Digital technologies for the sustainability of circular manufacturing processes: a review

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Abstract: Digital technologies have been recognized as a potential enabling factor for the implementation of circular economy in companies and organizations. They can support manufacturing companies in the redesign of products, processes, business models and supply chains according to the circular economy paradigm. For instance, the Internet of Things can be employed to monitor production data in a way to reduce materials scraps and increase the energy efficiency of production equipment. Big Data analytics can be used to transform product-in-use data into valuable knowledge to inform decision making, e.g. during the design phase of products to increase their modularity and ease disassembly. 3D printing may be adopted for enabling local and on-demand spare parts production for repair purposes. In general, these technologies can enable circularity and help in achieving sustainability benefits in different manufacturing and supply chain processes, ranging from product design to raw material acquisition, production, distribution, maintenance, reverse logistics and end-of-life. Despite an increasing interest on the application of digital technologies for the circular economy, the link between digital technologies, their implementation into different manufacturing and supply chain processes and the generation of sustainability benefits is still at a nascent stage of investigation. Therefore, the aim of this paper is to shed light on how digital technologies can bring sustainability benefits through the application of different R-strategies at different manufacturing and supply chain processes. A systematic literature review is carried out for that purpose, and a final sample of 24 scientific articles has been analyzed. Selected papers have been classified according to (i.) digital technologies investigated; (ii.) circular economy strategies; and (iii.) manufacturing processes. Results have been used to structure a preliminary framework which highlights potential circular economy adoption paths to generate sustainability benefits at different manufacturing processes.

Keywords: Manufacturing processes, Circular Economy, Sustainability, Literature Review.

I. INTRODUCTION

The linear economy model results in negative externalities, including resource depletion and environmental pollution (Suchek et al., 2021). Therefore, it is crucial for the manufacturing industry and supply chains to transition towards a circular economy (CE) where products are designed, produced, and consumed in a sustainable and resource-efficient manner.(Bressanelli et al., 2021) The concept of CE has gained momentum among scholars and practitioners due to its potential for sustainable manufacturing and resource reutilization. Industry 4.0 (I4.0) technologies can serve as enablers for CE, thereby facilitating the digital transformation required for organisations to achieve sustainable development objectives. Hence, it is worth investigating how the adoption of I4.0 technologies can support manufacturers in transitioning to the CE.

Given that research on the potential of I4.0 technologies for CE is still in its early stages, there is a need to explore their application for achieving sustainability and CE goals during the manufacturing stage. Limited research exists in this area, necessitating an investigation into how these technologies integrate CE practices, impact different manufacturing stages, contribute to sustainability throughout the lifecycle, and provide economic, environmental, and social benefits. To address this, a systematic literature review is adopted as the research methodology to comprehensively analyse existing knowledge and insights in this field.

The remaining sections of the paper are organised as follows: Section 2 provides an overview of the research design and methodology. Section 3 presents the descriptive analysis, and in Section 4, the content-based analysis of the literature is discussed, highlighting key digital technologies, circular economy practices, and manufacturing processes. Finally, Section 5 offers a discussion and concluding remarks.

II. MATERIALS AND METHODS

This study undertakes a systematic literature review in a methodical manner to effectively address the research objective. A systematic literature review is instrumental in providing crucial insights for investigating research in an emerging field. The review process adhered to a structured approach, summarizing the current academic research on various manufacturing processes, I4.0 technologies, and CE. The Preferred Reporting Items (see Fig 1). for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were followed to retrieve, select, and report the items for the systematic review (Moher et al., 2009).

The search process started with the selection of two sets of keywords: (1) 'Circular economy' and 'Sustainability,' and (2) 'Digital technologies' that included 'Internet of things', 'Cyber physical system', 'Cloud computing', 'Industrial robotics', 'Data analytics', 'big data', 'Additive manufacturing', '3d printing', and 'Industry 4.0' The keyword search was conducted on the Scopus database in March 2023, resulting in a sample of 6,751 articles. Screening was performed based on language, excluding articles written in languages other than English. The scientific rigor and quality of the research were ensured by including only articles published in peer-reviewed scientific journals. The search was further refined to focus on articles in the fields of engineering, business management, operations, services, and manufacturing, resulting in a total of 2,632 articles.

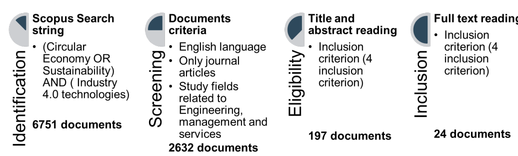

Figure 1. Literature Review methodology

In the eligibility phase, articles scrutinized based on four inclusion criteria assessing the titles, keywords, and abstracts to eliminate irrelevant studies. This rigorous process resulted in 197 articles suitable for further analysis. The inclusion criteria were as follows: (i) The article must focus on I4.0 technologies, Digital Technologies, Industry 4.0, or any technology similar to Digital Technology; (ii) The article must discuss Circular Strategies, Circularity, Circular Manufacturing, Circular Business Models, Smart Circular Economy, or Environmental Sustainability; (iii) The article must exclusively examine the technical aspects of the "butterfly diagram" (Ellen MacArthur Foundation)(Macarthur, 2013); (iv) The article must emphasize the manufacturing or production of physical products and discuss business processes, product development, the supply chain, and other production and manufacturing processes. In the final selection phase, the same inclusion criteria were applied during the full text reading phase, resulting in a final selection of 24 papers forming the basis of this research.

III. RESULTS

A. Descriptive analysis

Our study involved an analysis of 24 selected articles, with a particular emphasis on their publication year, originating journals, and key terminologies. Fig. 2 visually depicts the chronological distribution of these articles, all of which were published within the 2016 to 2022 period. A significant portion of the articles emerged after 2020, indicating a growing interest in the topic.

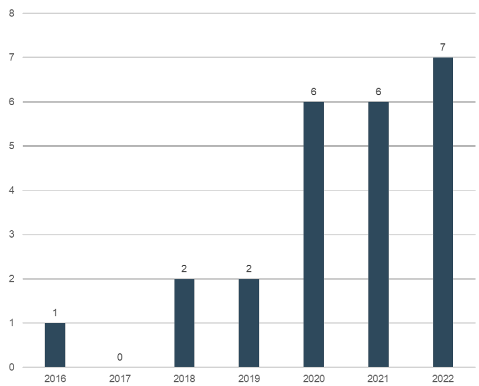

Figure 2. Distribution of publication per year

Fig. 3 presents the distribution of articles across various journals. The sample exhibited a fragmentation across different journals, with only three journals publishing two or more papers. Among the twenty-four papers, five appeared in the Journal of Cleaner Production.

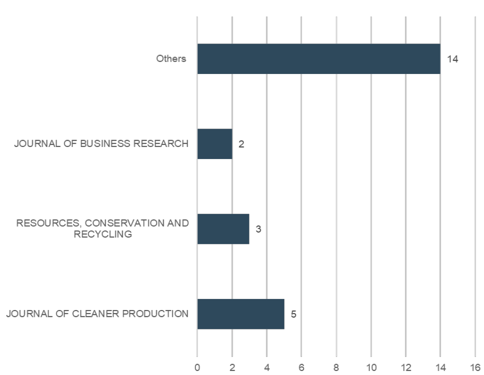

Figure 3. Distribution of publications per journal

To gain insights into the key themes, we analysed the author keywords. Table 1 presented the results of this analysis, highlighting the most frequently used keywords, namely 'Circular Economy' and 'Industry 4.0'. Among the technologies, the two most mentioned are Additive Manufacturing / 3D printing and Big Data Analytics.

TABLE 1. KEYWORD ANALYSIS

Keyword	No of Papers	% Papers
Circular Economy	16	66.7
Industry 4 0	12	50.0
Sustainability	7	29.2
Additive manufacturing	4	16.7
Big Data Analytics	3	12.5
Digitalization	3	12.5

B. Content based analysis.

Our content-based analysis, as shown in Table 2, encompasses three main dimensions: business management processes, investigated I4.0 technologies, and CE strategies. Within each dimension, we considered specific items of investigation. The dimension of business management processes identifies seven different processes, while the analysis of I4.0 technologies covers nine specific technologies. Lastly, the CE dimension focuses on the 4R strategies. By examining these dimensions, we can gain a comprehensive understanding of the subject matter. Table 2 also provides the classification of the set of 24 papers.

The distribution of articles analysed according to business management processes is depicted in Figure 4. Among the seven processes analysed, product development received the highest level of attention from researchers. Following product development, there have been frequent investigations into production processes, purchasing, and supply chain management. In contrast, reverse logistics, maintenance, and repair have garnered comparatively less attention in research studies.

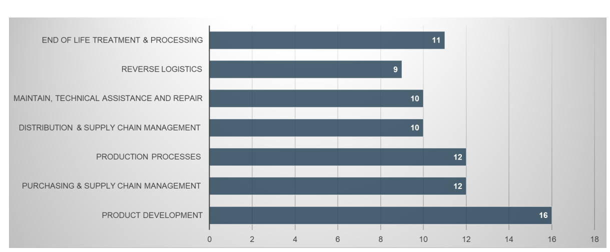

Figure 4. N. of Papers Exploring Business Management Processes

Product development is crucial for driving the circular economy as it enables the design of products that maintain their utility throughout their lifecycle. It emphasized principles such as product life extension and complete material recovery (Sauerwein et al., 2019). Designing products for disassembly, reassembly, and recycling simplifies end-of-life management (Bressanelli et al., 2021). Eisenreich et al.,(2022) investigated the relationship between innovation, technology, and product design to enhance the value chain. Additionally, Tao et al., (2018) explored the role of digital twins in conceptual and detailed product design, integrating data for design quality assessment and defect identification based on consumer behaviour and historical data. Additive manufacturing (AM) allows for complex geometries, improving customization and material consumption (Sauerwein et al., 2019). Big data technology enhanced design decision-making and addresses errors and failures in new product development (Bag, Yadav, et al., 2021).

Furthermore, this study focuses on the synergistic interplay between I4.0 and CE principles, uncovering their transformative impact on Purchasing & Supply Chain Management (Eisenreich et al., 2022). In this context, digital twins optimize resource allocation by delivering real-time information on capacity, quantity, and resource states (Tao et al., 2018). The sharing of supply and demand-related data through Internet of things (IoT) and cloud manufacturing empowers organizations to design customer-centric and sustainable services and products (Lopes de Sousa Jabbour et al., 2018), effectively responding to evolving market needs. Moreover, blockchain technology emerges as a powerful tool for promoting sustainable supply chain initiatives (Y. M. Tang et al., 2022).

Optimizing production processes can effectively reduce resource consumption in industries. The utilization of artificial intelligence (AI) can minimize energy usage in production processes by analysing consumption patterns (Umar & Ali, 2021). The role of IoT devices in enhancing production decisions and process flexibility are explored (Dev et al., 2020). Digital twins contribute to improved production planning, resource management, and process control(Tao et al., 2018). Meanwhile, distribution and supply chain management, particularly outbound logistics, are covered in 10 papers. Strandhagen et al.(2022) discussed real-time knowledge sharing, along with the use of blockchain and IoT, enhances product connectivity and addressed track-and-trace challenges. The implementation of circular principles leads to shorter supply chains, reduced transportation, localized repair and recycling, and on-demand supply (Cheng et al., 2022). Digital technologies support maintenance, technical assistance, and repair, such as predictive maintenance, consumer support agreements, and product repair. Digital twin technology enables virtual operation and maintenance of products (Tao et al., 2018). Combined with IoT and big data analytics (BDA), organizations can proactively monitor performance and maintenance requirements (Lopes de Sousa Jabbour et al., 2018). AM supports repair activities, enabling on-site component replacement (Sauerwein et al., 2019). Augmented Reality (AR) and Virtual Reality (VR) technologies are beneficial in defect detection and worker safety in high-risk environments like shipyards (Strandhagen et al., 2022). Reverse logistics plays a crucial role in resource recovery, product lifecycle extension, and establishing closed-loop supply chains. A cloud-based platform for end-to-end reverse logistics solutions optimizes procurement processes (Bergonzi & Vettori, 2021). Data acquisition capabilities facilitate integrating circular economy principles into reverse logistics (Khan et al., 2022). Sensors and RFID tags enhance tracking, tracing, and transparency (Dev et al., 2020). End-of-life management, which conserves resources, reduces waste, extends product lifespan, and minimizes environmental impact, is explored in 11 articles.

Fig. 5 depicted the focus of the analysed articles on the circular economy's four strategies. A majority of the articles, totalling 16, primarily concentrate on the "Recycle" strategy. Close behind is the "Reduce" strategy, with 13 articles and "Remanufacture" with 12. In contrast, the "Reuse" strategy received comparatively less attention, with 9 articles dedicated to exploring these aspects.

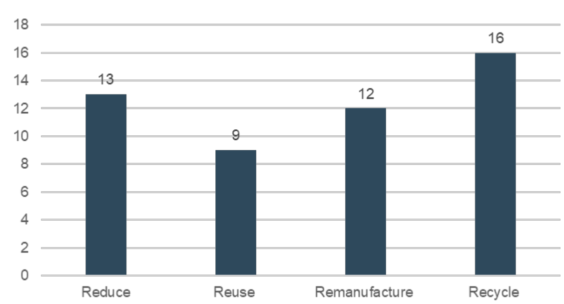

Figure 5. N. Of Papers exploring CE 'R' Strategies

Recycling plays a crucial role in material recovery from end-of-life products. Effective data and information sharing can enhance the utilization of reintroduced materials in the production cycle(Kintscher et al., 2020). It involves extracting valuable resources and materials from returned or discarded products, supported by smart bins that enable traceability of material location and quantity, facilitating appropriate end-of-life strategies (Kristoffersen et al., 2020). The articles extensively investigate practices that incentivize increased recycling and waste reduction (Kintscher et al., 2020). IoT and BDA with cyber-physical systems (CPS) can optimize energy management by analysing energy waste at the production level and selecting the most efficient machine configuration. Remanufacturing, utilizing I4.0 technologies like AM is recognized as an effective strategy for on-demand production of spare parts, reducing inventories, saving storage space, and improving repair accessibility (Bressanelli et al., 2021). The discussion allocates relatively less attention to the strategy of reuse. For instance, Cheng et al.(2022) explored the role of Cloud technology in facilitating the reuse of materials and components, ultimately leading to a reduction in the purchase of new materials .

Several I4.0 technologies can enhance manufacturing processes to implement CE practices in various ways. Fig 6 illustrated the distribution of focus in articles on nine digital technologies. Predominantly, 3D printing and AM, BDA, and IoT are discussed in several articles. In contrast, there are no articles covering horizontal and vertical integration.

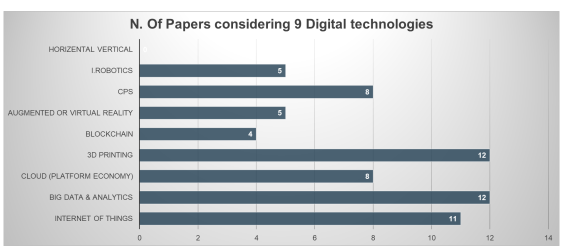

Figure 6. N. Of Papers considering each Digital technology

In this context, IoT plays a crucial role. Eisenreich et al., (2022) emphasized its application in tracking and tracing products throughout their life cycle to enhance reverse logistics. Moreover, BDA is utilized to analyze data and uncover valuable insights, aiding in improved planning and decision-making for businesses (Nascimento et al., 2019). Dev et al., (2020) explored how cloud computing facilitates consumer-supplier relationships, while Bag, Yadav, et al.(2021) delved into the relationship between IoT, cloud manufacturing, and inventory management across the supply chain. AM emerges as a frequently discussed topic. Priarone et al. (2021) explored the application of AM in remanufacturing operations, while Y. Tang et al., (2016) investigated design optimization to reduce the environmental impact of AM.

Blockchain technology, with its inherent data consistency and tamper-proof characteristics, finds relevance in data privacy and protection. Leng et al.(2020) examined blockchain-empowered sustainable manufacturing. Additionally, augmented virtual reality aids in maintenance strategies, virtual operations, and product maintenance. CPS and IoT enable work-in-process inventory identification and optimal order computation(Chaudhuri et al., 2022). Industrial Robotics (I Robotics) contribute to material sorting, recovery, recycling, and disassembly practices in manufacturing (Nascimento et al., 2019). The integration of IoT, BDA, AM, cloud, and blockchain technologies enhances business management processes (Kristoffersen et al., 2020). Finally, Bag, Gupta, et al., (2021) emphasized the utilization of RFID, IoT, and cloud technology for effective product tracking and tracing.

IV. Discussion and Conclusion

In a broad sense, the study sheds light on the role that I4.0 technologies may have in supporting the business management processes to enable CE benefits. This is achieved through a literature review of 24 selected articles. The study aims to explore the opportunities offered by individual and connected I4.0 technologies to foster the circular transition in the manufacturing industries.

By conducting our analysis, the study provides a systematic understanding of the technological aspects addressed in previous research within the context of business management processes. It also examines how CE has been connected to different manufacturing processes to achieve sustainability in the manufacturing scenario. Addressing these elements, we found that Internet of Things (IoT), Big Data Analytics (BDA), and additive manufacturing (AM) are the most discussed technologies. However, no paper discussed the horizontal and vertical integration. Regarding circular strategies, 'Recycle' and 'Reduce' were frequently mentioned strategies in the papers.

TABLE 2: EVALUATION OF 24 ARTICLES BASED ON I4.0 TECHNOLOGIES, BUSINESS OPERATION MANAGEMENT PROCESSES AND CE 'R' STRATEGY.

Sl No	Author	Product development	Purchasing & supply chain management	Production Processes	Distribution & supply chain management	Maintain, technical assistance and repair	Reverse Logistics	End of life treatment & processing	Internet of Things	Big Data & Analytics	Cloud (Platform Economy)	3D Printing	Blockchain	Augmented or Virtual Reality	Cyber Physical System	Industrial Robotics	Horizontal vertical Integration	Reduce	Reuse	Remanufacture	Recycle
1	(Eisenreich et al., 2022)	X	X	X	X	X	X	X	X		X	X			X			X	X	X	X
2	(Nascimento et al., 2019)			X			X	X			X	X			X	X					X
3	(Chaudhuri et al., 2022)	X		X			X	X				X	X								X
4	(Kintscher et al., 2020)							X	X	X						X					X
5	(Priarone et al., 2021)	X				X						X								X	
6	(Bag, Yadav, et al., 2021)	X			X					X								X			
7	(Dev et al., 2020)	X	X	X	X		X		X		X	X		X	X			X	X	X	
8	(Tao et al., 2018)	X	X	X	X	X			X	X				X	X			X			
9	(Lopes de Sousa Jabbour et al., 2018)	X	X	X	X	X	X		X	X	X	X			X			X	X	X	X
10	(Bag, Gupta, et al., 2021)		X	X			X			X						X			X	X	
11	(Leng et al., 2020)	X		X		X				X	X		X		X						
12	(Kristoffersen et al., 2020)					X		X	X	X								X	X		X
13	(Y. Tang et al., 2016)	X										X									
14	(Sauerwein et al., 2019)	X			X	X		X				X		X					X	X	X
15	(Bressanelli et al., 2021)	X	X		X	X	X		X	X	X										
16	(Cheng et al., 2022)		X		X					X								X			X
17	(Laskurain-iturbe et al., 2021)	X	X	X		X		X		X		X		X		X		X	X	X	X
18	(Umar & Ali, 2021)	X	X	X					X	X	X		X					X		X	X
19	(Y. M. Tang et al., 2022)	X	X	X	X			X	X				X					X		X	X
20	(Strandhagen et al., 2022)	X	X	X	X	X		X	X	X	X	X		X		X				X	X
21	(Rajput & Singh, 2022)						X		X	X					X			X	X	X	X
22	(Khan et al., 2022)						X		X		X				X			X	X	X	X
23	(Bergonzi & Vettori, 2021)	X						X				X									X
24	(Sun et al., 2020)		X					X				X						X			X

In the investigation of business management processes, product development emerges as the most discussed process in the study. It is regarded as a crucial enabler for the circular economy, as sustainability is integrated from the early stages of design. For instance, Dev et al.(2020) identified the role of IoT, 3D printing, and cloud platforms for product customization according to user needs. Tao et al.(2018) discussed how digital technology is interlinked with concept design and detailed design, with digital twin technology driving virtual verification that ultimately reduces material and energy consumption. Table 1 shows that, production processes are one of the areas that most studies have focused on, where different data technologies are used to optimize energy consumption and production decisions. Lopes de Sousa Jabbour et al., (2018) shaded light on how IoT can be used to help reduce resource consumption. (Leng et al.(2020) attempted to integrate blockchain and CPS to improve the quality of product management, while (Umar & Ali, 2021) explored the use of BDA for energy consumption. Moving to the supply chain, Bag, Yadav, et al.(2021) focused on material flow and resource optimization to minimize resource consumption, Cheng et al.(2022) discussed BDA collaboration among stakeholders in the supply chain, and Y. M. Tang et al., (2022) examined the role of blockchain in the transparency and traceability of materials and products.

Therefore, this study enhances understanding of how I4.0 technologies can contribute to achieving CE goals in the manufacturing industry.

However, further investigations are needed to address practical challenges in implementing CE strategies and develop overarching conceptual models. Detailed empirical research is necessary to explore the product management perspective across the entire life cycle. It should be noted that this study represents an ongoing content-based analysis, and the presented results are preliminary. Additional research by the authors of thus study is still underway to provide more comprehensive insights into the intersection of I4.0 and CE.

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