Mapping The Relationship Between Technologies and Circular Economy Strategies

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Abstract: With the continuous technological advancement and the more sustainability-oriented view of companies, there is a need to understand how technologies are being exploited and linked with circular economy strategies. Indeed, this study aims to point out the technologies used to implement the twin transition (green & digital transition) within the manufacturing sector. Through a literature review process, the authors have been able to map and list those technologies frequently mentioned within the articles. Key findings from the study emphasise the pivotal role of digital technologies such as IoT (Internet of Things), AI (Artificial Intelligence) and Blockchain towards the achievement of a more sustainable ecosystem. Digital technologies have emerged as indispensable tools for optimising energy consumption, refining production processes, and reducing waste generation. The integration of IoT devices and sensors facilitates real-time monitoring, enhancing resource efficiency and sustainability. The value of this work lies in its comprehensive examination of the technological tools promoting the twin transition within manufacturing. Through the synthesis of the information gathered, the study offers a holistic understanding of how technologies enable circular economy strategies, considering skills and competencies as facilitators. Ultimately, this research prepares stakeholders with the knowledge necessary to deal with the complexities of the evolving manufacturing landscape, driving progress towards a more resilient, resource-efficient and human-centric future, especially concerning the workers' skills.

Keywords: Circular Economy, Industry 4.0, Industry 5.0, Skills, Competencies

1. Introduction

The rapid pace of technological innovation is dramatically converting jobs and the nature of labour. This relentless improvement requires a reassessment of current competencies and a fast acquisition of new skills. As the world moves towards sustainability, circular economy policies are more and more important. These techniques intend to eliminate waste and develop new services and products to lessen negative effects on the planet. This paper explores the significance of updating expertise and innovative procedures to embed circular economy standards into employees' skills and competencies due to continuous technological advancement. Some studies highlight the urgency of improving workforce skills to keep pace with technological change (Schwab, 2017; Bughin et al., 2018). As automation and artificial intelligence become more frequently used across sectors, the demand for advanced technical skills, as well as adaptive and managerial skills, increases (Manyika et al., 2017). At the same moment, the circular economy paradigm emerges as a critical framework in response to environmental challenges and resource scarcity (Geissdoerfer *et al.*, 2017; Stahel, 2016). In the contemporary era, characterised by a rapid technological advancement, the importance of continuous skill development and competencies has never been more crucial. As industries transition towards more automated, digital processes, the traditional skills of the past decades are quickly becoming obsolete. This paper seeks to point out which are the most frequently used technologies and which kind of circular economy strategies are more frequently sought by companies, considering the evolving nature of job requirements and the consequent necessity for individuals to acquire new skills and competencies. With this work, the authors try to take stock of the types of technologies and circular economy strategies that are becoming critical for success and the strategies that companies should adopt to foster an environment of continuous learning and adaptability. In the following sections, a description of Industry 4.0, Circular Economy and competencies and skills needed nowadays will be presented.

1.1 Industry 4.0, Skills and Competencies

The concept of Industry 4.0 implies a tremendous shift in industrial production, characterised by the integration of digitization and an integration of emerging technologies. Several technologies have been pointed out as dominant in the transition to the fourth industrial revolution such as the Internet of Things (IoT), artificial intelligence (AI), robotics, and big data analytics, each playing a fundamental role in transforming the manufacturing production (Lasi *et al.*, 2014). The IoT technology enables connectivity across many manufacturing equipment such as wearables, allowing for real-time data exchange and automated decision-making processes with a positive effect on the optimization of the processes and a reduction of costs (Xu *et al.*, 2014). Artificial intelligence and machine learning technologies are revolutionizing production processes by leveraging predictive maintenance and solving complex manufacturing challenges, ameliorating efficiency and productivity (Rüßmann et al., 2015). Automation (e.g., robotics, etc.), now in its most developed form, is mixed with AI to perform tasks that require high precision and flexibility. For instance, the use of collaborative robots (cobots) that work alongside human workers demonstrates the synergistic potential of humans and machines coexisting in a shared workspace, which significantly impacts positively both safety and productivity (Gorecky *et al.*, 2014). Furthermore, BDA eases companies' efforts to manage the different kinds of data from connected devices to optimize operations, enhance product quality, and anticipate customer demands, to facilitate decision-making processes (Zhong *et al.*, 2017). Since these technologies are continuously evolving, creating the foundation of Industry 4.0 and the new so-called Industry 5.0 (Dautaj and Rossi, 2021), an understanding of what is the skills and competencies level of workers and employees in the manufacturing sector is of paramount importance. With this transformative era, there is a need to understand how digital tools can be leveraged to foster sustainable and efficient production systems. To thrive in this new landscape, professionals need to understand what technical skill sets their employees and workers should have in order to be aligned with the technologies and sustainable strategies used embedded within the manufacturing environment. The intersection of Industry 4.0 technologies with circular economic strategies targets highlights the need for a proper set of skills and competencies (Ritzén and Sandström, 2017). Within the set of skills, very crucial is the ability of critical thinking, useful for understanding and managing complex situations within the working environment. This competency is vital for professionals aiming to integrate circular economy principles with digital technologies, ensuring that sustainability is embedded in the design and optimization of processes (Bocken *et al.*, 2016). Moreover, proficiency in data analytics is becoming essential, because it enables workers to extract and interpret huge and different amounts of data generated by digital systems (Sousa-Zomer and Cauchick Miguel, 2018). Resilience and continuous learning are also crucial since required skills are continually being reshaped by new technologies. The dynamism of Industry 4.0 requires ongoing education and the willingness to continually update employees' and workers' skill sets, particularly in areas like AI, machine learning, and IoT applications (Schwab, 2017). Furthermore, soft skills in particular those related to collaboration as well as leadership in multidisciplinary teams are increasingly requested, as the challenges of implementing circular economy strategies often require efforts within a company. These competencies help professionals execute sustainable solutions seamlessly, thereby driving the implementation of new business models that are both technologically advanced and environmentally sound (Stahel, 2016).

1.2 Circular Economy

The circular economy (CE) is a new paradigm which aims to achieve sustainable growth by rethinking and redesigning the way we produce and consume goods and services. Predominant of this strategy is the principle of extending the lifecycle of resources, reducing waste, and recirculating resources with a closed-loop logic to create a regenerative system. A pivotal component of CE is embedded in the 10R framework, which categorizes strategies from "Refuse" and "Reduce" to "Recycle" and "Recover," guiding businesses and policymakers in implementing circular practices (Potting et al., 2017). As can be seen, the 10R framework has gained not only academic and industrial but also has received significant promotion from the Ellen MacArthur Foundation, a prominent non-profit organisation that helps businesses, universities and policymakers to integrate circular economy principles. The foundation underlines that the transition to circular economy practices is essential for the environment and the companies as sustainable businesses have both environmental and financial benefits (Ellen MacArthur Foundation, 2013). Incorporating these strategies includes re-evaluating conventional business models and manufacturing techniques to emphasize useful resource efficiency, waste reduction, and the revolutionary use of materials. Companies adopting the 10R standards frequently find that they could enhance their competitiveness by lowering prices and minimizing their environmental footprint, thereby aligning monetary incentives with ecological sustainability (Geissdoerfer *et al.*, 2017). This shift towards a circular economy requires a systemic change in how products are designed, resources are used, and end-of-life processes are managed, positioning the 10R framework as a comprehensive guide for organizations seeking to transition towards more sustainable practices. With the adoption of these principles, industries can improve their environmental footprint and establish a new standard for economic efficiency and responsibility.

The article is divided as follows: the first chapter is related to the introduction of the main topics of the study; the second chapter describes the methodology used; the third chapter sheds light on the list of technologies, circular economy strategies, skills and competencies found throughout the analysis; the fourth chapter discusses the results of the analysis clarifying how technologies enable circular economy strategies and what role skills and competencies have as facilitators; lastly, limitations and future research are pointed out.

2. Methodology

This work has been developed using a literature review approach (Snyder, 2019). The literature review is a method to review important literature in a specific field with a meticulous approach. The main steps of the review are going to be described. Firstly, the research question is the following: "What are the technologies and the circular economy strategies exploited by companies?" In order to answer this question, the authors gathered information related to the technologies and circular economy strategies within all the selected papers. Before this review, it has been conducted a preliminary study regarding the link between technologies and circular economy strategies, and it emerged that in several articles a particular focus on skills and competencies has been given, especially on the lack of proper workforce skills. Indeed, the originality of this work is based on the skimming criteria of the articles, and only those related to the skills and competencies of employees have been taken into consideration. This work is a taxonomy of all the technologies and circular economy described in the literature, particularly focusing on the link between the concepts of Industry 4.0 and Circular Economy. In order to obtain the articles and expand the literature, the research was conducted using Scopus as database. The query used is as follows: (TITLE-ABS-KEY (" industry 4.0 " OR " i4.0 " OR " 4th industrial revolution " OR " fourth industrial revolution ") AND TITLE-ABS-KEY ("circular*") AND TITLE-ABS-KEY (" skill* " OR " capabilit* " OR " expertise " OR " experience* " OR " abilit* " OR " competenc* ")).

The Literature review process is shown in Figure 1.

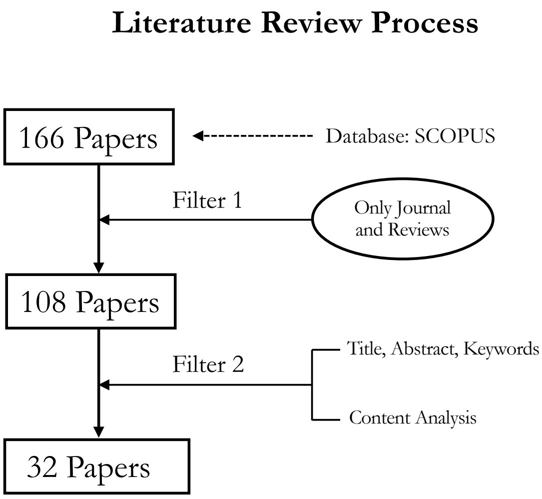

Figure 1. Literature Review Process

The total amount of articles found using these keywords was 166. The authors considered only journals and reviews since they have more scientific soundness. After considering only journals and reviews, the total number of articles was 108. After having this pool of 108 articles, a content analysis has been carried out. During the content analysis step, only articles mentioning "skill", "capability", "expertise", "experience", "ability", and "competency" as a limitation or essential to achieving circular economy strategies, have been considered. After the second and final step, a total of 32 articles have been considered useful for this analysis.

3. Results

This section shows all the information gathered during the analysis. It is characterised by 3 sub-sections, related to technologies, circular economy strategies and to skills and competencies.

3.1 Technologies

In this sub-section, the most frequent technologies found in the literature are going to be shown.

Table 1 shows the list of technologies gathered throughout the analysis. It is important to state that only those technologies mentioned more frequently (>= 7) have been added to the table. Furthermore, the column "#Mentions" states how many times each technology has been cited with every Circular Economy strategy. For instance, "Additive Manufacturing" has been linked twice as an enabler for "Reduce" strategy because this technology can promote resource efficiency (Ghobakhloo *et al.*, 2023; Hettiarachchi *et al.*, 2022), one as an enabler for "Refurbish", "Remanufacture", "Repair" (Ghobakhloo *et al.*, 2023) and one as a general enabler of Circular Economy Strategies since it has fundamental impact on supply chain and CE (Shayganmehr *et al.*, 2021).

Table 1. List of Technologies (no citations for space constraint)

Technology	#Mentions
Additive Manufacturing	6
Artificial Intelligence	19
Blockchain	7
Cyber-physical System	6
Internet of Things	11
Industry 4.0 (in general)	17
Others	61

Furthermore, for the last category "Others" (for space constraint), all those technologies less frequently mentioned, but not less important, have been allocated (e.g., BDA, Cloud Computing, Industrial Internet of Things, etc.).

3.2 Circular Economy

In this sub-section, the circular economy strategies found throughout the review are going to be shown.

From Table 2, it can be stated that the most frequent approaches used are Recycle, Reduce, Remanufacture, and Reuse. Within the "Other" category, as for the technologies section, those strategies less frequently mentioned have been allocated (i.e., Recovery, Redesign, Refurbish, Repurpose, and Rethink). It is important to point out that "Reduce" is the strategy with the highest number of references, and frequently it has been mentioned as enabled by "Artificial Intelligence" since this technology enhances operational efficiency and reduce waste (Abedsoltan, 2023; Bag *et al.*, 2021; Ghobakhloo *et al.*, 2023; Telukdarie *et al.*, 2024).

Table 2. List of Circular Economy Strategies (no citations for space constraint)

CE Strategy	#Mentions
Recycle	19

Reduce	23
Remanufacture	15
Reuse	13
CE (in general)	27
Others	30

3.3 Skills and Competencies

This sub-section underlines the fundamental skills, competencies, and mechanisms to implement circular economy strategies enabled by technologies.

Table 3 presents all the information gathered throughout the literature review. Training and awareness are more critical in almost all the papers analysed since a skilled workforce can be valuable for the implementation of CE strategies as well as efforts from the top management are fundamental to successfully implementing CE strategies (Khan et al., 2023).

Furthermore, collaboration is required for the success of circular economy strategies, especially in the supply chain, since a clear exchange of information, standard cooperation and development of operational links ensure a seamless implementation of CE strategies (Sehnem *et al.*, 2023).

Table 3. Skills List (no citations for space constraint)

Skills and Competencies	#Mentions
System Thinking	1
Collaboration	8
Multiple Life Cycle Thinking	1
Training	22
Awareness	20
Technological Gap	1
Knowledge	1
Digital Gap	1
Empowerment	1

4. Discussion

The principles of Industry 4.0 and Circular Economy (CE) are paramount to compete in the manufacturing segment. Characterized by a blend of digital technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), and Big Data Analytics (BDA), Industry 4.0 is revolutionising business production. These technologies provide connectivity, automation and production increases, improve efficiency and reduce costs. At the same time, there is the circular economy paradigm that promotes increased awareness of sustainability goals, in particular, CE aims to change the product life cycle from a linear logic to a circular one. This extends the life of resources, reduces waste, and promotes closed-loop materials recirculation. An emphasis is put on the importance of changing to the new logic, eliminating the traditional logic of "take-make-dispose" CE concepts incorporating Industry 4.0 technology provides a path to circular production that reduces environmental impact environment and production effects. Integrating CE concepts with Industry 4.0 technologies gives a pathway to circular manufacturing (Acerbi and Taisch, 2020) that reduces both environmental and production impact. From the analysis, it can be stated that many digital technologies are being exploited by companies and the awareness of embedding circular economy principles is increasing year by year. Nevertheless, it is evident from the articles that there is a need for a properly skilled workforce, and along with continuous technological advancement, tools and operations are becoming increasingly complex. As Lu *et al.* say "*Knowledge and skill incompetency is one of the biggest barriers in integrating CE and Industry 4.0. Industry 4.0 technologies require companies to*

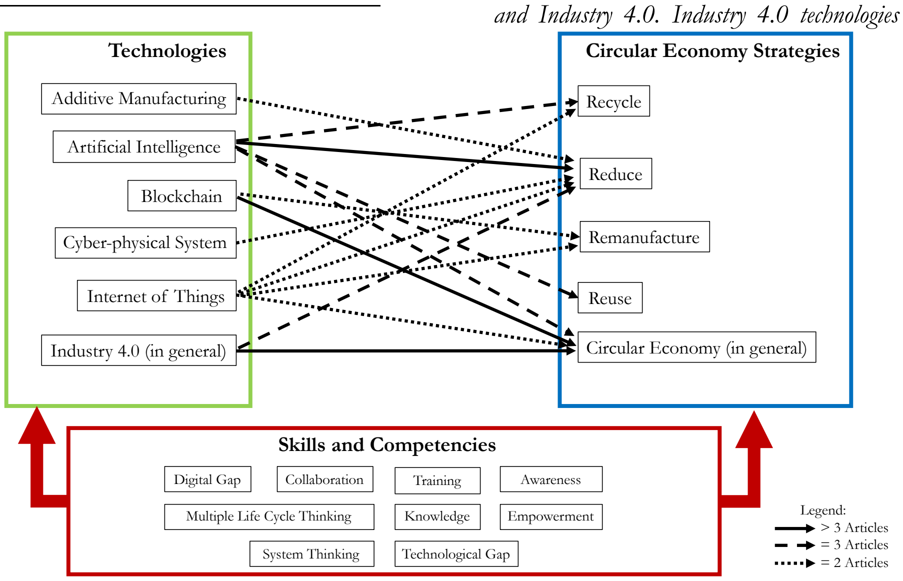

Figure 2. Link Between Technologies and Circular Economy Strategies and The Role of Skills and Competencies

capture and make sense of machine-generated data; in other words, it is a big challenge for many companies to analyse big data and use relevant analytical technologies and models to create value in their supply chain", meaning that not having awareness of these competencies and skills can hinder the companies' objectives (e.g., unskilled workforce, etc.) Ultimately, this paper contributes to pointing out the necessity of adapting to new technologies and systems by developing a skilled workforce capable of managing these complex tools and operations. The discussion points out that despite the growing adoption of digital technologies and circular economy principles, there is a significant gap in the skills available within the workforce, suggesting a crucial area for future research and development. Figure 2 points out the findings of this study. On the left-hand side, the frequent technologies have been pointed out, on the right-hand side the circular economy strategies and at the bottom of the figure skills and competencies. As evident from the picture, skills and competencies directly impact the utilization of technologies and implementation of circular economy strategies. Indeed, as Sánchez-García *et al.* pointed out, the government should prioritize training in emerging technologies and circular economy principles since it is fundamental that "human capital" can meet the business demand for a specialized workforce regarding design and implementation processes.

Furthermore, this work aimed at analysing the direct link between technologies and circular economy strategies, considering the former as the facilitator for implementing CE strategies. From Figure 2 it is evident how each technology is impacting a particular CE strategy. For instance, considering Artificial Intelligence, it emerged that AI is frequently enabling the "Reduce" strategy, through the adoption of specific digital toolset to reduce waste (Telukdarie *et al.*, 2024) and offering advantages in order to lower the waste (Bag *et al.*, 2021).

5. Conclusion and Future Research

The integration of Industry 4.0 and Circular Economy principles presents a transformative opportunity for the manufacturing sector. This study aims to understand the technologies which enable circular economy strategies mentioned in the literature which are essential for achieving sustainability. Nonetheless, from the analysis, a crucial challenge emerged which is the lack of a skilled workforce to handle technologies in order to achieve circular economy strategies, Sánchez-García *et al.* highlight the importance of addressing the skill gap as one of the main challenges, emphasizing the development of employees' technological capabilities as a crucial area for further research that. Indeed, in the future, the authors will conduct a structured case study to understand the specific skills needed as well as the level of expertise employees and workers have within the industrial environment (e.g., knowledge related to a specific technology, knowledge related to a specific circular economy strategy, etc.).

Lastly, this work is just a preview of the link between technologies and circular economy strategies, considering skills and competencies as facilitators to enable and implement them. In the future, the authors will deepen the connections amongst these three big categories, showing practical applications.

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