through their capabilities in “real-time, intelligent, and digital networking of people, equipment, and objects for the management of business processes and value-creating networks” (Luu *et al.*, 2023). Their adoption often focuses on promoting human-machine integration to enhance productivity and efficiency in operations (Ghobakhloo *et al.*, 2022; Rajput and Singh, 2021). Table 1 provides a categorization of the main technologies driving digitalization in the manufacturing sector, based on (Lu, 2017; Machado *et al.*, 2020; Paschou *et al.*, 2020; Russmann *et al.*, 2015).

Previous studies have examined how specific DTs support sustainable manufacturing and supply chain practices by reducing inefficiencies, waste, and non-value-added activities (Bag *et al.*, 2020; Di Maria *et al.*, 2022; Hmamed *et al.*, 2024; Neri *et al.*, 2023; Yu *et al.*, 2022). The IoT enables efficient data collection and sharing to monitor production data, which can reduce material waste and improve energy efficiency (Guo and Zhong, 2023; Rane *et al.*, 2023). Big Data Analytics (BDA), including machine learning and other AI methods, can transform product-in-use data into valuable information to minimize carbon emissions (Bag *et al.*, 2020). The integration of these technologies can optimize performances in areas such as inventory management and efficient material processing (Del Giudice *et al.*, 2021; Edwin Cheng *et al.*, 2022; Rane *et al.*, 2023). For example, Walmart implemented AI for predictive maintenance,

Table 1. Digital technologies categorization

Digital technology	Description
Internet of Things (IoT)	IoT refers to a network of connected devices that communicate with each other and share data
Big Data and Analytics (BDA)	BDA, including Artificial Intelligence and Machine Learning technologies, perform the analysis and interpretation of large and complex datasets
Cloud Computing (CC)	CC permits the storage and analysis of massive amounts of data on remote servers. It reduces the need for on-premises infrastructure and enable the creation of virtualized environments that can be easily duplicated and shared
Additive Manufacturing/3D Printing (AM)	AM is a fabrication technique that involves the progressive deposition of material onto a substrate, layer by layer, enabling the creation of high-complexity and/or personalized parts
Blockchain and Cybersecurity (BLC)	BLC technology is a secure, decentralized system for recording transactions, while cybersecurity is more focused on protecting networks, programs, devices and data from unauthorized access. Together, they support firms in tracking supply chain activities, ensuring product authenticity, protecting processes and systems that operate online
Augmented and Virtual Reality (AR/VR)	AR integrates the real and virtual worlds, creating environments where physical and digital objects coexist and interact in real-time. VR, on the other hand, offers a fully immersive digital experience that replaces the real world with a simulated environment
Cyber physical systems, Digital Twins and simulation (CPSDTS)	CPSDTS are technologies that integrate physical and virtual components, including virtual models of physical objects to monitor and control manufacturing processes and carry out simulation analyses to support decision-making
Industrial Robotics (IR)	IR encompasses the deployment of robots in industrial environments for the purpose of automating tasks, enhancing efficiency, productivity, flexibility, facilitating interactions with other machines, and ensuring safe collaboration with humans
Horizontal-Vertical integration (HVI)	HVI technology entails the integration of structural changes in the organization, the management of physical objects, and the establishment of connections with information systems (e.g. Enterprise Resource Planning)

Source(s): Authors’ own work

resulting in a 5–7% reduction in maintenance costs and a 6% decrease in energy consumption (IEA, 2025). Furthermore, Cloud Computing (CC) platforms offer organizations an efficient and scalable data storage solution on the Internet, providing faster services and enhanced accessibility (Sharma, 2023). Blockchain technology (BCT) and Cybersecurity, instead, enhances transparency and traceability in supply chains by providing visibility into product flows and the history of raw materials (Younis *et al.*, 2024). Process-driven or smart manufacturing technologies, such as Industrial Robotics (IR), Cyber Physical Systems (CPS) and Additive Manufacturing (AM), support minimizing waste and energy consumption (Aldrighetti *et al.*, 2023). Additionally, they support recycling and remanufacturing processes, thus closing the loop in material cycles and reducing the demand for virgin resources (Schlesinger *et al.*, 2023; Thao, 2023). Lastly, AM enables local, on-demand production of spare parts to support repair, which extends the lifetime of products (Ferreira *et al.*, 2023a, b).

2.2 Operations management processes

OM processes refer to the activities and systems that organizations use to oversee the production and delivery of goods and services. These processes focus on efficiently managing resources, optimizing the production process, and ensuring smooth material and information flows, to achieve cost minimization, greater customer satisfaction, or both. In the context of a Circular Economy (CE), OM must consider the closed-loop nature of logistics systems and consequently extend their spatial and temporal horizon throughout the product lifecycle, including end-of-life management aspects (Kleindorfer *et al.*, 2005; Aldrighetti *et al.*, 2023). Managing, planning and executing OM processes is complex and inherently interdisciplinary; operating closed-loop supply chains such as managing product returns, sorting, and recycling, in particular, presents additional challenges and complexities (Guo and Zhong, 2023). Based on the literature, OM processes can be grouped into seven classes, as reported in Table 2 (based on (Cannas *et al.*, 2024; Kleindorfer *et al.*, 2005)).

2.3 Environmental drivers

Environmental sustainability is the preservation of nature's services at an appropriate level, achieved by enhancing the integrity of the Earth's life-supporting systems (Moldan *et al.*, 2012). Previous studies have highlighted various ways DTs can achieve sustainability benefits in manufacturing, such as by reducing resource consumption or increasing the utilization of existing assets (e.g. through sharing) (Ferreira *et al.*, 2023a, b). However, the adoption of DTs does not inevitably lead to environmental sustainability: reasons are related to environmental impact inherent to the use of DTs, and the so-called rebound effects (Sorrell and Dimitropoulos, 2008). In fact, environmental benefits are achieved when operating mechanisms are aligned with factors triggering environmental sustainability, such as resource consumption, lifecycle duration, or prevention of CO_2 emissions, counterbalancing any potential negative impact. Saccani *et al.* (2024)'s study synthesizes from the literature a set of factors that drive improved

Table 2. Operations Management processes categorization

OM process	Description
Product development (PD)	Process of creating and designing new products to meet consumer needs
Procurement, inbound Logistics and Upstream Supply chain management (PLUS)	Process of procuring raw materials and components, managing their inventories, ensuring efficient inbound transportation, warehousing and handling of materials, components, and products, and managing relationships with suppliers
Production (PROD)	Set of activities and procedures involved in transforming raw materials into finished goods
Distribution, Outbound Logistics and downstream Supply chain management (DOLS)	Process of managing the distribution of goods, their inventories, material handling and outbound logistics; it requires coordinating and optimizing all the steps and actors involved towards the final customer
Maintain, technical assistance and repair (MAINT)	Activities including maintenance (regularly updating and checking the performance of the system/product), technical assistance (offering expert help to resolve issues or enhance the functionality of assets and products); and repair (fixing products' issues or malfunctions)
Reverse logistics (REVLOG)	Return of products from customers back to the manufacturer/seller or end-of-life centres for reasons such as reuse, refurbish, recycling, or disposal. It includes the orchestration or management of the actors involved in such processes
End-of-life treatment and processing (EOL)	End-of-life treatments and procedures to remanufacture or recycle a product or its components once they have reached the end of their useful life

Source(s): Authors' own work

environmental performance, referred to as environmental value drivers. Building on that study, this research focuses on investigating five key drivers of environmental sustainability and circularity, relevant for the adoption of DTs in OM processes. These *environmental drivers* are described in Table 3 (adapted from Saccani *et al.*, 2024).

2.4 Research gap

Table 4 summarizes recent literature reviews that examine the intersection of DTs and environmental sustainability or CE, specifically within the context of OM or supply chain management to identify current knowledge and gaps. The table excluded bibliometric literature reviews, focusing instead on review articles (systematic literature reviews or content-based analyses) directly relevant to the integration of DTs and sustainability or CE.

Overall, the analysed literature highlights that DTs facilitate the adoption of sustainability and CE principles across a range of manufacturing and supply chain activities (Kristoffersen *et al.*, 2020; Luthra *et al.*, 2020). However, despite their potential environmental benefits have been acknowledged across various domains, a comprehensive analysis of how DTs act on different OM processes to realize these benefits is still lacking. In particular, existing reviews tend to either focus narrowly on individual technologies (such as BDA, IoT, AI or BLC) or discuss DTs in broad but rather unspecific terms, frequently within the context of servitized or circular business models. Furthermore, most reviews do not address the role of DTs in OM processes, or concentrate on one OM process alone, such as production. As a result, there is a lack of in-depth analysis on how these DTs specifically connect with OM processes and to the abstraction of the mechanisms that generate sustainability and circularity benefits. Most

Table 3. Environmental drivers triggered by digital technologies

Environmental driver	Description
Resource efficiency	Resource efficiency for finished products and assets refers to the ratio of a product's added value to the value of resources used in its production. By considering the product's operation and resource usage, efficiency can be achieved by reducing the need for resources (materials, energy, water, etc.) during the usage phase
Reduced usage of hazardous, toxic or critical materials	Strategies to minimize pollutants, hazardous and critical materials include product redesign, use of clean materials and processes, and implementation of reuse practices
Lifetime extension	Lifetime extension allows products to remain in use for longer. This can be achieved through regular maintenance, provider ownership, or product redesign. This extends the lifespan of goods and reduces the need for new materials, thereby lowering resource consumption and mitigating resource depletion across the product lifecycle
Intensified asset usage	Intensifying asset usage aims to maximize the utilization of existing assets/products in terms of time, capacity, or functionality, thereby reducing the number of product units needed to meet usage demands
Dematerialization and transparency	Dematerialization of assets is achieved by leveraging services that minimize material consumption throughout a product's lifecycle. Additionally, digital technologies enhance transparency by enabling the identification, traceability, and monitoring of product-related data, such as location, composition, condition, maintenance history, and performance, or the virtualization of assets (e.g. thanks to digital twins), increasing visibility across the value chain
Closing the loop	"Keep products in the loop" through multiple usage cycles, minimizing the need for new resources; "close the loop" between post-use and production enabling recycling, resulting in a circular flow of resources

Source(s): Authors' own work

Table 4. Recent literature reviews addressing the role of digital technologies for sustainability and circularity

Paper	No. of articles analysed	Digital technologies covered	Reference to operations management processes	Environmental drivers mentioned	Findings
Rejeb *et al.* (2022)	170	IoT	unspecific	Resource efficiency, lifetime extension, Closing the loop	IoT is a key enabler for accelerating the transition towards CE. IoT supports CE principles such as resource efficiency and waste reduction. The paper further explores IoT role in supporting servitized and circular business models and its contribution to environmental, economic and social performance
Patyal *et al.* (2022)	76	IoT, BDA, CC, Autonomous Robots, AM, CPS, AR	unspecific	Not mentioned	The study examines how Industry 4.0 supports the RESOLVE framework but fails to analyse the role of individual technologies or their synergistic combinations
Santos and Sant'Anna (2024)	42	Cloud-edge, BCT, CPS, digital twin, AM, IoT, AI, BDA, Industry 4.0	Production processes	Not mentioned	The study focuses on the application of I4.0 technologies and their impact on circular production, proposing a product life cycle framework. However, it emphasizes technological applications in production processes rather than structurally addressing environmental sustainability mechanisms
Khan *et al.* (2021)	81	I4.0 in broader context	Not mentioned	Not mentioned	The study explores the role of Industry 4.0 in supporting the Triple Bottom Line through Sustainable Business Models (SBMs) and Circular Economy (CE)
Rizvi *et al.* (2021)	63	IoT & BDA	Reverse supply chain management	Resource Efficiency, closed loop	The study discusses the applications of IT tools (predominantly IoT and big data) in reverse supply chains
Du *et al.* (2024)	164	AI, BLC, BDA, IoT	unspecific	Not mentioned	The study focuses on the relationship between CE and digital transformation (DT) in supply chain management, waste management, and production

(*continued*)

Table 4. Continued

Paper	No. of articles analysed	Digital technologies covered	Reference to operations management processes	Environmental drivers mentioned	Findings
Romero *et al.* (2021)	41	BDA, Industrial Automation, Simulations, Integration Systems, IoT, Cybersecurity, CC, AM, AR/VR	Not mentioned	Not mentioned	The study provides a descriptive analysis of the literature discussing CE and Industry 4.0 technologies in general, discussing their broad impact on sustainability, people, and society
Bag and Pretorius (2022)	Not Available (NA)	BDA and AI	Unspecific	Not mentioned	The study identifies barriers, drivers, challenges, and opportunities for integrating Industry 4.0 technologies, sustainable manufacturing and CE. It focuses on the role of institutional pressure and workforce skills as reasons for developing BDA and AI, and their positive impact on generic sustainable manufacturing and CE capabilities
Gebhardt *et al.* (2022)	76	AI, AM, BDA, BLC, Cyber security, CPS, digital twin, IoT	Supply chain collaboration	Not mentioned	This paper focuses on how Industry 4.0 technologies enable circular supply chain collaboration, discussing their mechanisms and directions in a generalized manner
Dantas *et al.* (2021)	50	In broader context	Unspecific	Not mentioned	The study investigates the CE-I4.0 nexus and its benefits for achieving Sustainable Development Goals (SDGs)
Manavalan and Jayakrishna (2019)	115	I4.0 in general, but focus on IoT and Enterprise Resource Planning (ERP) systems	Supply chain in general	Resource efficiency, Closing the loop, Intensified product usage	The paper reviews the role of IoT and ERP systems in optimizing supply chains
Esmaeilian *et al.* (2020)	Not Available	Blockchain Technology	Not mentioned	Resource Efficiency, closing the loop	The study provides an overview of blockchain technology and Industry 4.0 for advancing supply chain sustainability
Liu *et al.* (2022)	174	I4.0 in general but more focus on IoT & BDA	Not mentioned	Closing the loop, Intensified product usage, Lifetime extension	The paper focuses on the digital functions of digital technologies and how they contribute to operationalize CE strategies
Chauhan *et al.* (2022)	123	IoT, BDA, AI, BLC	Focused more on Circular Business Model	Not mentioned	The paper identifies major themes at the CE-I4.0 intersection but does not address the mechanisms to achieve environmental benefits

Source(s): Authors’ own work

papers do not address the specific environmental drivers or mechanisms leading to sustainability benefits, besides the examples provided. In sum, despite the attention recently devoted to the topic, the literature has overlooked investigating with a comprehensive perspective the linkage between DTs and OM processes as the key domain where the generation of environmental benefits occurs, as well as the mechanisms of the DT-OM processes interplay – in terms of specific impact areas and environmental sustainability drivers triggered (Das *et al.*, 2024; Schilling and Seuring, 2024).

2.5 Initial research framework

Based on the theoretical background and research gap described above, Figure 1 proposes the conceptual research framework used in this study to address the sustainability and circularity impacts of DTs in their interplay with OM processes. As illustrated in the framework, the nine DTs described in section 2.1 act on the seven OM processes categorized in section 2.2, potentially activating the environmental drivers described in section 2.3, leading to environmental sustainability and circularity benefits.

The research framework allows to operationalize the research question introduced in section 1. In particular, this study will identify *which are* the main environmental drivers *activated by each DT when adopted in (each) OM process*.

3. Methodology

This study is based on a systematic literature review (Tranfield *et al.*, 2003).

3.1 Literature selection

The selection process was guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher *et al.*, 2009) to ensure clarity, transparency, and limited bias. The followed steps are depicted in Figure 2.

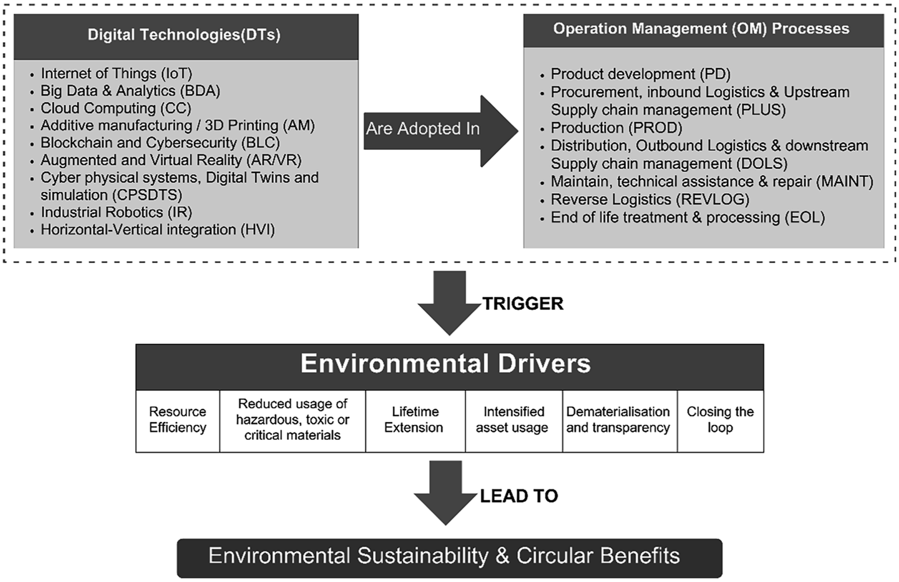

Figure 1. Proposed research framework. Source: Authors’ own work

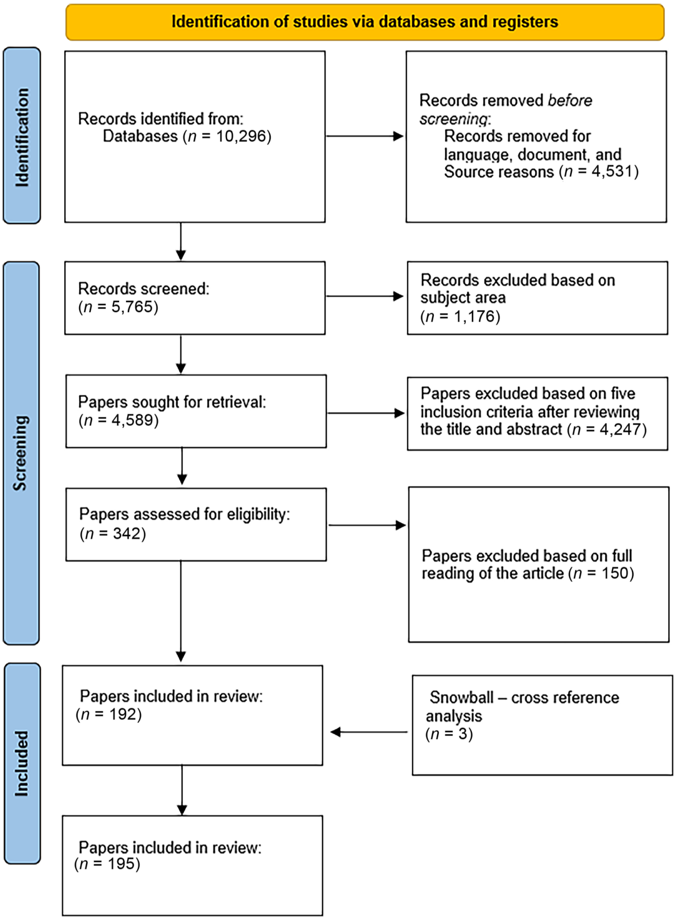

Figure 2. Flow diagram for the selection of the literature based on PRISMA guidelines. Source: Authors' own work

First, to identify relevant articles, a review protocol and search strategy were developed. The search strategy consists of two sets of keywords. The first set of keywords focused on DTs, and the second set of keywords was based on "Circular economy" and "Sustainability". The search was conducted using the search string TITLE-ABS-KEY ("Internet of Things" OR "Cyber physical systems" OR "Cloud computing" OR "Industrial robotics" OR "Data analytics" OR "Big data" OR "Additive manufacturing" OR "3D printing" OR "Industry 4.0" OR "Digital Technologies") AND TITLE-ABS-KEY ('Circular Economy' OR 'Sustainability'), which resulted in the extraction of 10,296 articles.

The second phase involved practical screening of the articles extracted. During the screening process, only journal articles published in English language were included: conference papers, books, and other sources were excluded. This was done to ensure that only peer-reviewed papers were selected for further analysis. Then, the articles were scrutinized to include only those subject areas such as engineering, operations, services, manufacturing, computer and social sciences, and business management. This step led to select 4,589 relevant articles among all the retrieved papers.

Then, the titles and abstracts of the papers were reviewed. Given the objective of this study, only the papers that met the following inclusion criteria were selected:

1. Have a specific focus on DTs or Industry 4.0/5.0, rather than discussing these topics in general terms.
2. Have a specific focus on CE or environmental sustainability, rather than discussing these topics in general terms or merely acknowledging them as relevant trends.
3. Focus on the manufacturing or business OM processes of manufacturing goods.
4. Discuss the application of DTs on one or more among the OM processes described in Table 2.
5. Are not based purely on a literature review but include analytical or conceptual modelling or empirical analyses (e.g. case studies, surveys, etc.).

Applying these criteria end to a set of 342 pertinent articles for detailed analysis. During the full reading step, all inclusion criteria were again applied, leading to 192 articles. To mitigate potential keyword limitations in the database search, cross-reference analysis was also employed, leading to the identification of three additional papers. As a result, a total of 195 papers are included in the literature sample of this study. Additionally, some relevant recent grey literature was considered in the background part of this study (IEA, 2025; MIMIT, Italian Ministry for Entreprises and Made in Italy, 2025; World Economic Forum, 2022; Gleiser I. 2023; European Policy Centre, 2020; ETC CE, 2025).

3.2 Literature analysis

We carried out descriptive, content, frequency and contingency analyses.

A *descriptive analysis* was carried out based on the paper classification by publication year and outlet.

A *content-based analysis* was carried out to uncover insights and patterns within the articles' content. A structured approach was followed to classify the 195 articles, based on the research framework of Figure 1 and a MS Excel database of the literature. The analysis incorporates the DTs addressed (options are reported in Table 1), the OM processes addressed (options in Table 2), the impact domain (how DTs acts on the OM process, qualitative classification), the environmental drivers activated (options in Table 3) and the environmental benefits (qualitative classification). The data resulted from the content-based analysis coding was subject to a *frequency analysis*, to understand the diffusion of the three coded constructs (DTs, OM processes and environmental drivers) in the literature sample. The codebook's validity was ensured through multiple reviews, aligning it with the framework. A single researcher conducted the coding, with support and quality checks from co-authors.

Content analysis alone often has limited value when viewed as individual items, since it lacks the ability to establish links between different constructs. A *contingency analysis* was therefore carried out to explore the relationships between constructs within the articles (de Lima *et al.*, 2022; Fleiss *et al.*, 2003). The contingency analysis was conducted in other literature reviews related to sustainable supply chain management and DTs (de Lima *et al.*, 2022; Hettiarachchi *et al.*, 2022; Schilling and Seuring, 2024). In particular, the aim of the contingency analysis is to identify associations from co-occurrences of DTs and OM processes, using contingency tables, comparing the observed and expected frequency of observation of each couple DT-OM process in the framework, and assessing them for statistically significant correlation. The "crosstabs" function of the statistical software SPSS 26.0. is used to analyse each relationship. The contingency analysis included carrying out a *Chi-square* test to determine the *phi coefficient*, which indicates the strength of the association between the constructs and the significance value (*p*-value) (Fleiss *et al.*, 2003). A *p*-value lower than 0.05 identifies a significant relationship, and a phi coefficient greater than 0.1 is considered an enough strong association between the dimensions (Akoglu, 2018).

4. Results

4.1 Descriptive results

Concerning the time distribution, the earliest publication analysed dates to 2014: the growth in publications started in 2018, with exponential increase in 2022 and 2023.

Figure 3 represents the journal distribution of the sample. The 195 analysed articles are spread across 85 journals. Only 11 journals published 4 papers or more. Notably, a substantial portion (48%) of the articles can be found in relevant journals within the fields of CE, sustainability and OM. These include *Journal of Cleaner Production*, *Business Strategy and the Environment*, *Computers and Industrial Engineering*, *Production Planning and Control*, *International Journal of Advanced Manufacturing Technology*, *International Journal of Production Economics*, and *Resource, Conservation and Recycling*.

4.2 Frequency analysis

Figure 4 illustrates the number of articles addressing the nine DTs. It is observed that IoT (addressed by 57%, of the sample), BDA (56%) followed by AM (51%) are the most investigated technologies. IoT and BDA enable data acquisition, transfer and elaboration (Rizvi *et al.*, 2023). They may optimize resource management (Chiarini *et al.*, 2020) and improve performance throughout the value chain (Kristoffersen *et al.*, 2020) through real-time information sharing (Dev *et al.*, 2020), cooperation (Gupta *et al.*, 2021), and coordination among processes (Kusi-Sarpong *et al.*, 2023). AM enhances production processes, making them suitable for high product complexity and customization, enabling minimal material consumption and greater energy efficiency compared to traditional manufacturing (Kahhal *et al.*, 2023). On the other hand, AR/VR and Horizontal-Vertical Integration (HVI) are the least discussed DTs. This may reflect their relatively recent relevance to OM processes.

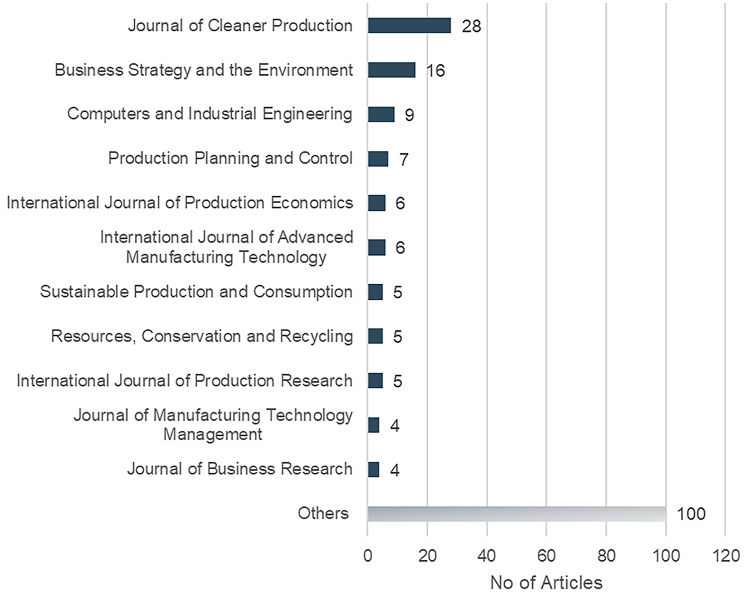

Figure 3. Distribution of articles per journal. Source: Authors' own work

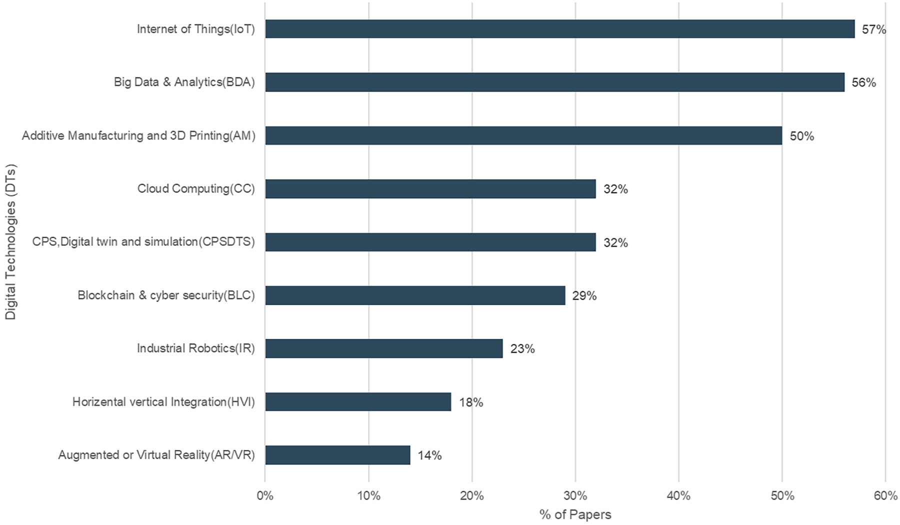

Figure 4. Frequency of digital technologies across the literature sample. Source: Authors' own work

Figure 5 illustrates how frequently the OM processes have been addressed in the literature. The PROD process (49%) was the most frequently discussed, followed by PLUS (45%) and End-of-life treatment and processing (EOL) (43%). The frequent discussion surrounding PROD highlights how DTs can reduce environmental impacts by increasing efficiency and optimizing the use of resources and energy. Papers dealing with PLUS highlighted the role of DTs in transforming traditional supply chains into digital ones, thereby offering logistic advantages, enhancing operational efficiency and improving supplier coordination (Ali *et al.*, 2023; Kusi-Sarpong *et al.*, 2023; Tavana *et al.*, 2023). From a CE standpoint, EOL management is critical: the reviewed papers highlight the importance of DTs for technically

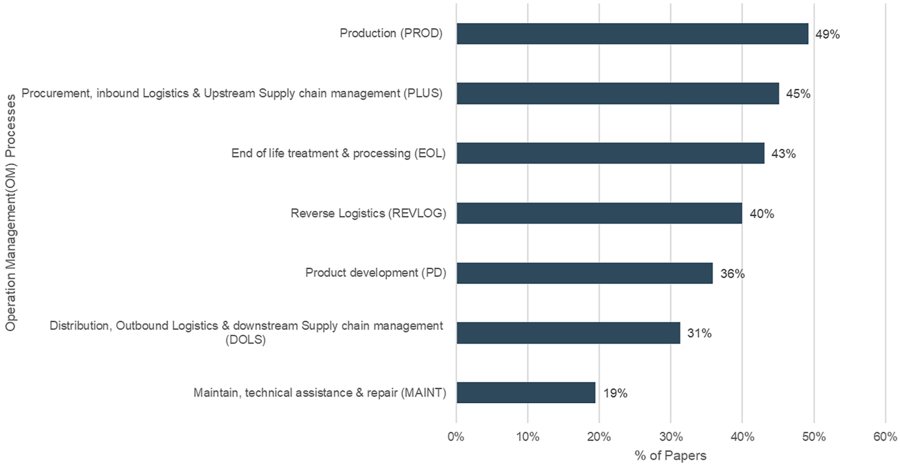

Figure 5. Frequency of Operations Management processes across the literature sample. Source: Authors' own work

improving or optimizing EOL activities, including disassembly, material sorting, recovery, recycling, upcycling, and non-organic material reuse (Delpla *et al.*, 2022; Garrido-Hidalgo *et al.*, 2020; Kumar *et al.*, 2023). Finally, Maintain, technical assistance and repair (MAINT) was the least addressed process, indicating a limited investigation of the role of DTs in these activities.

4.3 Results of contingency and content analyses

The literature sample was analysed to first explore the contingency relationships among the different DTs, and then between DTs and OM processes.

4.3.1 Step 1: Contingency relationships among DTs. The first contingency analysis among DTs was carried out to identify significant correlations among DTs and to support their grouping, so to simplify and increase the conceptual relevance of the subsequent contingency analysis between DTs and OM processes. Figure 6 shows the contingency relationships between pairs of technologies expressed through the values of phi coefficients. The 20 relationships with phi coefficient exceeding 0.3 and *p*-value lower than 0.05 are reported, in order to focus only on the strongest and statistically significant relationships.

The relationship between IoT and BDA has the greatest strength (phi value of 0.636), demonstrating the strong interdependence between the two, as IoT acts as a base technology for BDA. Similarly, the strong relationship between IoT and CC (phi 0.518), suggests a critical role of CC in providing data storage and computational resources. Also, BDA and CC exhibit a strong relationship (0.427). These dependencies are essential within manufacturing systems, given the complementary roles of these technologies in collecting and managing data, facilitating interconnectivity, and transforming the information flow within the system (Di Maria *et al.*, 2022; Lopes de Sousa Jabbour *et al.*, 2023). As a result of their interdependence, IoT, BDA, and CC are grouped into one technological group named “Data collection and processing technology (DCPT)”, as supported by the extant literature (Di Maria *et al.*, 2022; Prakash and Ambedkar, 2023). On the other hand, Cyber physical systems, Digital Twins and simulation (CPSDTS), IR, and AR/VR are recognized as automation technologies by the literature (Di Maria *et al.*, 2022). However, the grouping of these technologies is less apparent because CPSDTS is more strongly linked with HVI (0.517) and IoT (0.488) than IR (0.421) and AR/VR (0.427). Again, IR is more strongly associated with CC (0.496) than with AR/VR (0.461) and CPSDTS (0.421). This suggests that while these technologies are all related to automation, their relationships and co-applications with other technologies can differ. Moreover, HVI is connected with five technologies, as shown in Figure 6. Kusi-Sarpong *et al.* (2023) considered HVI as a key and foundational technology for integration and information flows and one of the strongest enablers of circularity. Finally, BLC and AM exhibit no significant connections with other technologies and thus have emerged as standalone technologies.

Based on these findings, DCPT, is considered as a single “macro” technology group and substitute IoT, BDA and CC for the second step of analysis, along with the six other DTs (BLC, HVI, AM, CPSDTS, IR, and AR/VR).

4.3.2 Step 2: Contingency relationships between DTs and OM processes. The 49 relationships among the seven DTs resulting from Step 1 and the seven OM processes have been investigated through a contingency analysis. The 21 relationships exhibiting statistical significance (*p*-values lower than 0.05) and significant strength (phi >0.1), indicating relevant connections, are listed in Table 5. The observed frequency in the table provides the actual number of papers where the mentioned DTs and OM processes are jointly discussed. On the other hand, the expected frequency represents the anticipated count for a particular relationship based on probability count (see section 3.2).

Figure 7 visualizes the 21 significant relationships reported in Table 5, reporting the observed frequency and the phi coefficient (indicating the strength of the relationship). This

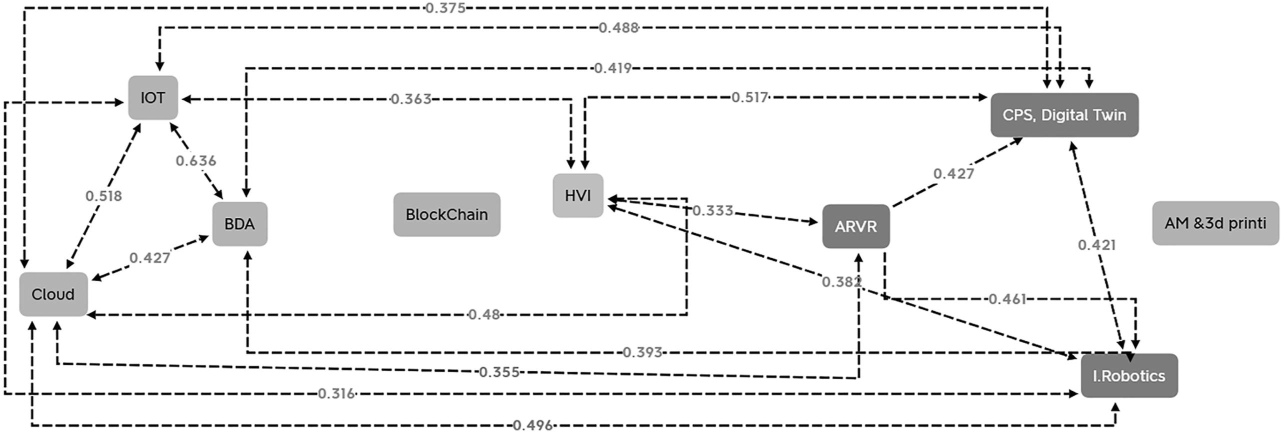

Figure 6. Contingency relationship between digital technologies. Source: Authors' own work

Table 5. Contingency relationships between different digital technologies and Operations Management processes

#	Technology	OM process	Observed freq	Expected freq	*p*-value	Phi coeff
1	Data Collection and Processing Technology (DCPT)	Procurement, inbound Logistics and Upstream Supply chain management (PLUS)	70	52.8	0.0001	0.362
2	Horizontal-Vertical integration (HVI)	Procurement, inbound Logistics and Upstream Supply chain management (PLUS)	28	16.2	0.0001	0.312
3	Cyber physical systems, Digital Twins and simulation (CPSDTS)	Procurement, inbound Logistics and Upstream Supply chain management (PLUS)	41	28	0.0001	0.288
4	Augmented and Virtual Reality (AR/VR)	Maintain, technical assistance and repair (MAINT)	12	5.5	0.001	0.242
5	Additive manufacturing/ 3D Printing (AM)	Production (PROD)	59	47.3	0.001	0.241
6	Industrial Robotics (IR)	Maintain, technical assistance and repair (MAINT)	16	8.6	0.001	0.23
7	Industrial Robotics (IR)	Procurement, inbound Logistics and Upstream Supply chain management (PLUS)	29	19.9	0.002	0.225
8	Blockchain and Cybersecurity (BLC)	Reverse Logistics (REVLOG)	32	22	0.001	0.223
9	Horizontal-Vertical integration (HVI)	Distribution, Outbound Logistics and downstream Supply chain management (DOLS)	19	11.3	0.002	0.221
10	Additive manufacturing/ 3D Printing (AM)	End-of-life treatment and processing (EOL)	52	41.4	0.002	0.221
11	Data Collection and Processing Technology (DCPT)	Reverse Logistics (REVLOG)	57	46.8	0.002	0.218
12	Data Collection and Processing Technology (DCPT)	Distribution, Outbound Logistics and downstream Supply chain management (DOLS)	46	36.6	0.003	0.212
13	Blockchain and Cybersecurity (BLC)	Procurement, inbound Logistics and Upstream Supply chain management (PLUS)	34	24.8	0.003	0.21
14	Horizontal-Vertical integration (HVI)	Maintain, technical assistance and repair (MAINT)	13	7	0.005	0.20
15	Industrial Robotics (IR)	Distribution, Outbound Logistics and downstream Supply chain management (DOLS)	21	13.8	0.008	0.191
16	Industrial Robotics (IR)	Product development	23	15.8	0.01	0.184
17	Horizontal-Vertical integration (HVI)	Reverse Logistics (REVLOG)	21	14.4	0.013	0.178

(*continued*)

Table 5. Continued

#	Technology	OM process	Observed freq	Expected freq	*p*-value	Phi coeff
18	Augmented and Virtual Reality (AR/VR)	Procurement, inbound Logistics and Upstream Supply chain management (PLUS)	18	12.6	0.028	0.158
19	Cyber physical systems, Digital Twins and simulation (CPSDTS)	Distribution, Outbound Logistics and downstream Supply chain management (DOLS)	26	19.4	0.028	0.157
20	Industrial Robotics (IR)	Production (PROD)	28	21.7	0.03	0.156
21	Cyber physical systems, Digital Twins and simulation (CPSDTS)	Production (PROD)	37	30.5	0.046	0.143

Source(s): Authors' own work

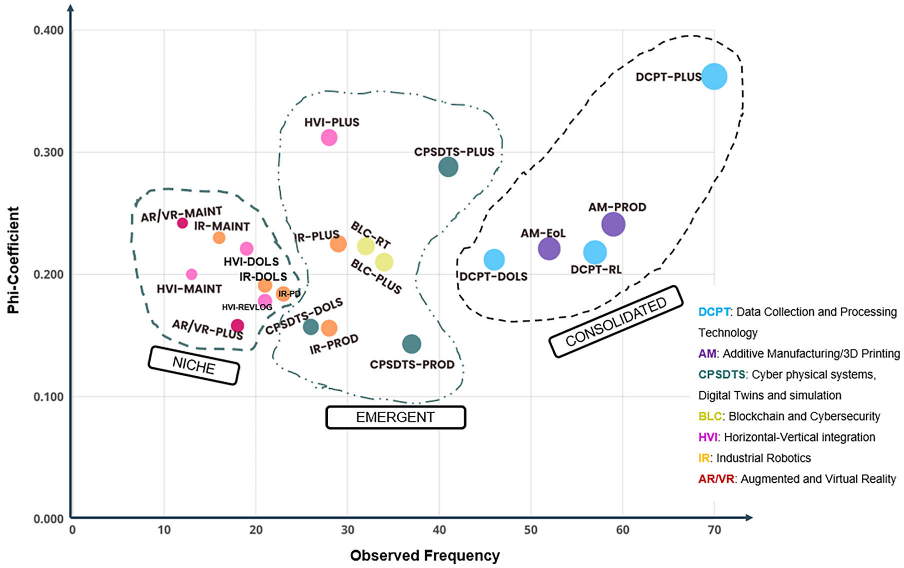

Figure 7. Visualization of the contingency relationships for the 21 significant DT-OM process couples. Source: Authors' own work

visualization allows identifying three groups of relationships: *Consolidated*, *Emerging* and *Niche*.

The *Consolidated* group consists of the 5 couples with the highest observed frequency and medium-to-high phi coefficient values. It involves only two technologies, DCPT and AM, covering all their contingency relationships with five different OM processes. The *Emergent* group includes 8 relationships with medium frequency. In this group, a significant focus concerns the PLUS process: it is addressed for the sustainability and circularity potential enabled by four different technologies (CPSDTS, BLC, IR and HVI). All the relationships involving CPS and BLC fall within this group. The relationships involving HVI and IR, instead, are distributed between the Emergent and the Niche groups, due to their low degree of investigation and a wide number of relationships. The *Niche* group highlights significant relationships, despite their limited frequency: it consists of 8 relationships, connecting HVI, IR and AR/VR with four different OM processes (PD, PLUS, DOLS, REVLOG and MAINT). MAINT appears three times, having been less investigated in the literature sample compared to the other OM processes, but at the same time proving significantly impacted by DTs.

The results from the content analysis for each of the 21 relationship are then presented in Table 6. For each DT, the table summarizes the OM processes connected, the impact domains (i.e. where and how the DTs act within the OM process), and the activated environmental drivers. It also illustrates the strength of each environmental driver activation, based on distinct impact domains involved in the DT–OM process association (the number of '●' in the table represents the strength of the links, which is qualitatively assessed based on the number of impact domains involved). A detailed description of the findings in Table 6 and of the impact domains activated is available in the **supplementary material**. In the next section, these findings are discussed in the light of the research framework.

5. Discussion

Based on the results of the literature analysis, the framework of Figure 1 has been revisited and re-populated, as suggested by (Durach and Wieland, 2017). The final framework is shown in Figure 8. In the upper part, the 21 significant relationships between DTs and OM processes are illustrated. In the lower part, instead, the environmental drivers have been re-ordered based on the intensity they are triggered in the 21 contingency relationships.

Also, Table 7 provides a summary - organized according to DTs - of the findings about the relationships with OM processes, impacted domains, environmental drivers triggered (the number of '●' in the table reflects a qualitative understanding of the driver's relevance across multiple impact domains) and research directions identified. They are discussed hereafter.

Combining the frequency and contingency analyses, we observe that two technologies, namely DCPT and CPSDTS, have had both a large coverage of literature and contingency relationships with a significant number of OM processes (3 each). DCPT groups three lower-level technologies (IoT, CC and BDA) and is a foundational data collection and sharing technology (Di Maria *et al*., 2022) that enables or empowers other DTs, such as CPSDTS, HVI, AR/VR, and IR, as shown by the contingency analysis within DTs in section 4.3.1 (Marković and Jemović, 2024). Moreover, this study highlights that DCPT allows achieving sustainability benefits when is adopted in the three external interfaces of OM processes: with upstream, forward downstream, and reverse supply chain partners, supporting previous findings (Gholami *et al*., 2022). Through real-time information sharing, visibility and enhanced data analysis, DCPT supports optimized decision-making (Yadav *et al*., 2020). Thus, sustainability benefits are achieved mainly leveraging *resource* (material and especially energy) *efficiency* and *dematerialization* ("*make information flows work instead than materials*" (Bressanelli *et al*., 2022)), and only to a lesser extent triggering the other environmental drivers.

CPSDTS (Cyber-Physical Systems, Digital Twin and Simulation) have also been significantly addressed in the literature. Differently from DCPT, CPSDTS act especially within internal activities (production, inbound and outbound logistics and warehousing) supporting the optimization of execution and planning through virtualization and simulation. The environmental drivers activated to achieve sustainability are again mainly *resource and energy efficiency*, and *dematerialization*. The transition to DCPT is proving to be a game-changer for older factories, significantly enhancing their productivity and operational efficiency. For example, LG Electronics in Korea implemented a digital twin and AI-enabled material transport system, resulting in a 17% increase in productivity and a substantial reduction in line downtime (World Economic Forum, 2022). So, while CPSDTS is empowered by the adoption of DCPT, it reveals to be complementary to DCPT in reducing resource consumption and waste in a range of internal (to the manufacturing company) OM activities.

Table 6. Summary of the relationships between digital technologies and Operations Management processes

				Activated environmental drivers (and their intensity ‘ ●●● ’ = stronger; ‘●’ = weaker)					
Technology	OM process	Impact domains	No of studies	Resource efficiency	Hazardous/ toxic/ critical substances reduction	Lifetime extension	Intensified asset usage	Dematerialization and transparency	Closing the loop
DCPT	PLUS	Information sharing and coordination Inventory management optimization (e.g. through real-time data and improved demand forecasting) Raw material information and traceability Risk management	70	● ● ●	●		●	● ●	●
DCPT	DOLS	Logistic route optimization Warehouse management optimization	46	● ●			●	●	
DCPT	REVLOG	Optimization of reverse logistic information management systems Route optimization Enhance tactical and strategic Reverse Logistics (REVLOG) decisions	57	● ● ●	● ●	●		● ●	● ●
BLC	PLUS	Supporting collaborative relationships and sharing information with suppliers uncertainty and risk mitigation in the supply chain	34	●	● ●			● ●	
BLC	REVLOG	Tracking product lifecycle data to support effective reverse logistics planning and decision-making Increasing the participation of customers and supply chain stakeholder in reverse logistics	32		● ●	●	● ●	● ●	●
HVI	PLUS	Improving buyer -supplier information sharing and trust	28	●				●	

(*continued*)

Table 6. Continued

				Activated environmental drivers (and their intensity ‘ ●●● ’ = stronger; ‘●’ = weaker)					
Technology	OM process	Impact domains	No of studies	Resource efficiency	Hazardous/toxic/critical substances reduction	Lifetime extension	Intensified asset usage	Dematerialization and transparency	Closing the loop
HVI	DOLS	Improving planning and downstream supply chain coordination through information sharing Increasing operations and transportation efficiency	19	●			●	●	
HVI	MAINT	Real-time monitoring of production shopfloor for early detection of breakdowns and preventive maintenance	13	●		●			
HVI	REVLOG	Optimization of material flows and industrial symbiosis	21	●	●			●	●
AR/VR	PLUS	Increasing efficiency, effectiveness and safety of warehouse operations	18	●					
AR/VR	MAINT	Enhanced machine inspection, improved training Remote assistance, guidance to remote technicians	12	● ●	●	● ●		●	
CPSDTS	PLUS	Handling supply chain uncertainties and the upstream impacts of demand fluctuations Green supplier selection	41	● ●	●			● ●	
CPSDTS	DOLS	Enhancing the product delivery and distribution systems	26	● ●				●	
CPSDTS	PROD	Optimization of production parameters using simulation Evaluating production process, technology and scheduling alternatives	37	●	●	●	●	●	

(*continued*)

Table 6. Continued

				Activated environmental drivers (and their intensity ‘ ●●● ’ = stronger; ‘●’ = weaker)					
Technology	OM process	Impact domains	No of studies	Resource efficiency	Hazardous/ toxic/ critical substances reduction	Lifetime extension	Intensified asset usage	Dematerialization and transparency	Closing the loop
IR	PROD	Streamlined production process, reducing human error, and support in higher precision and accuracy in quality control	28	● ●					
IR	MAINT	Facilitated maintenance activities (e.g. more efficient inspection, disassembly and serviceability, addressing challenging environmental conditions . . .)	16	● ●	●	●			●
IR	PLUS	Automation in inbound and internal handling	29	● ●					
IR	DOLS	Streamlined warehouse activity	21	● ●					
AM	PD	Improved and more efficient prototyping	23	●	●	●			
AM	PROD	Supporting design and production flexibility and customization (on demand) Supporting local and on-demand manufacturing	59	● ●		●	● ●		● ●
AM	EOL	Reusing waste as secondary raw materials	52		●				● ●

Source(s): Authors’ own work

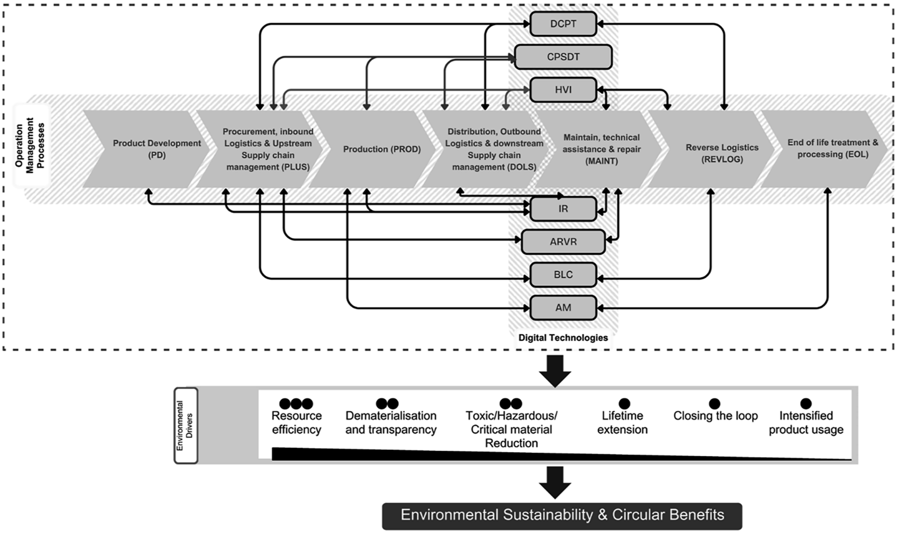

Figure 8. A framework for the role of digital technologies applied to Operations Management processes in activating environmental sustainability and circularity drivers. Source: Authors’ own work

AM, the second most addressed technology in the literature sample, has a more focused role: it has been extensively associated to production and end-of-life treatment. The potential for waste and energy consumption reduction, and the opportunity it provides to enable local, closed-loop supply chains for secondary raw materials have been highlighted (Walachowicz *et al.*, 2017; Wu *et al.*, 2022). Therefore, along with resource efficiency, AM triggers also the *“closing the loop”* environmental driver, enabling circularity. Research gaps in this case are mainly on the technical side: detailed sustainability evaluation of recycling and manufacturing methods should be carried out, as well as the use of secondary raw materials as AM powders, and design reverse supply chains to collect them (Das *et al.*, 2024; Ferreira *et al.*, 2023a, b).

BLC also encountered a focused interest in the literature. They trigger environmental sustainability through *dematerialization and virtualization*, i.e. enabling the tracking and security of materials and product history data, allowing for upstream traceability and digital product passports (Schilling and Seuring, 2024), or smart contracts providing rewards to circular consumers behaviour (Chaouni Benabdellah *et al.*, 2023; Younis *et al.*, 2024). This leads to the ability to *reduce hazardous, toxic and critical raw materials* usage and waste within the product lifecycle, especially thanks to lifecycle data visibility and green procurement. Further research and practical implementation are needed to fully realize the potential of these emerging technologies, as the current literature lacks extensive empirical studies (Ghobakhloo *et al.*, 2022), and challenges to their adoption are persistent, such as the lack of specialized tools and applications for BLC in remanufacturing operations (Govindan, 2022).

A call for further investigation about the role of IR, HVI and AR/VR for environmental sustainability emerges from our study. IR and HVI have a higher number of relevant relationships with OM processes than any other DTs. IR is connected to five OM processes, and its potential for *resource efficiency* across physical activities from warehousing and handling to maintenance has been highlighted, supporting also *lifetime extension* through improved asset lifetime service. Beyond theoretical relationships, practical implementations are already showcasing IR’s impact. For instance, Johnson and Johnson’ Latina facility implemented robotics-enabled logistics, resulting in a 10% increase in resource efficiency

Table 7. Summary of the findings and research directions

Digital technology	Characteristics*	Impacted processes/ activities**	Investigation popularity**	Environmental drivers triggered***	Research directions***
Data collection and processing technology (DCPT)	Foundational to other DTs	Several interface supply chain activities (Upstream, Downstream, Reverse Logistics)	Consolidated	●●● Resource Efficiency ●● Dematerialization ● Others	Relationship with circular drivers (lifetime extension, intensified asset usage, closing the loop)
Horizontal-Vertical integration (HVI)	Foundational for other DTs	Several interface supply chain activities (Upstream, Downstream, Maintenance, Reverse Logistics)	Niche	● Resource Efficiency ● Dematerialization	Deeper investigation of significant relationships; Challenges in data management and integration
Cyber physical systems, Digital Twins and simulation (CPSDTS)	Connected to several other DT, empowered by DCPT	Several internal activities (production, inbound and outbound, material handling warehousing and logistics)	Emerging	●● Resource Efficiency ●● Dematerialization	Complementary role with DCPT and benefits of joint adoption
Industrial Robotics (IR)	Connected to several other DTs	Several physical activities (production, material handling, product development, Maintenance)	Niche–Emerging	●● Resource Efficiency ● Others	Deeper investigation of significant relationships with OM processes
Augmented and Virtual Reality (AR/VR)	Connected to several other DTs	Focused – physical activities (maintenance, warehousing)	Niche	●● Resource Efficiency ● Dematerialization ● Lifetime Extension	Deeper investigation of significant relationships with OM processes; Empirical/ quantitative research on practical implementation, obstacles and outcomes

(*continued*)

Table 7. Continued

Digital technology	Characteristics*	Impacted processes/ activities**	Investigation popularity**	Environmental drivers triggered***	Research directions***
Additive manufacturing/ 3D printing (AM)	Standalone	Focused – physical activities (production, end-of-life treatment)	Consolidated	●● Closing the loop ●● Resource Efficiency	Technical developments to expand the adoption of AM and achieve the promised benefits on a large scale
Blockchain and Cybersecurity (BLC)	Standalone	Focused – interface activities (tracking in procurement and reverse logistics)	Emerging	●● Dematerialization ●● Hazardous/ toxic/critical mat reduction	Empirical/ quantitative research on practical implementation, obstacles and outcomes

Note(s): * based on the contingency relationships among DTs,
** based on the contingency relationships between DTs and OM processes and frequency analysis,
*** based on the content analysis (number of "●" represents the intensity: "●●●" = stronger, "●" = weaker)
Source(s): Authors' own work

across distribution operations. This example illustrates the role of IR in streamlining downstream supply chain processes and supporting more sustainable manufacturing practices (World Economic Forum, 2022). HVI, as DCPT, emerges from the contingency analysis as a foundational technology for integration and information flows, and it is related to four OM processes. Similarly to DCPT, its role in enabling environmental sustainability occurs especially within interface activities and HVI mainly triggers *resource efficiency* and *dematerialization*. However, it has been much less investigated in the literature with respect to DCPT.

Finally, AR/VR has a strong relevance especially for MAINT, enabling *lifetime extension* and *resource efficiency* through *dematerialization*, yet it has received limited investigation in the literature. Despite this focused potential, widespread adoption of these technologies in "after-sales" service is challenging due to their implementation complexity linked to high costs, limited accessibility, technical setup difficulties, remote connectivity limitations, the need for significant computing power to deliver high-quality data, latency issues and integration challenges with existing information technology infrastructure (Aquino *et al.*, 2023). While several articles discussed the promising role of DTs, some of them also acknowledged their potential negative or rebound effects (OECD, 2022). The growing reliance on DTs can lead to new environmental burdens, including increased resource consumption, substantial waste generation, energy use, and greenhouse gas emissions associated with the development and maintenance of digital infrastructure (Alcayaga *et al.*, 2019; Dantas *et al.*, 2021). Consequently, adopting a more balanced and critical approach is essential to ensure that the twin transition (Digital-Circular economy) progresses in a sustainable and resilient manner. Therefore, future research should assess both the positive and negative impacts of this nexus using different methodologies, such as Life Cycle Assessment (Bressanelli *et al.*, 2024).

Moreover, the populated research framework of Figure 8 points to the relevance of environmental drivers as a means to achieve circularity and sustainability. From the analysis of the relationships among DTs and OM processes (see section 4.3.3), *resource efficiency* stands out as the predominant environmental driver triggered by DTs in OM processes. The adoption of DTs leads to reduced energy or fuel consumption through the monitoring and optimization of physical activities, and to reduced material consumption thanks to process optimization (e.g. waste reduction) and informed decision-making (e.g. improved recovery rates, or optimal scheduling of transportation or production activities). Resource efficiency is the main sustainability driver across all the different DTs and OM processes (with one exception), supporting that DTs are seen primarily as a way to make manufacturing and supply chain operations more efficient (Neri *et al*., 2023; Schöggl *et al*., 2024). The underlying equation is that through greater operational efficiency and productivity, DTs entail cost savings that translate also into environmental benefits (Gupta *et al*., 2021; Nascimento *et al*., 2019). Schilling and Seuring (2024) found similar evidence, but while their research focused on the supply chain management practices entailed by generic DTs, this study provides deeper insights on the detailed role of each DT and of its impact mechanisms on OM processes (Table 6). The only DT with a different prominent environmental impact is BLC that triggers *dematerialisation/transparency* and *reduction of hazardous/toxic/critical materials* more extensively than resource efficiency, thanks to its peculiar role. In fact, it guarantees information reliability and security, especially supporting material-related decision-making.

Other two sustainability drivers are frequently entailed in the impact mechanisms analysed. *Dematerialization and transparency* is quite obviously triggered by DTs, since they allow the virtualization of previously physical activities, reducing material flows and connected environmental impacts. Reduced usage of *hazardous, toxic or critical materials* is another frequent driver, mainly activated by DTs in PLUS process (as a result of traceability and green purchasing practices), and REVLOG, based on improved decision-making about repurposing products and materials (e.g. defining the best strategy among reuse, remanufacture or recycle).

The other drivers are much less apparent in the literature in the action of DTs on OM processes. However, Table 6 suggests that DTs also trigger other environmental drivers, when applied to niche OM processes. For instance, DTs in REVLOG allow for effectively *closing the loop*. The same driver is activated by DTs in end-of-life. *Lifetime extension,* instead, is mainly enabled by DTs acting on the MAINT process (notably AR/VR, HVI and IR). These technologies enhance decision-making and augment physical and technical capabilities of the workforce servicing assets, thus increasing their repairability and lifetime duration. Therefore, a call emerges for investigating the potential of DTs to trigger *closing the loop*, *lifetime extension* and *intensified asset usage*, i.e. drivers that go beyond sustainability gains purely achieved through efficiency and optimization, towards a fully circular approach.

6. Conclusions

DTs for manufacturing and supply chains have been among the most popular topics in information and OM research since more than a decade. However, their implications for environmental sustainability and circularity have been addressed only recently. This study provides four main conceptual contributions to knowledge accumulation in this domain, by addressing *how DTs acting on OM processes contribute to foster environmental sustainability and circularity.*

First, this study adopts a systemic and comprehensive approach in interpreting the literature about the role of DTs for sustainability, by explicitly analysing their interplay with OM processes and the environmental drivers activated as a means to improve environmental sustainability and circularity. To the best of our knowledge, this is the first study to date to adopt this theoretical approach, illustrated by the initial and final research frameworks of Figures 1 and 8.

Second, the findings shed light on the "*how*" - i.e. the mechanisms through which DTs acting on OM processes lead to environmental sustainability and circularity, thus unveiling antecedent-process-outcome patterns (Schilling and Seuring, 2024). Such type of knowledge is needed to achieve a thorough understanding of the role of DTs for sustainability and inspire managerial practice. This study suggests that *the environmental benefits of DTs are contingent on the OM process to which they are applied and the mechanisms, i.e. the environmental drivers, triggered*. The specific findings, including the maturity of investigation of each DTs, their interrelations with other DTs and OM processes, as well as areas for future research have been discussed in Section 5 and summarized in Table 7.

Third, this study points out that DTs, with limited exceptions, lead to environmental benefits through increased efficiency of operations, triggering the *resource efficiency* driver as a consequence of the productivity and cost reduction effects of DTs' adoption. *Dematerialization* and, to a lesser extent, reduced usage of *hazardous, toxic or critical materials* are frequently activated drivers, too. Other environmental drivers have been rather under-investigated, disclosing the need for research to move forward, thoroughly addressing how DTs can lead to achieving the promise of truly circular supply chains, in particular through *intensified asset usage*, *lifetime extension*, and *closing the loop*.

Fourth, from a methodological point of view, this paper carries out a structured content analysis, using a statistical methodology to analyse *contingency relationships*. Thus, it contributes to the diffusion of such a methodology in OM research, as posited by recent studies (de Lima *et al.*, 2022; Schilling and Seuring, 2024).

The fine-grained yet systemic analysis of the relationships among the three constructs (DTs, OM processes and environmental drivers) for sustainability and circular outcomes also entails managerial implications. In particular, it calls for practitioners to consider the environmental implications when making managerial decisions about DTs implementation and OM processes redesign. Companies most often implement DTs to achieve operational or cost advantages: environmental implications come as an afterthought, and managers are confronted with how to best deploy DTs to achieve also environmental benefits (Das *et al.*, 2024). The relationships illustrated in Figure 8 and the impact mechanisms illustrated in Table 6 can serve as guidelines to identify how to best employ an already-selected DT for environmental benefits. Conversely, the findings support decision-making by managers willing to define investments in DT adoption in the light of their environmental potential. In particular, they can draw indications on where (which OM processes and impact domains) to apply DTs to trigger which environmental driver(s), and thus sustainability or circularity improvements. To ensure the effective adoption of DTs in industries, transformative industrial policy from the government is essential (Javaid *et al.*, 2022). For instance, the Italian government "Transition 5.0" plan offers tax credits and grants to encourage companies to implement DTs that lead reduction of energy consumption (MIMIT, Italian Ministry for Entreprises and Made in Italy, 2025). More generally, public bodies play a critical role in facilitating the adoption of DTs and CE practices by improving infrastructure, reducing taxes on technology investments, and providing subsidies or funding support. Therefore, our findings offer valuable insights for policymakers to better understand dynamics triggering environmental value generation and to design future strategies and incentives effectively.

As any research, this study has acknowledged limitations, too. Despite adopting a rigorous approach in the selection and analysis of the literature, relevant studies in the area may have been overlooked. Moreover, the content analysis has inherent limitations, particularly the risk of subjectivity. In particular, this study primarily focuses on academic literature, considering limited real-world case studies from industry. Hence, future research could aim to empirically validate the proposed mechanisms in the conceptual framework by performing qualitative interviews and industry-based case studies. As well, the research directions suggested may not be comprehensive of all areas and gaps. Therefore, further research investigating especially the DTs and the OM processes that received less attention would be helpful to deepen or disconfirm the findings summarized in Table 7. Finally, we indicated that DTs through environmental drivers lead to sustainability and circularity outcomes; however, fundamental questions about how these outcomes are measured and whether DTs adoption may lead to different magnitudes of environmental benefits have not been in the scope of this study. In addition, this study overlooks the potentially negative impact of DTs on sustainability and circularity, highlighting the need for a more critical perspective (Denu *et al.*, 2023). Investigating such aspects would constitute an extension to this research with relevant conceptual and practical implications.

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Supplementary material
The supplementary material for this article can be found online.

References

Akoglu, H. (2018), "User's guide to correlation coefficients", *Turkish Journal of Emergency Medicine*, Vol. 18 No. 3, pp. 91-93, doi: 10.1016/j.tjem.2018.08.001.

Alcayaga, A., Wiener, M. and Hansen, E.G. (2019), "Towards a framework of smart-circular systems: an integrative literature review", *Journal of Cleaner Production*, Vol. 221, pp. 622-634, doi: 10.1016/j.jclepro.2019.02.085.

Aldrighetti, R., Battini, D., Das, A. and Simonetto, M. (2023), "The performance impact of industry 4.0 technologies on closed-loop supply chains: insights from an Italy based survey", *International Journal of Production Research*, Vol. 61 No. 9, pp. 3003-3028, doi: 10.1080/00207543.2022.2075291.

Ali, H., Zhang, J. and Shoaib, M. (2023), "A hybrid approach for sustainable-circular supplier selection based on industry 4.0 framework to make the supply chain smart and eco-friendly", in *Environment, Development and Sustainability (Issue 0123456789)*, Springer, Netherlands, doi: 10.1007/s10668-023-03567-5.

Aquino, S., Rapaccini, M., Adrodegari, F. and Pezzotta, G. (2023), "Augmented reality for industrial services provision: the factors influencing a successful adoption in manufacturing companies", *Journal of Manufacturing Technology Management*, Vol. 34 No. 4, pp. 601-620, doi: 10.1108/JMTM-02-2022-0077.

Bag, S. and Pretorius, J.H.C. (2022), "Relationships between Industry 4.0, sustainable manufacturing and circular economy: proposal of a research framework", *International Journal of Organizational Analysis*, Vol. 30 No. 4, pp. 864-898, doi: 10.1108/IJOA-04-2020-2120.

Bag, S., Yadav, G., Wood, L.C., Dhamija, P. and Joshi, S. (2020), "Industry 4.0 and the circular economy: resource melioration in logistics", *Resources Policy*, Vol. 68, 101776, doi: 10.1016/j.resourpol.2020.101776.

Barteková, E. and Börkey, P. (2022), "Digitalisation for the transition to a resource efficient and circular economy", *OECD Environment Working Papers*, Vol. 192, doi: 10.1787/6f6d18e7-en.

Birkel, H. and Müller, J.M. (2021), "Potentials of Industry 4.0 for supply chain management within the triple bottom line of sustainability – a systematic literature review", *Journal of Cleaner Production*, Vol. 289, 125612, doi: 10.1016/j.jclepro.2020.125612.

Bressanelli, G., Adrodegari, F., Pigosso, D.C.A. and Parida, V. (2022), "Towards the smart circular economy paradigm: a definition, conceptualization, and research agenda", *Sustainability*, Vol. 14 No. 9, p. 4960, doi: 10.3390/su14094960.

Bressanelli, G., Saccani, N. and Perona, M. (2024), "Are digital servitization-based circular economy business models sustainable? A systemic what-if simulation model", *Journal of Cleaner Production*, Vol. 458, 142512, doi: 10.1016/j.jclepro.2024.142512.

Cannas, V.G., Ciano, M.P., Saltalamacchia, M. and Secchi, R. (2024), "Artificial intelligence in supply chain and operations management: a multiple case study research", *International Journal of Production Research*, Vol. 62 No. 9, pp. 3333-3360, doi: 10.1080/00207543.2023.2232050.

Chaouni Benabdellah, A., Zekhnini, K., Cherrafi, A., Garza-Reyes, J.A., Kumar, A. and El Baz, J. (2023), "Blockchain technology for viable circular digital supplychains: an integrated approach for evaluating the implementation barriers", *Benchmarking: An International JournalBenchmarking*, Vol. 30 No. 10, pp. 4397-4424, doi: 10.1108/BIJ-04-2022-0240.

Chauhan, C., Parida, V. and Dhir, A. (2022), "Linking circular economy and digitalisation technologies: a systematic literature review of past achievements and future promises", *Technological Forecasting and Social Change*, Vol. 177, 121508, doi: 10.1016/j.techfore.2022.121508.

Chiarini, A., Belvedere, V. and Grando, A. (2020), "Industry 4.0 strategies and technological developments. An exploratory research from Italian manufacturing companies", *Production Planning and Control*, Vol. 31 No. 16, pp. 1385-1398, doi: 10.1080/09537287.2019.1710304.

Dantas, T.E.T., De-Souza, E.D., Destro, I.R., Hammes, G., Rodriguez, C.M.T. and Soares, S.R. (2021), "How the combination of circular economy and Industry 4.0 can contribute towards achieving the sustainable development goals", *Sustainable Production and Consumption*, Vol. 26, pp. 213-227, doi: 10.1016/j.spc.2020.10.005.

Das, S.K., Bressanelli, G. and Saccani, N. (2024), "Clustering the research at the intersection of Industry 4.0 technologies, environmental sustainability and circular economy: evidence from literature and future research directions", *Circular Economy and Sustainability*, Vol. 4 No. 4, pp. 2473-2504, doi: 10.1007/s43615-024-00393-3.

De Lima, F.A., Seuring, S. and Sauer, P.C. (2022), "A systematic literature review exploring uncertainty management and sustainability outcomes in circular supply chains", *International Journal of Production Research*, Vol. 60 No. 19, pp. 6013-6046, doi: 10.1080/00207543.2021.1976859.

Del Giudice, M., Chierici, R., Mazzucchelli, A. and Fiano, F. (2021), "Supply chain management in the era of circular economy: the moderating effect of big data", *International Journal of Logistics Management*, Vol. 32 No. 2, pp. 337-356, doi: 10.1108/IJLM-03-2020-0119.

Delpla, V., Kenné, J.-P. and Hof, L.A. (2022), "Circular manufacturing 4.0: towards internet of things embedded closed-loop supply chains", *The International Journal of Advanced Manufacturing Technology*, Vol. 118 Nos 9-10, pp. 3241-3264, doi: 10.1007/s00170-021-08058-3.

Denu, M., David, P., Landry, A. and Mangione, F. (2023), "Exploring opportunities and barriers of digital technologies in circular manufacturing systems: an overview and a research roadmap", *Sustainable Production and Consumption*, Vol. 43, pp. 400-421, doi: 10.1016/j.spc.2023.11.015.

Dev, N.K., Shankar, R. and Qaiser, F.H. (2020), "Industry 4.0 and circular economy: operational excellence for sustainable reverse supply chain performance", *Resources, Conservation and Recycling*, Vol. 153, 104583, doi: 10.1016/j.resconrec.2019.104583.

Di Maria, E., De Marchi, V. and Galeazzo, A. (2022), "Industry 4.0 technologies and circular economy: the mediating role of supply chain integration", *Business Strategy and the Environment*, Vol. 31 No. 2, pp. 619-632, doi: 10.1002/bse.2940.

Du, Y., Xu, J. and Yuan, X. (2024), "The development relationship between circular economy and advanced digital technology: based on an innovative literature review method", *Environmental Technology Reviews*, Vol. 13 No. 1, pp. 614-638, doi: 10.1080/21622515.2024.2406988.

Durach, C.F. and Wieland, A. (2017), "A new paradigm for systematic literature reviews in supply chain management at Berlin", *Journal of Supply Chain Management*, Vol. 53, pp. 67-85, doi: 10.1111/jscm.12145.

Edwin Cheng, T.C., Kamble, S.S., Belhadi, A., Ndubisi, N.O., Lai, K. and Kharat, M.G. (2022), "Linkages between big data analytics, circular economy, sustainable supply chain flexibility, and sustainable performance in manufacturing firms", *International Journal of Production Research*, Vol. 60 No. 22, pp. 6908-6922, doi: 10.1080/00207543.2021.1906971.

Esmaeilian, B., Sarkis, J., Lewis, K. and Behdad, S. (2020), "Blockchain for the future of sustainable supply chain management in industry 4.0", *Resources, Conservation and Recycling*, Vol. 163, 105064, doi: 10.1016/j.resconrec.2020.105064.

Etc, C.E. (2025), Textiles and the environment – the role of digital technologies in Europe's circular economy (main authors: manshoven, saskia smeets, anse christis, maarten vito, duhoux norion, dina lingås cscp, Francesca grossi Fogh, Lars Clarke, James).

European Policy Centre (2020), "The circular economy: going digital", *Main Authors: Hedberg A, Šipka S.*

Ferreira, I.A., Godina, R., Pinto, A., Pinto, P. and Carvalho, H. (2023a), "Boosting additive circular economy ecosystems using blockchain: an exploratory case study", *Computers and Industrial Engineering*, Vol. 175, 108916, doi: 10.1016/j.cie.2022.108916.

Ferreira, J.J., Lopes, J.M., Gomes, S. and Rammal, H.G. (2023b), "Industry 4.0 implementation: environmental and social sustainability in manufacturing multinational enterprises", *Journal of Cleaner Production*, Vol. 404, 136841, doi: 10.1016/j.jclepro.2023.136841.

Fleiss, J.L., Levin, B. and Paik, M.C. (2003), *Statistical Methods for Rates and Proportions*, 3rd ed., Wiley, Hoboken, NJ. doi: 10.1002/0471445428.

Frank, A.G., Dalenogare, L.S. and Ayala, N.F. (2019), "Industry 4.0 technologies: implementation patterns in manufacturing companies", *International Journal of Production Economics*, Vol. 210, pp. 15-26, doi: 10.1016/j.ijpe.2019.01.004.

Garrido-Hidalgo, C., Ramirez, F.J., Olivares, T. and Roda-Sanchez, L. (2020), "The adoption of internet of things in a circular supply chain framework for the recovery of WEEE: the case of lithium-ion electric vehicle battery packs", *Waste Management*, Vol. 103, pp. 32-44, doi: 10.1016/j.wasman.2019.09.045.

Gebhardt, M., Kopyto, M., Birkel, H. and Hartmann, E. (2022), "Industry 4.0 technologies as enablers of collaboration in circular supply chains: a systematic literature review", *International Journal of Production Research*, Vol. 60 No. 23, pp. 6967-6995, doi: 10.1080/00207543.2021.1999521.

Ghobakhloo, M., Iranmanesh, M., Mubarak, M.F., Mubarik, M., Rejeb, A. and Nilashi, M. (2022), "Identifying industry 5.0 contributions to sustainable development: a strategy roadmap for delivering sustainability values", *Sustainable Production and Consumption*, Vol. 33, pp. 716-737, doi: 10.1016/j.spc.2022.08.003.

Gholami, H., Hashemi, A., Lee, J.K.Y., Abdul-Nour, G. and Salameh, A.A. (2022), "Scrutinizing state-of-the-art I4.0 technologies toward sustainable products development under fuzzy environment", *Journal of Cleaner Production*, Vol. 377, 134327, doi: 10.1016/j.jclepro.2022.134327.

Gleiser, I. (2023), "How to make digital technologies for the circular economy work for your business", available at: https://aws.amazon.com/it/blogs/hpc/how-to-make-digital-technologies-for-the-circular-economy-work-for-your-business/ (accessed 19 June 2025)

Govindan, K. (2022), "Tunneling the barriers of blockchain technology in remanufacturing for achieving sustainable development goals: a circular manufacturing perspective", *Business Strategy and the Environment*, Vol. 31 No. 8, pp. 3769-3785, doi: 10.1002/bse.3031.

Guo, R. and Zhong, Z. (2023), "A customer-centric IoT-based novel closed-loop supply chain model for WEEE management", *Advanced Engineering Informatics*, Vol. 55, 101899, doi: 10.1016/j.aei.2023.101899.

Gupta, H., Kumar, A. and Wasan, P. (2021), "Industry 4.0, cleaner production and circular economy: an integrative framework for evaluating ethical and sustainable business performance of manufacturing organizations", *Journal of Cleaner Production*, Vol. 295, 126253, doi: 10.1016/j.jclepro.2021.126253.

Hettiarachchi, B.D., Brandenburg, M. and Seuring, S. (2022), "Connecting additive manufacturing to circular economy implementation strategies: links, contingencies and causal loops", *International Journal of Production Economics*, Vol. 246, 108414, doi: 10.1016/j.ijpe.2022.108414.

Hmamed, H., Cherrafi, A., Benghabrit, A., Tiwari, S. and Sharma, P. (2024), "The adoption of I4.0 technologies for a sustainable and circular supply chain: an industry-based SEM analysis from the textile sector", *Business Strategy and the Environment*, Vol. 33 No. 4, pp. 2949-2968, doi: 10.1002/bse.3645.

International Energy Agency (IEA) (2025), "Energy and AI. World energy outlook special report", (main authors: D'Ambrosio, D., Hopewell, H., Jacamon, V., Martinos, A., Salmon N. & Wanner B.).

Javaid, M., Haleem, A., Singh, R.P., Suman, R. and Gonzalez, E.S. (2022), "Understanding the adoption of Industry 4.0 technologies in improving environmental sustainability", *Sustainable Operations and Computers*, Vol. 3, pp. 203-217, doi: 10.1016/j.susoc.2022.01.008.

Kahhal, P., Jo, Y.K. and Park, S.H. (2023), “Recent progress in remanufacturing technologies using metal additive manufacturing processes and surface treatment”, in *International Journal of Precision Engineering and Manufacturing - Green Technology*, Korean Society for Precision Engineeing. doi: 10.1007/s40684-023-00551-2.

Khan, I.S., Ahmad, M.O. and Majava, J. (2021), “Industry 4.0 and sustainable development: a systematic mapping of triple bottom line, circular economy and sustainable business models perspectives”, *Journal of Cleaner Production*, Vol. 297, 126655, doi: 10.1016/j.jclepro.2021.126655.

Kleindorfer, P.R., Singhal, K. and Van Wassenhove, L.N. (2005), “Sustainable operations management”, *Production and Operations Management*, Vol. 14 No. 4, pp. 482-492, doi: 10.1111/j.1937-5956.2005.tb00235.x.

Kristoffersen, E., Blomsma, F., Mikalef, P. and Li, J. (2020), “The smart circular economy: a digital-enabled circular strategies framework for manufacturing companies”, *Journal of Business Research*, Vol. 120, pp. 241-261, doi: 10.1016/j.jbusres.2020.07.044.

Kumar, D., Agrawal, S., Singh, R.K. and Singh, R.K. (2023), “Coordination of circular supply chain for online recommerce platform in Industry 4.0 environment: a game-theoretic approach”, *Operations Management Research*, Vol. 16 No. 4, pp. 2081-2103, doi: 10.1007/s12063-023-00384-x.

Kusi-Sarpong, S., Gupta, H., Khan, S.A., Chiappetta Jabbour, C.J., Rehman, S.T. and Kusi-Sarpong, H. (2023), “Sustainable supplier selection based on Industry 4.0 initiatives within the context of circular economy implementation in supply chain operations”, *Production Planning and Control*, Vol. 34 No. 10, pp. 999-1019, doi: 10.1080/09537287.2021.1980906.

Liu, Q., Trevisan, A.H., Yang, M. and Mascarenhas, J. (2022), “A framework of digital technologies for the circular economy: digital functions and mechanisms”, *Business Strategy and the Environment*, Vol. 31 No. 5, pp. 2171-2192, doi: 10.1002/bse.3015.

Lopes de Sousa Jabbour, A.B., Latan, H., Chiappetta Jabbour, C.J. and Seles, B.M.R.P. (2023), “Does applying a circular business model lead to organizational resilience? Mediating effects of Industry 4.0 and customers integration”, *Technological Forecasting and Social Change*, Vol. 194, 122672, doi: 10.1016/j.techfore.2023.122672.

Lu, Y. (2017), “Industry 4.0: a survey on technologies, applications and open research issues”, *Journal of Industrial Information Integration*, Vol. 6, pp. 1-10, doi: 10.1016/j.jii.2017.04.005.

Luthra, S., Kumar, A., Zavadskas, E.K., Mangla, S.K. and Garza-Reyes, J.A. (2020), “Industry 4.0 as an enabler of sustainability diffusion in supply chain: an analysis of influential strength of drivers in an emerging economy”, *International Journal of Production Research*, Vol. 58 No. 5, pp. 1505-1521, doi: 10.1080/00207543.2019.1660828.

Luu, T.Van, Chromjaková, F. and Nguyen, H.Q. (2023), “A model of Industry 4.0 and a circular economy for green logistics and a sustainable supply chain”, *Business Strategy and Development*, Vol. 6 No. 4, pp. 897-920, doi: 10.1002/bsd2.286.

Machado, C.G., Winroth, M.P. and Ribeiro da Silva, E.H.D. (2020), “Sustainable manufacturing in Industry 4.0: an emerging research agenda”, *International Journal of Production Research*, Vol. 58 No. 5, pp. 1462-1484, doi: 10.1080/00207543.2019.1652777.

Manavalan, E. and Jayakrishna, K. (2019), “A review of internet of Things (IoT) embedded sustainable supply chain for Industry 4.0 requirements”, *Computers and Industrial Engineering*, Vol. 127, pp. 925-953, doi: 10.1016/j.cie.2018.11.030.

Marković, I. and Jemović, M. (2024), “Artificial intelligence, big data and iot in circular economy: research trends and perspectives”, *Facta Universitatis – Series: Economics and Organization*, Vol. 21, p. 285, doi: 10.22190/FUEO241104019M.

MIMIT, Italian Ministry for Entreprises and Made in Italy (2025), “Transition 5.0 plan”, available at: https://www.mimit.gov.it/it/incentivi/piano-transizione-5-0 (accessed 15 June 2025)

Moher, D., Liberati, A., Tetzlaff, J. and Altman, D.G. (2009), “Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement”, *PLoS Medicine*, Vol. 6 No. 7, e1000097, doi: 10.1371/journal.pmed.1000097.

Moldan, B., Janoušková, S. and Hák, T. (2012), "How to understand and measure environmental sustainability: indicators and targets", *Ecological Indicators*, Vol. 17, pp. 4-13, doi: 10.1016/j.ecolind.2011.04.033.

Nascimento, D.L.M., Alencastro, V., Quelhas, O.L.G., Caiado, R.G.G., Garza-Reyes, J.A., Lona, L.R. and Tortorella, G. (2019), "Exploring Industry 4.0 technologies to enable circular economy practices in a manufacturing context: a business model proposal", *Journal of Manufacturing Technology Management*, Vol. 30 No. 3, pp. 607-627, doi: 10.1108/JMTM-03-2018-0071.

Neri, A., Negri, M., Cagno, E., Franzò, S., Kumar, V., Lampertico, T. and Bassani, C.A. (2023), "The role of digital technologies in supporting the implementation of circular economy practices by industrial small and medium enterprises", *Business Strategy and the Environment*, Vol. 32 No. 7, pp. 4693-4718, doi: 10.1002/bse.3388.

OECD (2022), "Digitalisation for the transition to a resource efficient and circular economy". doi: 10.1787/6f6d18e7-en

Paschou, T., Rapaccini, M., Adrodegari, F. and Saccani, N. (2020), "Digital servitization in manufacturing: a systematic literature review and research agenda", *Industrial Marketing Management*, Vol. 89, pp. 278-292, doi: 10.1016/j.indmarman.2020.02.012.

Patyal, V.S., Sarma, P.R.S., Modgil, S., Nag, T. and Dennehy, D. (2022), "Mapping the links between Industry 4.0, circular economy and sustainability: a systematic literature review", *Journal of Enterprise Information Management*, Vol. 35 No. 1, pp. 1-35, doi: 10.1108/JEIM-05-2021-0197.

Prakash, G. and Ambedkar, K. (2023), "Digitalization of manufacturing for implanting value, configuring circularity and achieving sustainability", *Journal of Advances in Management Research*, Vol. 20 No. 1, pp. 116-139, doi: 10.1108/JAMR-01-2022-0010.

Rajput, S. and Singh, S.P. (2021), "Industry 4.0 – challenges to implement circular economy", *Benchmarking: An International Journal*, Vol. 28 No. 5, pp. 1717-1739, doi: 10.1108/BIJ-12-2018-0430.

Rane, S.B., Potdar, P.R. and Aware, S. (2023), "Strategies for development of smart and green products using Blockchain-IoT integrated architecture", *Operations Management Research*, Vol. 16 No. 4, pp. 1830-1857, doi: 10.1007/s12063-023-00398-5.

Rejeb, A., Suhaiza, Z., Rejeb, K., Seuring, S. and Treiblmaier, H. (2022), "The internet of things and the circular economy: a systematic literature review and research agenda", *Journal of Cleaner Production*, Vol. 350, 131439, doi: 10.1016/j.jclepro.2022.131439.

Rizvi, S.W.H., Agrawal, S. and Murtaza, Q. (2021), "Circular economy under the impact of IT tools: a content-based review", *International Journal of Sustainable Engineering*, Vol. 14 No. 2, pp. 87-97, doi: 10.1080/19397038.2020.1773567.

Rizvi, S.W.H., Agrawal, S. and Murtaza, Q. (2023), "Automotive industry and Industry 4.0-circular economy nexus through the consumers' and manufacturers' perspectives: a case study", *Renewable and Sustainable Energy Reviews*, Vol. 183, 113517, doi: 10.1016/j.rser.2023.113517.

Romero, C.A.T., Castro, D.F., Ortiz, J.H., Khalaf, O.I. and Vargas, M.A. (2021), "Synergy between circular economy and Industry 4.0: a literature review", *Sustainability*, Vol. 13 No. 8, pp. 1-18, doi: 10.3390/su13084331.

Russmann, M., Lorenz, M. and Gerbert, P. (2015), "Industry 4.0: the future of productivity and growth in manufacturing industries", available at: https://www.bcg.com/publications/2015/engineered_products_project_business_industry_4_future_productivity_growth_manufacturing_industries

Saccani, N., Adrodegari, F. and Scalvini, L. (2024), "Aligning product-service systems with environmental sustainability: investigating the key role of revenue and pricing mechanisms", *Resources, Conservation and Recycling*, Vol. 209, 107792, doi: 10.1016/j.resconrec.2024.107792.

Santos, A.d.M. and Sant'Anna, Â.M.O. (2024), "Industry 4.0 technologies for sustainability within small and medium enterprises: a systematic literature review and future directions", *Journal of Cleaner Production*, Vol. 467, 143023, doi: 10.1016/j.jclepro.2024.143023.

Schilling, L. and Seuring, S. (2024), "Linking the digital and sustainable transformation with supply chain practices", *International Journal of Production Research*, Vol. 62 No. 3, pp. 949-973, doi: 10.1080/00207543.2023.2173502.

Schlesinger, L., Koller, J., Pagels, M. and Döpper, F. (2023), "Alignment of design rules for additive manufacturing and remanufacturing", *Journal of Remanufacturing*, Vol. 13 No. 2, pp. 99-119, doi: 10.1007/s13243-022-00122-9.

Schöggl, J.P., Stumpf, L. and Baumgartner, R.J. (2024), "The role of interorganizational collaboration and digital technologies in the implementation of circular economy practices—empirical evidence from manufacturing firms", *Business Strategy and the Environment*, Vol. 33 No. 3, pp. 2225-2249, doi: 10.1002/bse.3593.

Sharma, M.K. (2023), "Prioritization of overall sustainability factors of cloud manufacturing through ahp and fuzzy ahp approach", *Scientific Journal of Silesian University of Technology. Series Transport*, Vol. 119, pp. 37-61, doi: 10.20858/sjsutst.2023.119.3.

Sorrell, S. and Dimitropoulos, J. (2008), "The rebound effect: microeconomic definitions, limitations and extensions", *Ecological Economics*, Vol. 65 No. 3, pp. 636-649, doi: 10.1016/j.ecolecon.2007.08.013.

Taddei, E., Sassanelli, C., Rosa, P. and Terzi, S. (2022), "Circular supply chains in the era of Industry 4.0: a systematic literature review", *Computers and Industrial Engineering*, Vol. 170, 108268, doi: 10.1016/j.cie.2022.108268.

Tavana, M., Sorooshian, S. and Mina, H. (2023), "An integrated group fuzzy inference and best–worst method for supplier selection in intelligent circular supply chains", *Annals of Operations Research*, Vol. 342 No. 1, pp. 803-844, doi: 10.1007/s10479-023-05680-0.

Thao, L.Q. (2023), "An automated waste management system using artificial intelligence and robotics", *Journal of Material Cycles and Waste Management*, Vol. 25 No. 6, pp. 3791-3800, doi: 10.1007/s10163-023-01796-4.

Tranfield, D., Denyer, D. and Smart, P. (2003), "Towards a methodology for developing evidence-informed management knowledge by means of systematic review", *British Journal of Management*, Vol. 14 No. 3, pp. 207-222, doi: 10.1111/1467-8551.00375.

Walachowicz, F., Bernsdorf, I., Papenfuss, U., Zeller, C., Graichen, A., Navrotsky, V., Rajvanshi, N. and Kiener, C. (2017), "Comparative energy, resource and recycling lifecycle analysis of the industrial repair process of gas turbine burners using conventional machining and additive manufacturing", *Journal of Industrial Ecology*, Vol. 21, pp. 203-215, doi: 10.1111/jiec.12637.

World Economic Forum (2022), *The Global Lighthouse Network Playbook for Responsible Industry Transformation*, March.

Wu, H., Mehrabi, H., Naveed, N. and Karagiannidis, P. (2022), "A business model for additive manufacturing of recycled plastics towards sustainability", *The International Journal of Advanced Manufacturing Technology*, Vol. 120 Nos 11-12, pp. 7997-8011, doi: 10.1007/s00170-022-09269-y.

Yadav, G., Luthra, S., Jakhar, S.K., Mangla, S.K. and Rai, D.P. (2020), "A framework to overcome sustainable supply chain challenges through solution measures of Industry 4.0 and circular economy: an automotive case", *Journal of Cleaner Production*, Vol. 254, 120112, doi: 10.1016/j.jclepro.2020.120112.

Younis, H., Bwaliez, O.M., Al-Okaily, M. and Tanveer, M.I. (2024), "Revolutionizing supply chain management: a critical meta-analysis of empowerment and constraint factors in blockchain technology adoption", *Business Process Management Journal*, Vol. 30 No. 5, pp. 1472-1500, doi: 10.1108/BPMJ-10-2023-0805.

Yu, Z., Khan, S.A.R. and Umar, M. (2022), "Circular economy practices and industry 4.0 technologies: a strategic move of automobile industry", *Business Strategy and the Environment*, Vol. 31 No. 3, pp. 796-809, doi: 10.1002/bse.2918.

Further reading

D'Ambrosio, D., Hugh, H., Vincent, J. and Martinos, A. (2020), "Energy and AI energy and AI", *World Energy Outlook Special Report*, Vol. 1, pp. 1-12.

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