Journal of Cleaner Production 474 (2024) 143603

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Review

Skills for the twin transition in manufacturing: A systematic literature review

Adriana Hofmann Trevisan [a,c], Federica Acerbi [c], Iskra Dukovska-Popovska [d], Sergio Terzi [c], Claudio Sassanelli [b,*]

[a] *São Carlos School of Engineering, University of São Paulo, 13566 São Carlos, Brazil*
[b] *Department of Mechanics, Mathematics and Management, Politecnico di Bari, 70125 Bari, Italy*
[c] *Department of Management, Economics and Industrial Engineering, Politecnico di Milano, 20133 Milan, Italy*
[d] *Materials and Production, Aalborg University, 9220 Aalborg, Denmark*

ARTICLE INFO

Handling Editor: Xin Tong

Keywords:
Sustainability
Digital transformation
Competencies
Human capabilities
Education
Training programs

ABSTRACT

The twin transition is drawing the attention not only in the manufacturing sector but also in supply chains, ecosystems, and society (involving different stakeholders such as managers, scholars and policymakers) as digital technologies have been proven to promote circular economy (CE) strategies. Circular and digital transformations require a paradigm shift, which depends on professional skills that translate emerging challenges into economic, social, and environmental advantages. However, prior research has offered limited contributions to skills and competences needed for enabling CE transition considering the parallel digital transformation of sociotechnical systems. To address this gap, this study relies on a systematic literature review to clarify which professional skills are fundamental for a successful twin transition in the manufacturing sector. As a result, 40 skills have been identified, categorized into three dimensions: (1) Resilience skills, (2) Digital technologies skills, and (3) Specialized/Technical skills. The findings reveal the multidisciplinary nature of the skills, which should be combined to reach circularity goals. Overall, this study enhances the understanding of critical skills, enabling academics and training providers to better structure courses and curricula that meet current market requirements. It also gives managers greater clarity about the skills that require more attention and need to be deepened through further education and training sessions within the organizational context.

1. Introduction

In the contemporary manufacturing sector, it is essential for the new generation of workers to acquire key skills and fill job profiles for the industry's success (Beducci et al., 2024). Skill can be understood as "the ability to use one's knowledge effectively and readily in execution or performance" (Merriam-Webster Dictionary, 2024). According to Akyazi et al. (2022), the manufacturing sector will need a multi-skilled workforce to remain competitive and sustainable in the long term. This is particularly true when there is a need to translate the challenges of the twin transition into opportunities for innovation. Different studies on the effect of the transition to Circular Economy (CE) and the adoption of the European Green Deal identify and forecast net positive effect on employment as well as increasing requirements for upskilling (Cavallini and Soldi, 2023). Furthermore, the same study, focusing on the Nordic region, finds that science, technology, engineering, and mathematics (STEM) professions, which are key to the transition to CE, are required to widen their horizontal knowledge with sustainability competences. The link among STEM professions, CE, and sustainability competences has driven the European Commission to launch a number of initiatives and instruments since 2020 that will facilitate upskilling and reskilling in Europe (Cavallini and Soldi, 2023). A quick search of the Erasmus+ EU programme for education and training shows an increasing number of funded projects on CE (from 4 projects in 2014 to 675 in 2023) as well as on the twin transition (from 1 project in 2016 to 55 projects in 2024).

The idea of the twin transition, which refers to "an intertwined and simultaneous green and digital transition to offset companies' carbon footprint" (Rehman et al., 2023, p. 1), has been attracting the attention of recent literature and also from managers and policymakers. In line with previous literature (Findik et al., 2023; Uhrenholt et al., 2022), the twin transition combines the transformations arising from the implementation of the CE and industry 4.0 technologies. The benefits of

* Corresponding author.
E-mail address: claudio.sassanelli@poliba.it (C. Sassanelli).

https://doi.org/10.1016/j.jclepro.2024.143603
Received 3 April 2024; Received in revised form 1 July 2024; Accepted 7 September 2024
Available online 7 September 2024

digital technologies (DTs) for enhancing CE strategies is highly discussed by scholarship (Liu et al., 2022; Rosa et al., 2020; Sassanelli et al., 2023). For instance, DTs enable the optimization of operational processes alongside the empowerment of strategic decision-making (Kristoffersen et al., 2020). However, designing and implementing circular strategies is not an easy task. It requires knowledge of various technologies and treatments to determine the most sustainable options (Colangelo et al., 2023; Vitti et al., 2024), along with in-depth expertise and adequate training (Spreafico and Landi, 2022), especially when adopting digital technologies to extract value from information (Kinkel et al., 2022). Thus, it is increasingly crucial for professionals and organizations to have the skills required for the simultaneous transition.

Previous studies have already highlighted the critical skills needed to address contemporary transitions. Acerbi et al. (2022) developed a model to evaluate the workforce's readiness for the demands of Industry 4.0. The model presents maturity levels considering hard and soft skills, although not focusing on circular or sustainable discourse. Knudby and Larsen (2017) addressed how to educate engineers to operationalize circularity-oriented supply chains and provided a set of skills and teaching methods. This study is insightful for establishing educational programs, however, its focus is not directed towards fostering skills for the twin transition. Straub et al. (2023) found six categories of skills related to circular business model implementation. Although the study provides a comprehensive taxonomy for skills, the frame is oriented to circular startups.

However, despite the valuable insights into skills and professional growth provided by previous scholarship, theoretical endeavors remain fragmented across different domains and have not given sufficient attention to the skills that combine circular and digital transformations (i.e. twin transition). Although studies address skills separately, focusing only on Industry 4.0 (e.g., Acerbi et al., 2022), or targeting startup business models (e.g., Straub et al., 2023), a deeper skill set comprehension oriented towards the manufacturing sector remains unexplored. This aspect becomes even more critical when considering the rapid changes of the digital era (Dąbrowska et al., 2022), where skills need to be constantly updated (Sumter et al., 2021), and has an impact in the human dimension of industrial activities (Beducci et al., 2024).Therefore, this study aims to explore and understand which skills are essential for a CE in the manufacturing sector, including those needed to leverage digital technologies for a circular approach. In this case, a systematic literature review combined with bibliometric analysis is essential as it allows for a synthesis of previous knowledge not yet covered by scholars, the identification of key skills, and the outlining of guidelines for future studies. The article provides comprehensive synthesis of skills based on a systematic literature review combining bibliometric analysis and content analysis. As a result, 40 skills have been identified and categorized into three dimensions: (1) Resilience skills, (2) Digital technologies skills, and (3) Specialized/Technical skills. Responding to a constant call from the scientific community (e.g., Sumter et al., 2021; Pinzone and Taisch, 2023), this study contributes to current scholarship revealing the skills and multidisciplinary nature of knowledge required for a successful twin transition. Additionally, a research agenda covering six critical areas for future study is provided. By providing this evidence, the paper not only offers insights for increasing the resilience of production systems, but also provides guidelines for developing new studies and training programs grounded on high-quality education that encompasses digital, technical, and resilience skills.

The article is structured as follows. Section 2 addresses the methodological procedures regarding the systematic literature review. Section 3 unveils the research findings, including a deep analysis of the main skills for circular transition. Section 4 presents the discussion and theoretical and practical contributions. Finally, Section 5 outlines the conclusions, limitations, and possibilities for future research.

2. Research methodology

A Systematic Literature Review (SLR) was performed to explore and understand which skills are essential for a CE in the manufacturing sector, including those needed to leverage digital technologies for a circular approach. Drawing from the existing body of literature, this method is particularly relevant as it synthesizes the skills that scholars are discussing as fundamental for transitioning. The SLR was adopted following the guidelines of Tranfield et al. (2003) and Moher et al. (2009), and the process began with the selection of databases and the development of the search string. The Scopus and Web of Science search platforms were chosen as databases. In line with Rosa et al. (2020), these platforms were selected because they are internationally recognized and encompass a greater number of high-impact journals and studies in the CE domain. Besides, Scopus and Web of Science are usually selected in studies exploring circular manufacturing due to their extensive coverage in industrial engineering (e.g., Acerbi and Taisch, 2020; Beducci et al., 2024).

The search string combined terms related to skills, competencies, and education with CE and manufacturing. The terms associated with skills and education were selected because they are common in previous studies in this field (e.g., de Miranda et al., 2021; Pinzone and Taisch, 2023) and the use of the Boolean operator "OR" allowed a wide range of articles to be retrieved on this topic. The keyword "circular*" was selected to encompass papers that deal with the CE but may use other semantic variations, such as circularity, circular ecology, or circulatory economy (Nobre and Tavares, 2020). Consistent with Acerbi and Taisch (2020), the keyword "manufacturing" was chosen to narrow the scope of this research, with the manufacturing sector as the focus of analysis. Additionally, the term "digital" was not included in the string because it was observed that studies addressing skills (regardless of whether digital or not) within the context of circular manufacturing were already covered by the previously selected keywords. Furthermore, variations of the term "digital" (e.g., digitalization, digital technologies, etc.) were not included to avoid excluding articles that also discuss soft skills. Fig. 1 presents the transparent and replicable approach, including the documents' inclusion and exclusion criteria.

The searches were conducted on September 14, 2023, and only articles published in English and available in peer-to-peer journals and conferences were considered. Additionally, only papers published after 2012 were selected, as this marks the publication year of the first report by the Ellen MacArthur Foundation (The Ellen MacArthur Foundation, 2013), which globally popularized the term CE. Since that year, the quantity of articles exploring the principles of CE has exponentially increased (Kirchherr et al., 2017), contributing to confining the sample of articles most relevant to our analysis. In total, 669 records were identified after removing duplicates, which were first screened based on Title, Abstract, and Keywords.

During the first screening stage, articles addressing mathematical models and algorithm development unrelated to the CE research field were eliminated. Papers using the term "circular" in contexts unrelated to circular manufacturing and design, such as circular cylinders, circular milling technology, or circularity errors, were also excluded from consideration. In the second evaluation stage, articles were read thoroughly, and only those focusing on skills, capabilities, and competencies for the CE were selected. The final sample resulted in 58 papers, including five additional papers found through a backward snowballing process. This method involved utilizing the reference lists of the initially selected papers to uncover supplementary relevant documents (Wohlin, 2014). The entire screening process was carried out simultaneously and autonomously by two authors to reduce bias.

Consistent with previous studies (i.e., Acerbi and Taisch, 2020; Sassanelli et al., 2020), the dimensions extracted in the selected articles included: year of publication, research type (categorized as Action Research/Application Case; (Multiple) Case studies; Mixed methods; Surveys; Literature review; other), publication source (Journal or

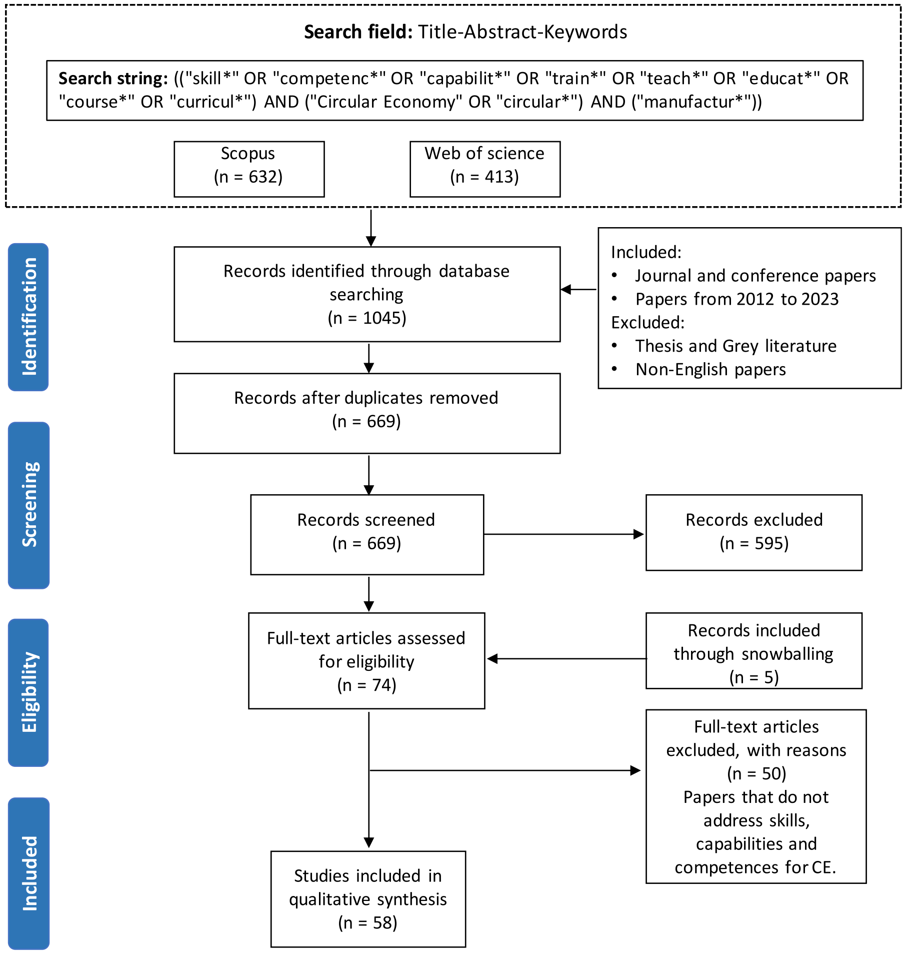

Fig. 1. Research strategy (adapted from the PRISMA guidelines (Moher et al., 2009)).

Conference), nation of the first author, and industries. In addition, skills mentioned in each paper were also extracted. To support the data analysis process, the authors utilized both Microsoft Office's Excel spreadsheets and the qualitative analysis software Maxqda®. Following the recommendations of Miles et al. (2014) and Elo and Kyngäs (2008), a meticulous content analysis process was conducted for the identification of skills categories, considering coding and categorization of the data (Fig. 2).

In the first coding cycle, texts were extracted based on "in vivo" codes, representing short phrases (skills) mentioned in the analysed articles (Miles et al., 2014). At this stage, three different authors identified 498 textual segments (representative quotes) reported in the "code structure" sheet of the Supplementary material.xlsx file, which were grouped into 40 first-order codes. For example, the textual segments "*Ability to work with data*" (de Miranda et al., 2021) and "*In this digital era, knowledge of big data analytics (BDA) […] has proven to be a tacit resource*" (Bag et al., 2021a) were grouped under the code "Data management and analytical skills". Subsequently, the authors looked for patterns in the second coding cycle and created 7 second-order codes that best represented the analysed data. After extensive discussions and consensus-building among the authors, the second-order codes were aggregated into 3 macro-dimensions (categories), encompassing all the skills identified in the literature. The 3 aggregated dimensions were (1) Resilience skills, (2) Digital Technologies skills, and (3) Specialized/Technical skills. Fig. 2 provides an example of the code structure related to the aggregated dimension "Digital Technologies skills". In section 3.2, a detailed description of the three aggregated skill dimensions is presented.

3. Main findings

3.1. Descriptive analysis

In this section, the descriptive analysis of the 58 selected papers is presented. The results were structured according to.

- historical publication trend by year,
- research method used,
- distribution of papers by source of publication,
- publishing countries,
- collaboration analysis of co-authorship,
- industry type,
- co-occurrence of keywords.

The historical publication trend (Fig. 3) shows a growing interest in skills for CE. This analysis is particularly relevant as it provides a temporal context for the evolution of the skills-focused research field. Overall, attention to the topic began later after the publication of the EMF report in 2012, which was remarkable for disseminating the concept of CE. However, it was only in 2015 that scholars began discussing education and skill development, crucial aspects of the transition. This can be explained in part by the fact that in the mid-2010s, the topic of circularity attracted attention within political discourse, and the following years culminated in the implementation of several policies oriented toward the CE (Weick and Ray, 2022). The year 2021 contains the highest number of publications (12 in total), and this can be attributed to the increased likelihood of digital technology adoption

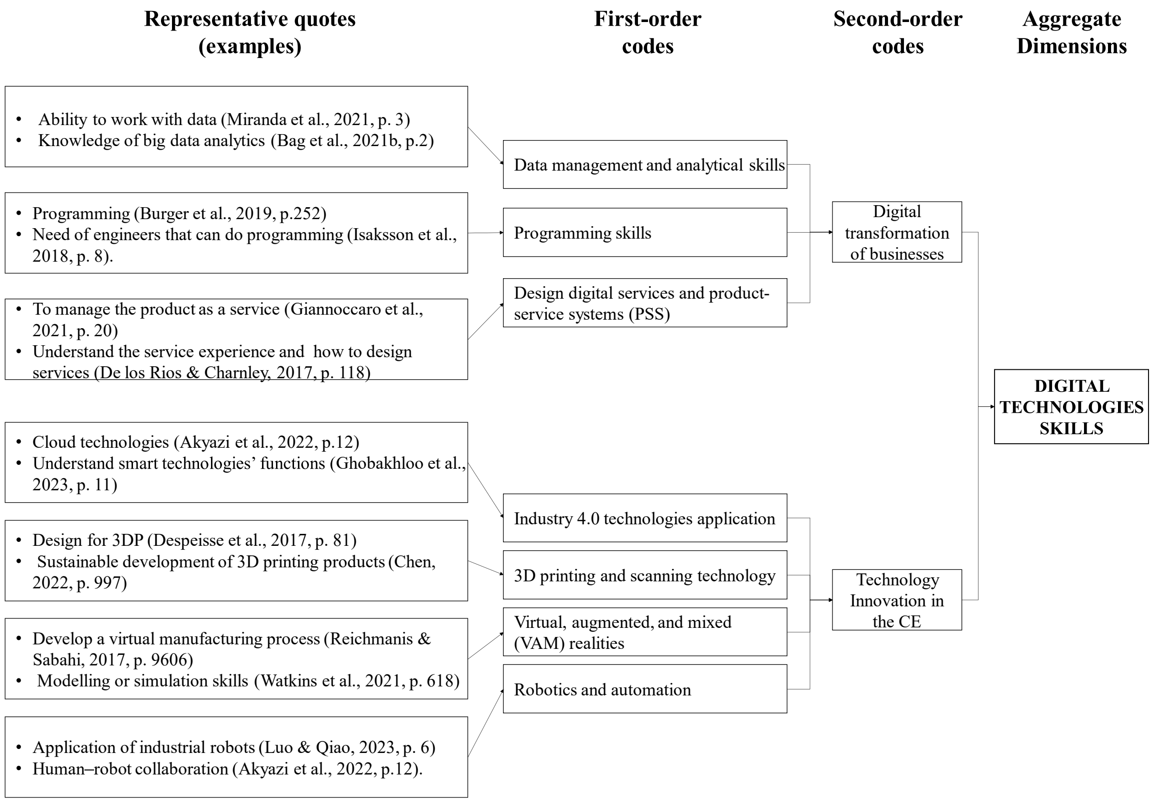

Fig. 2. An example of the coding process.

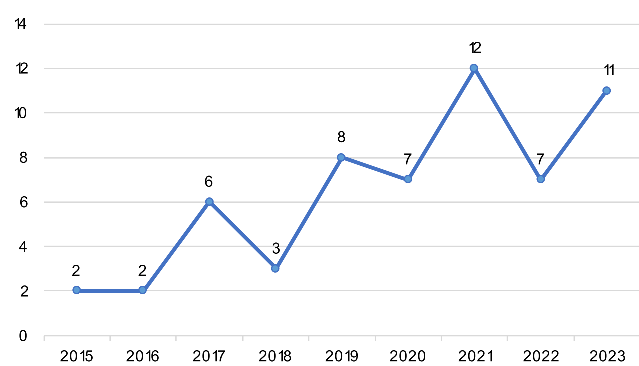

Fig. 3. Historical publication trend by year.

(digitalization) by companies driven by the COVID-19 pandemic (Bai et al., 2021) and also by the increasing number of CE related regulations (e.g., European Green Deal in 2019, EU Circular Economy Action plan in 2020, etc.).

An analysis was performed to reveal the dominant methodological trends in the area regarding the research methods used by the articles (Table 1). This analysis compares the different approaches the scholarship employs in the literature and shows possible methods that can be used in future studies. In general, the majority of them adopted a more practical methodological approach by employing action research (25,9%), where results stem from educational processes or projects developed to foster the skills of undergraduate and graduate students. (Multiple) case studies also showed an elevated adoption (20,7%), followed by mixed methods that combine more than one methodological approach (15,5%). Surveys and literature reviews represent 10,3% and 8,6%, respectively, and eleven articles (19%) adopted other methods such as workshops, panel discussions, system dynamics, and others.

Table 1
Research type.

Used methodologies	N° of papers
Action Research/Application Case	15
(Multiple) Case studies	12
Mixed methods	9
Surveys	6
Literature review	5
Other[a]	11

[a] Workshops, panel discussion, system dynamics, agent-based approaches, analyses of programs, courses, and education data.

The publication sources of the papers were quite diverse (41 identified sources), distributed among journals and conferences. The most relevant publication sources (Fig. 4) were Sustainability MDPI (8), followed by the Journal of Cleaner Production (7). One conference, the SEFI Conference, appeared in the top ten ranking with 2 publications. This analysis is especially relevant as it demonstrates that the topic is interdisciplinary and attracts attention from various publishing sources, while also providing guidance on where to target future publication of studies.

A more in-depth analysis to detect the geographic distribution of publications and collaboration among authors from different nations was conducted (Figs. 5 and 6). This analysis is notably relevant for demonstrating a geographical contextualization of the study topic. Through Fig. 5, it is possible to observe which countries are leading scientific publications in the field. In terms of the distribution of papers by nationality, the majority of contributions came from the European continent, with Italy (10) holding a prominent position, followed by the United Kingdom (9), Spain (5), and the Netherlands (4). The African

Fig. 4. Paper distribution across journals and conferences (Top 10).

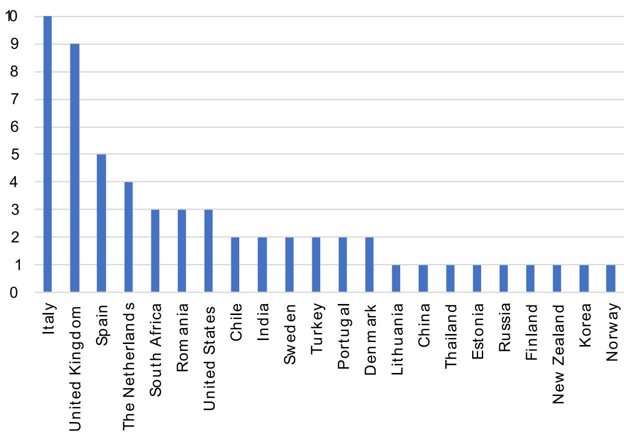

Fig. 5. Distribution of papers by the main author's country of origin.

continent, South Africa, and in the American continent, the United States, presented each 3 publications. Other countries showed fewer publications (between 1 and 2), indicating that this theme has not yet become a priority in those nations.

Through a bibliometric analysis using VosViewer software, it was possible to identify four main clusters of collaboration among authors, as in Fig. 6. The collaboration analysis is valuable for guiding future researchers in establishing strategic partnerships to develop new studies, mainly to guide researchers from geographical regions not yet covered in the literature in fostering international cooperation. As observed in the current studies, the authors have established partnerships among different countries and institutions, especially in Europe. The large nodes symbolize nations with significant influence on the topic, while the connections between nodes represent collaborative relationships among universities and institutes. As a result, developed countries are more attentive to better preparing for the transition to the CE. This also implies that emerging economies, for example, in South America, need to establish solid partnerships to conduct further studies on this subject, considering the unique aspects of their economies and their cultural and

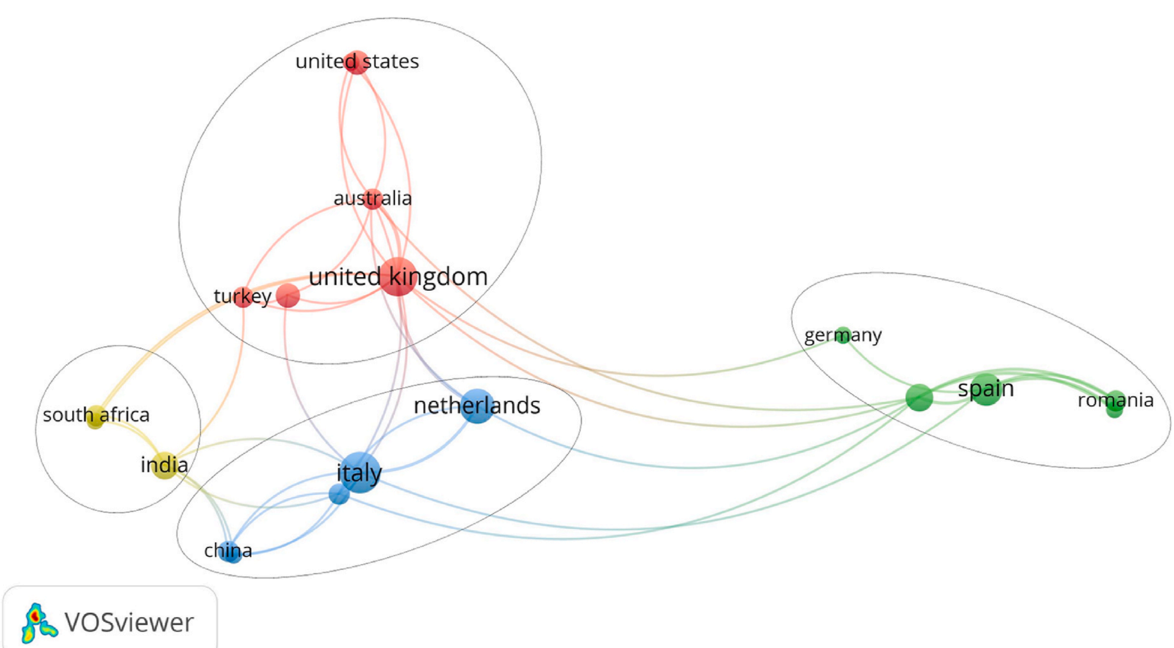

Fig. 6. Country co-authorship network (Collaboration analysis) developed through the software VosViewer.

geographical characteristics. In terms of multi-geographic studies, Giannoccaro et al. (2021) evidenced that it is critical to conduct research that address similarities and differences in teaching approaches among different countries, while also considering the skills demanded by the market.

In terms of the industrial sectors covered in the selected sample (Fig. 7), practically half of the documents (26 articles) do not specify the type of sector or industry of focus. This analysis was essential to reveal whether the identified skills are capable of generalization across various manufacturing sectors and to uncover opportunities for future studies in sectors that are still under-researched or have received little investigation. In this context, the CE skills mentioned are comprehensive and applicable to different industries. In the analysed papers, seven articles investigated multiple industrial sectors. For example, De los Rios and Charnley (2017), explored a variety of industries, such as electronics, automobile, fast moving consumer goods, and furniture. Regarding the papers that focused in a specific sector, the textile, footwear, and fashion segments presented the highest number of publications (7), followed by the chemical manufacturing (4), automotive (3), construction, and cement industry (3).

In Fig. 8, a keyword co-occurrence analysis was performed with keywords that appeared at least in three papers of the SLR sample. This analysis provides an overview of the most relevant hotspots within the field of knowledge (Ranjbari et al., 2021). The network analysis also demonstrates the interconnections in the literature among the themes that permeate the circular and digital transition, and further showed the interdisciplinary nature associated with the skills within this domain. This analysis shows that topics such as “product design”, “students”, and “engineering education” have already attracted attention in the past, but that currently research is more focused on “industry 4.0”, “sustainable manufacturing”, “skills”, and “economic conditions”. The most frequent keyword was “circular economy”, with 39 occurrences. The second most was sustainability/sustainable development, with 30, followed by product design, with 13 occurrences.

3.2. Circularity skills analysis

Grounded on the systematic literature review, 40 skills were identified, categorized into three main dimensions: (1) Resilience skills, (2) Digital Technologies skills, and (3) Specialized/technical skills. The resilience category addresses twenty-three skills that support restructuring current socio-technical regimes towards more resilient production systems, such as designing circular business models and exploring systemic thinking. The digital technologies category encompasses seven skills directly related to business digitalization processes, such as implementing industry 4.0 technologies, proficiency in programming and developing digital solutions. Finally, in the specialized/technical category, ten skills related to in-depth knowledge of the CE are provided, including life cycle management, resource use, and efficient management.

Fig. 9 shows the distribution of the number of articles analysed (58 in total) by category. This analysis was performed to verify which skill category is most frequent in the literature. Overall, the majority of papers addressed skills associated with the three domains investigated. Notably, the 79.3% of the sample mentioned some type of resilience skills, followed by the 74.1% discussing some type of technical skill, and less than half of the papers (36.2%) presented skills relating to digital technologies.

In terms of the most frequently mentioned skill (Fig. 10), there is an emphasis on the technical skill of circular product design, referenced in 24 papers. This skill is directly associated with the manufacturing industry, which, in seeking to develop more sustainable products, should consider the development of solutions that incorporate circular principles from the initial design stage. This result also highlights the importance of this skill during the transition. Therefore, it should be prioritized in the provision of courses and training programs focused on the CE. Another skill deserving attention is the design of circular business models and circular supply chains (CSC), mentioned in 19 articles. The literature on CE sheds light on the demand for professionals with the ability to propose and implement successful business models that are economically viable, supported by environmentally appropriate actions, and respecting social aspects.

Digital technology skills, as observed in Figs. 9 and 10, were the least mentioned by the literature. Skills such as programming, 3D printing and scanning technology, virtual and augmented reality (VAM), and robotics and automation were discussed in fewer than five articles each.

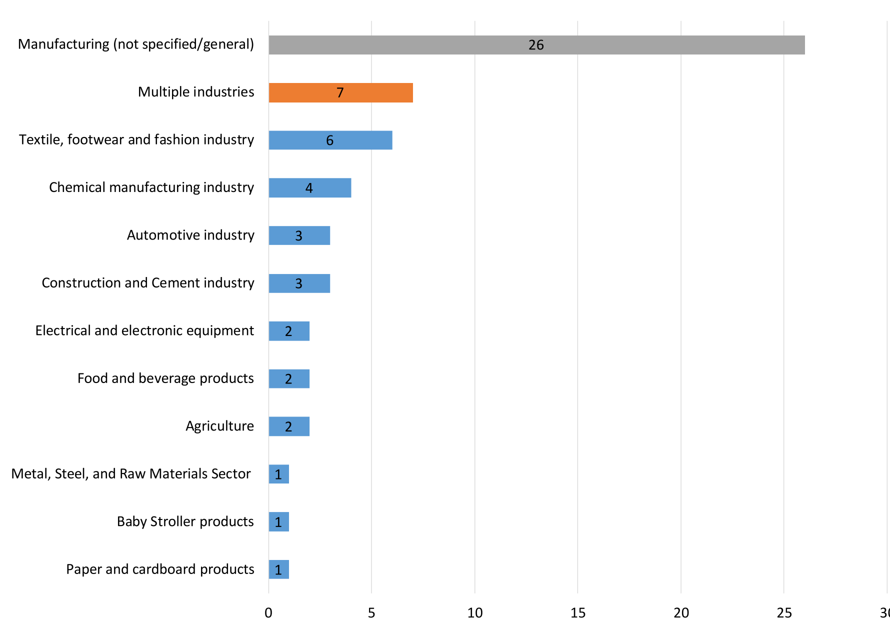

Fig. 7. Industrial sectors covered in the papers.

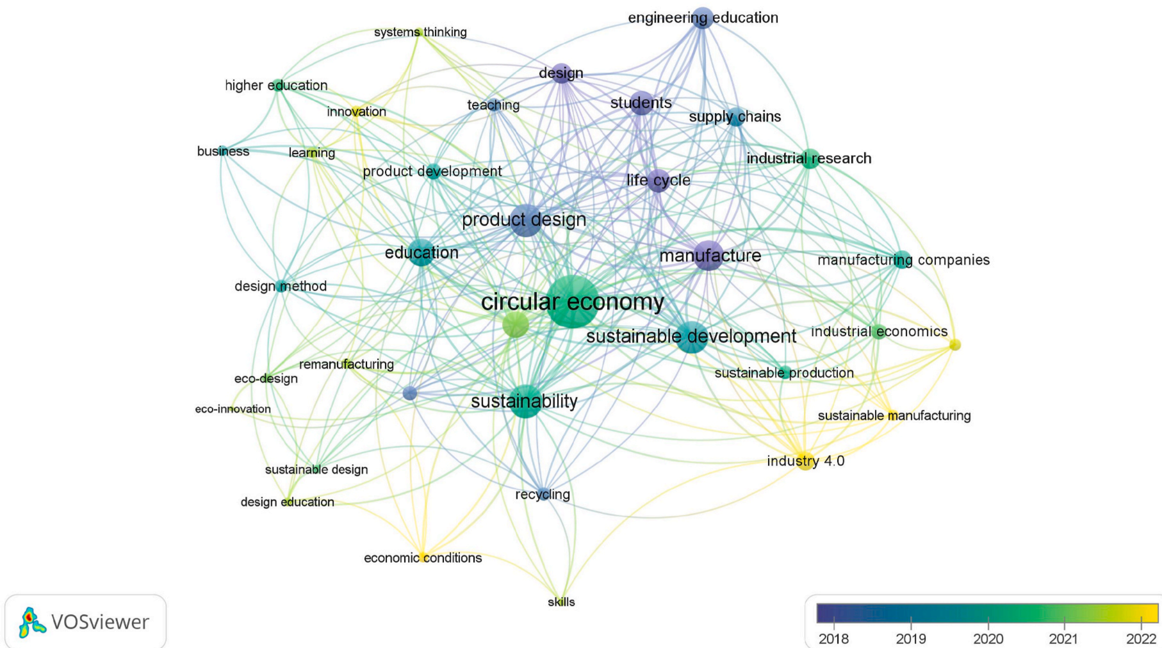

Fig. 8. Co-occurrence of keywords developed through the software VosViewer.

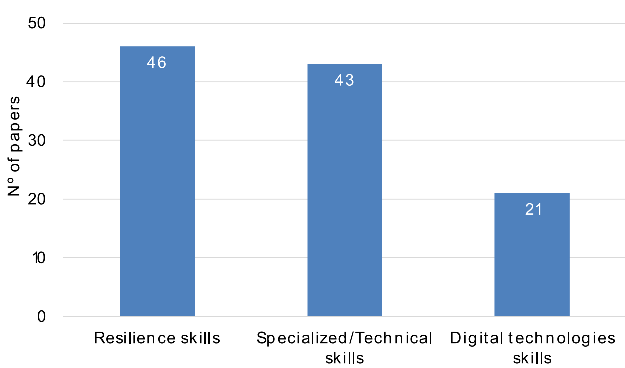

Fig. 9. Distribution of categories per number of analysed papers.

However, it is noteworthy that these skills have gained more emphasis in recent literature, particularly since the year 2020. New studies are exploring the impact of digital technologies on enabling circularity-oriented initiatives and the required knowledge. In the following sections, each skill identified in the literature will be detailed, along with its implications for theory and practice. Thus, although these skills have not been highlighted in the literature so far, compared to resilience and technical skills, new courses and training programs should include this domain to meet contemporary challenges.

3.2.1. Resilience skills analysis

This category encompasses 23 skills divided into two subcategories: *cross-cutting* and *soft skills* (Table 2). The cross-cutting subcategory includes fundamental skills for developing business models, establishing strategic partnerships, and managing different essential aspects in a CE model. The soft skills subcategory contains the interpersonal skills necessary in the workplace, allowing greater engagement, flexibility, and creativity regarding circular practices.

3.2.1.1. Cross-cutting skills. Business management and strategy refer to the skills a professional must possess when successfully managing a solution. This skill includes properly understanding team roles and responsibilities (Reichmanis and Sabahi, 2017), analysing, and evaluating the market to gain a comprehensive overview of sustainability issues (Sumter et al., 2018), creating sustainable marketing plans (Pinzone and Taisch, 2023; Summerton et al., 2019), and managing risks while engaging in entrepreneurial actions (Giannoccaro et al., 2021; Watkins et al., 2021).

The *collaboration and network connection* skill is widely discussed in CE literature. Professionals with this type of skill can build business partnerships (Akyazi et al., 2022), apply collective intelligence facilitation tools (Akyazi et al., 2023), work in multidisciplinary groups (Sanchez-Romaguera et al., 2016), make horizontal and vertical integrations of value partners (Ghobakhloo et al., 2023), as well as engaging in the co-creation of circular solutions (Walker et al., 2023). According to Can Saglam (2023), this skill is critical as it makes it easier to overcome barriers and enjoy benefits, that a firm would not achieve alone.

Another essential skill within cross-cutting is *coordination*. The CE requires alignment and coordination of partners towards the same goals. This skill reinforces the importance of coordination among the workforce of a single company but also among actors in the supply chain (Bag et al., 2021a) and the entire innovation ecosystem. Furthermore, the ability to coordinate is not only limited to the actors but also includes operational, communication, and training activities (Akyazi et al., 2022) that should be synchronized to reduce possible conflicts.

Customer and user-focused design is also crucial to develop circular solutions. Professionals with this skill can understand users' experience and their expectations and perception of value (De los Rios and Charnley, 2017). They can comprehend market needs (Walker et al., 2023) and have knowledge about consumer behaviour (Giannoccaro et al., 2021). It is a skill that supports the co-creation of value with clients and the acquisition of feedback to improve products and services.

Throughout the implementation of a CE model, it is essential to evaluate the performance of corporate employees (Akyazi et al., 2022). For this reason, the *design and implementation of training programs* skill is applied. This skill is not frequently mentioned in the literature, being addressed in only two articles (Akyazi et al., 2023; Ghobakhloo et al., 2023). However, it is core for keeping employees engaged, developing

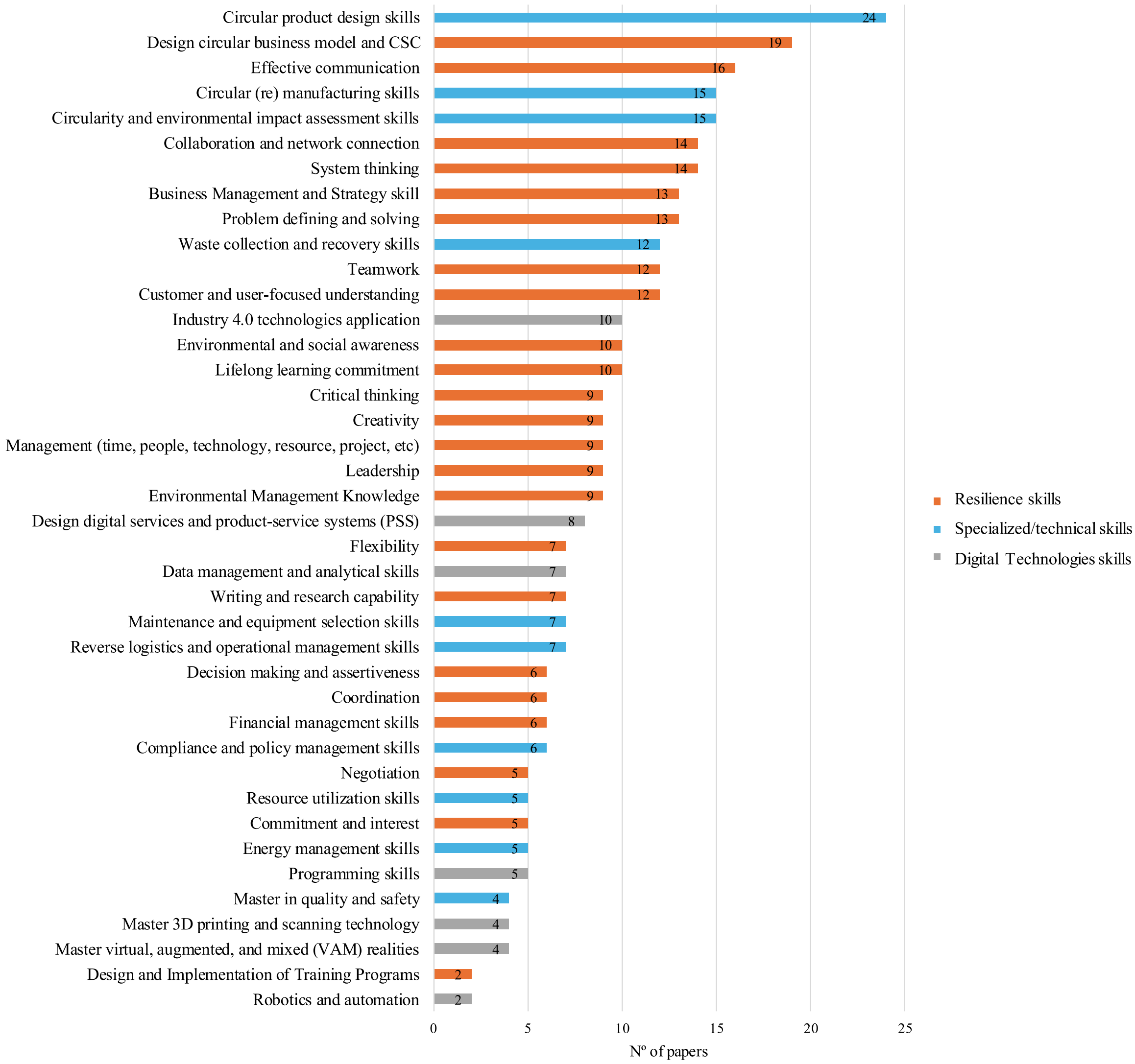

Fig. 10. Distribution of skills per number of analysed papers.

employee retention programs, and promoting professional improvement in response to new market demands.

One of the skills that deserves to be highlighted within the cross-cutting subcategory is the *design of circular business models and supply chains*. This skill covers knowledge related to innovation and business transformation (Burger et al., 2019; Sanchez-Romaguera et al., 2016), prototyping, testing of solutions (Watkins et al., 2021), the management of CSCs (Giannoccaro et al., 2021), and ideation of value proposition with impact in the social, economic, and environmental domain (Walker et al., 2023). Collaborators with these skills can understand the organizational context to develop business models integrating different digital technologies and multidisciplinary knowledge (Giannoccaro et al., 2021).

However, to structure a CSC and design new businesses, an indispensable skill is *environmental and social awareness*. In line with Akyazi et al. (2023), this skill concerns consciously using resources such as energy and materials, including the choice of more environmentally friendly production processes and technologies. Also, the social and ethical aspects cannot be neglected when strategically applying circular practices (Sanchez-Romaguera et al., 2016). This includes not only looking at the external organizational context but also at health safety and working conditions (Avadanei et al., 2020).

Another required skill is extensive *environmental management knowledge*. This skill refers to understanding key concepts such as sustainability and CE as their main strategies (including closing and slowing down resource flows) (Esparragoza and Mesa-Cogollo, 2019). Knowledge oriented towards recycling, reducing waste and increasing energy efficiency is expected from a professional (Cassells and Lewis, 2017). Knowledge about industrial symbiosis, production and responsible consumption is also part of the scope of this skill (Akyazi et al., 2023; Llorens et al., 2019).

Circular manufacturing processes mostly require *management* skills. This skill encompasses four critical aspects. First, time management is essential for developing products and services aligned with current market demands (Burger et al., 2019). Second, resources, including human, physical, and natural resources, must also be managed (Akyazi et al., 2022; Watkins et al., 2021). Third, it is necessary to manage knowledge, whether associated with a technology or the market, as well as develop project management plans to implement or improve existing solutions (Alonso-Muñoz et al., 2021; Sanchez-Romaguera et al., 2016). Finally, self-reflection (Lanz et al., 2019) helps improve the worker's actions and behaviours, leading to initiatives that are more consistent with CE.

Given that the implementation of a circular model involves complex activities and requires a holistic view of processes and resources, it is crucial for professionals to have a *system thinking*. This skill enables

Table 2
Skills regarding the **Resilience category**.

Sub-category	Skills	Representative codes	Reference
Cross-cutting skills **refer to abilities applicable across different domains and contexts within and across organizations to implement circular practices.**	Business Management and Strategy skill	Entrepreneurship, sustainable marketing, risk management, develop markets.	(Akyazi et al., 2022; Alonso-Muñoz et al., 2021; Giannoccaro et al., 2021; Knudby and Larsen, 2017; Kopnina, 2019; Lanz et al., 2019; Pinzone and Taisch, 2023; Raeva et al., 2021; Reichmanis and Sabahi, 2017; Summerton et al., 2019; Sumter et al., 2018; Vihma and Moora, 2020; Watkins et al., 2021)
	Collaboration and network connection	Collaboration, build business relationships, develop professional network, networking and cooperation between stakeholders, multidisciplinary collaboration, rich network connections, collaborate to create joint value, engaging strategic partners in collaboration.	(Akyazi et al., 2022; Burger et al., 2019; Can Saglam, 2023; Chen, 2022; Fernandes et al., 2018; Ghobakhloo et al., 2023; Mondal et al., 2023; Onpraphai et al., 2021; Pinzone and Taisch, 2023; Sanchez-Romaguera et al., 2016; Sumter et al., 2018, 2021; Walker et al., 2023; Watkins et al., 2021)
	Coordination	Coordinate operational activities, coordination, coordinating.	(Akyazi et al., 2022, 2023; Bag et al., 2021a; Burger et al., 2019; Can Saglam, 2023; Sumter et al., 2021)
	Customer and user-focused understanding	Understand factors of the use experience, understanding the role of consumer behaviour, customer awareness, circular user engagement, understand user expectations, customer and end-user needs, empathic user-focused understanding & observation (user-centered design), listening and responding to client feedback.	(Akyazi et al., 2022; Alonso-Muñoz et al., 2021; De los Rios and Charnley, 2017; Giannoccaro et al., 2021; Sanchez-Romaguera et al., 2016; Spreafico and Landi, 2022; Sumter et al., 2021; Vihma and Moora, 2020; Vogt Duberg et al., 2020; Walker et al., 2023; Watkins et al., 2021; Whitehill et al., 2022)
	Design and Implementation of Training Programs	Develop employee retention programmes, adapt training to labour market, evaluate training, develop corporate training programmes.	(Akyazi et al., 2022; Ghobakhloo et al., 2023)
	Design circular business model and CSC	Circular supply chain, design, and management of circular value chains, ideating and developing value propositions with environmental and/or social impact, design a successful circular business model, circular value propositions and business models, sustainable/circular business models, business model design, modern business models.	(Akyazi et al., 2022; Avadanei et al., 2020, 2021; Bag et al., 2021a; Burger et al., 2019; Giannoccaro et al., 2021; Isaksson et al., 2018; Knudby and Larsen, 2017; Lanz et al., 2019; Pinzone and Taisch, 2023; Sanchez-Romaguera et al., 2016; Summerton et al., 2019; Sumter et al., 2018, 2021; Walker et al., 2023; Watkins et al., 2021; Whitehill et al., 2022)
	Environmental and social awareness	Cultural empathy, promote environmental awareness, awareness of responsibility, understanding of social issues, fundamental values, and possibilities of sustainable development, recognize social issues, social responsibility, ethical responsibility, social perceptiveness.	(Akyazi et al., 2022, 2023; Avadanei et al., 2020; Burger et al., 2019; Kim and Lee, 2022; Llorens et al., 2019; Sanchez-Romaguera et al., 2016; Torreggiani et al., 2021; Watkins et al., 2021; Whitehill et al., 2022)
	Environmental Management Knowledge	Industrial symbiosis basic understanding, understanding environmental management, knowledge of environmentally oriented practices, environmental administration practices, knowledge about sustainability, corporate sustainability, basics of sustainable development and circular economy.	(Akyazi et al., 2022, 2023; Can Saglam, 2023; Cassells and Lewis, 2017; Esparragoza and Mesa-Cogollo, 2019; Giannoccaro et al., 2021; Llorens et al., 2019; Pinzone and Taisch, 2023; Watkins et al., 2021)
	Management (time, people, technology, resource, project, etc)	Sustainable resource management, planning and scheduling, project planning and management, people management, time management.	(Akyazi et al., 2022; Alonso-Muñoz et al., 2021; Burger et al., 2019; Chen, 2022; Fernandes et al., 2018; Lanz et al., 2019; Sanchez-Romaguera et al., 2016; Watkins et al., 2021)
	System thinking	Systems thinking, apply strategic thinking, circular systems thinking.	(Akyazi et al., 2022, 2023; Alarcón et al., 2019; Cappelletti et al., 2022; Cozma et al., 2020; Kopnina, 2019; Leal et al., 2020; Mayer, 2020; Pinzone and Taisch, 2023; Reichmanis and Sabahi, 2017; Summerton et al., 2019; Sumter et al., 2021; Watkins et al., 2021; Whitehill et al., 2022)
	Writing and research capability	Report on environmental issues, perform scientific research, information research and literacy, research capability, writing.	(Akyazi et al., 2022; Burger et al., 2019; Onpraphai et al., 2021; Sanchez-Romaguera et al., 2016; Summerton et al., 2019; Vihma and Moora, 2020; Watkins et al., 2021)
	Financial management skills	Product costing, manage budgets, financial planning, management of financial resources, justification of lifecycle costs, managerial and financial impact.	(Akyazi et al., 2022, 2023; Burger et al., 2019; Knudby and Larsen, 2017; Sanchez-Romaguera et al., 2016; Watkins et al., 2021)
Soft skills **refer to interpersonal and social skills, including attitudes and behaviours aligned with a harmonious work environment for circular transition.**	Decision making and assertiveness	Judgment, decision making, opportunity assessment, identification of potential opportunities, assertiveness.	(Ada et al., 2023; Akyazi et al., 2022, 2023; de Miranda et al., 2021; Sanchez-Romaguera et al., 2016; Watkins et al., 2021)
	Commitment and interest	Motivation and interest, initiative taking, commitment.	(Ada et al., 2023; Akyazi et al., 2023; Alarcón et al., 2019; Ul-Durar et al., 2023; Walker et al., 2023)
	Effective communication	Circular economy communication, technical communication, communication planning and	(Akyazi et al., 2022; Bag et al., 2021a, 2021b; Burger et al., 2019; Can Saglam, 2023; Chen, 2022;

(*continued on next page*)

Table 2 (*continued*)

Sub-category	Skills	Representative codes	Reference
		implementation, effective communication, communication ability, speaking, interpersonal communication.	Ghobakhloo et al., 2023; Giannoccaro et al., 2021; Kopnina, 2019; Reichmanis and Sabahi, 2017; Sanchez-Romaguera et al., 2016; Summerton et al., 2019; Sumter et al., 2021; Torreggiani et al., 2021; Watkins et al., 2021; Whitehill et al., 2022)
	Creativity	Creative thinking, creativity, creation of innovation, out of the box thinking.	(Ada et al., 2023; Alarcón et al., 2019; Giannoccaro et al., 2021; Kim and Lee, 2022; Mondal et al., 2023; Pinzone and Taisch, 2023; Vihma and Moora, 2020; Watkins et al., 2021; Whitehill et al., 2022)
	Critical thinking	Critical thinking, critical understanding of innovation.	(Akyazi et al., 2022, 2023; Burger et al., 2019; Kopnina, 2019; Pinzone and Taisch, 2023; Summerton et al., 2019; Torreggiani et al., 2021; Watkins et al., 2021; Whitehill et al., 2022)
	Flexibility	Flexibility, agility, adaptability to change, adjust to changes, adaptability and ability to change, psychological and mental flexibility, flexible and adaptable.	(Ada et al., 2023; Akyazi et al., 2022, 2023; de Miranda et al., 2021; Ghobakhloo et al., 2023; Pinzone and Taisch, 2023; Ul-Durar et al., 2023)
	Leadership	Leadership, give constructive feedback, identify necessary human resources, ability to enact positive change for the future, management leadership.	(Akyazi et al., 2022; Bag et al., 2021b; Ghobakhloo et al., 2023; Isaksson et al., 2018; Mondal et al., 2023; Torreggiani et al., 2021; Vihma and Moora, 2020; Watkins et al., 2021; Whitehill et al., 2022)
	Lifelong learning commitment	Active listening, autonomy, continuous learning, lifelong learning, commitment to lifelong learning.	(Akyazi et al., 2022, 2023; Burger et al., 2019; de Miranda et al., 2021; Ghobakhloo et al., 2023; Isaksson et al., 2018; Lanz et al., 2019; Pinzone and Taisch, 2023; Vihma and Moora, 2020; Watkins et al., 2021)
	Negotiation	Negotiate employment agreements, negotiate with employment agencies, negotiation, persuasion.	(Akyazi et al., 2022; Burger et al., 2019; Ghobakhloo et al., 2023; Sanchez-Romaguera et al., 2016; Watkins et al., 2021)
	Problem defining and solving	Solve aesthetic and structural problems, problem solving, complex problem-solving, troubleshooting, find solutions to problems.	(Akyazi et al., 2023, 2022; Burger et al., 2019; De los Rios and Charnley, 2017; Ghobakhloo et al., 2023; Kim and Lee, 2022; Knudby and Larsen, 2017; Lanz et al., 2019; Mondal et al., 2023; Pinzone and Taisch, 2023; Reichmanis and Sabahi, 2017; Summerton et al., 2019; Watkins et al., 2021)
	Teamwork	Work in cross-disciplinary teams, teamwork, multidisciplinary teamwork, working in team, team identity, cross-functional teamwork.	(Akyazi et al., 2022; Bag et al., 2021b; de Miranda et al., 2021; Ghobakhloo et al., 2023; Knudby and Larsen, 2017; Onpraphai et al., 2021; Pinzone and Taisch, 2023; Raeva et al., 2021; Sanchez-Romaguera et al., 2016; Summerton et al., 2019; Torreggiani et al., 2021; Watkins et al., 2021)

individuals to make predictions about future scenarios, understand internal and external contexts, as well as grasp emerging trends (Pinzone and Taisch, 2023). Furthermore, it allows the entire product lifecycle to be considered when operationalizing circular practices, going beyond a single specific stage such as the beginning of life or end of life (Cappelletti et al., 2022; Watkins et al., 2021).

The skill to *write and conduct research* also demands attention, whether for data collection, investigating new practices to be implemented or for effective communication of environmental issues (Onpraphai et al., 2021; Sanchez-Romaguera et al., 2016; Vihma and Moora, 2020). Professionals must be able to prepare reports in a technical yet comprehensive manner, according to each public (audience) they intend to reach (Akyazi et al., 2022; Burger et al., 2019).

Finally, the last skill within the cross-cutting subcategory is *financial management.* When transitioning to the CE, it is crucial to have a clear understanding of the financial impacts, the costs associated with each strategy, and the return-on-investment time (Akyazi et al., 2022; Knudby and Larsen, 2017; Watkins et al., 2021). Financial planning ensures that potential constraints do not emerge along the way, preventing them from becoming significant bottlenecks during the transition.

3.2.1.2. Soft skills. Within the subcategory of soft skills, product designers are required to possess *decision-making and assertiveness* skill. This demands that professionals have the ability to think logically (Akyazi et al., 2023) and to identify and evaluate business opportunities (Akyazi et al., 2022). They need to develop decision-making criteria and not merely make choices based on personal and pre-established biases.

To know the best choices to make, it is important for the professional also to have *commitment and interest* in exploring new areas of knowledge. CE requires changes throughout the value chain (Ada et al., 2023), and this demands commitment, support from senior management (Walker et al., 2023), and motivation to transform ideas into actions (Akyazi et al., 2023). According to Akyazi et al. (2023, p. 5), this skill "*helps inspire stakeholders to become more involved and committed*" during the business transformation stages.

Another skill that is highly highlighted in the literature is *effective communication.* This skill refers to the exchange of information, opinions, knowledge, and ideas in a clear way, where interlocutors can understand the dialogue and the message that they want to transmit (Akyazi et al., 2023). To do this, the individual needs to master communication techniques, such as storytelling, where it is possible to create a vocabulary to involve stakeholders and disseminate the circular practices applied (Sumter et al., 2021).

Creativity also stands out as a soft skill to be fostered. Given that significant organizational changes need to be implemented, workers need to leave their comfort zones (Ada et al., 2023) and be able to use their imagination to devise new solutions and processes (Akyazi et al., 2023). Contrary to what common sense believes, Torreggiani et al. (2021) argue that creativity is not restricted only to an inherently inherited talent. Using simple strategies (e.g. DIY), it is possible to provoke individual creative thinking.

Professionals also need to be able to adapt quickly to changes in the work environment (Ghobakhloo et al., 2023). *Flexibility* helps the team to face unexpected challenges quickly and assertively that may emerge along the way (Akyazi et al., 2023). Therefore, being open to new adaptations and changes in the work routine is a key factor for companies that are seeking to integrate circular principles.

Leadership skill is also frequently mentioned by CE scholars. This skill is significantly related to adopting Industry 4.0 digital technologies (Bag et al., 2021b). It covers aspects such as providing constructive feedback to the team and identifying, in addition to allocating, appropriate human capital (Akyazi et al., 2022). In accordance with Mondal et al. (2023, p. 6), "*strong leadership and supportive organizational culture can inspire employees to embrace sustainability*".

Lifelong learning commitment is a skill that enables professionals to learn from their mistakes (Lanz et al., 2019). The continuous and active search for knowledge allows them to update themselves and acquire new skills constantly. This ability also encompasses active listening (Burger et al., 2019), in which the individual learns by paying careful attention to what other people say, understanding, agreeing, or disagreeing with the points of view presented.

By paying attention to others and the external environment, professionals can better apply *negotiation* tactics. Expertise in negotiation helps to change behaviour and strategically direct actions that need to be implemented. Negotiation applies not only to commercial transactions but also to establishing work agreements that satisfy both parties (Akyazi et al., 2022).

An additional and crucial skill in a CE is *problem defining and solving*. This skill is applied to solve complex and new problems that emerge in industrial systems (Burger et al., 2019). It encompasses identifying, analysing, and establishing strategies to address the challenges and difficulties that arise. It is necessary to devise intelligent ways to solve problems, optimizing the use of resources and reducing the time required.

Finally, *teamwork* deserves attention within the soft skills subcategory. This skill is "*characterized by a unified commitment to achieving a given goal, participating equally, maintaining open communication, facilitating effective usage of ideas*" (Akyazi et al., 2023, p. 19). Teamwork requires profoundly strengthening collaborative ties, as individuals must build cross-disciplinary teams (Knudby and Larsen, 2017) and create a trust-based structure (Ghobakhloo et al., 2023).

3.2.2. Digital technologies skills analysis

This category encompasses seven skills grouped into two subcategories: *Digital transformation of businesses* and *Technology innovation in the CE* (Table 3). The subcategory of digital transformation of businesses covers skills associated with digitalization and business data management processes. The technology innovation subcategory includes skills relating to applying specific digital technologies that promote circularity, such as 3D printing and virtual, augmented, and mixed realities, among others.

3.2.2.1. Digital transformation of business. The first skill within this subcategory refers to *data management and analytical skills*. The digital transformation associated with implementing circular strategies demands to professionals the knowledge of working with large data sets, from generation, collection, storage, sharing, cybersecurity, applications, and visualizations (Akyazi et al., 2022; de Miranda et al., 2021). According to Bag et al. (2021b), this ability is already recognized as an implicit resource coming from the workforce. Professionals who master data analysis tools and techniques may be able to extract valuable insights (Akyazi et al., 2023) that support decision-making.

Furthermore, an ability that the market has increasingly demanded is *programming skills* integrated with developing new software and

Table 3
Skills regarding the Digital technologies category.

Sub-category	Skills	Representative codes	Reference
Digital transformation of businesses **refers to skills associated with analysis, and proposition of digital solutions.**	Data management and analytical skills	Big data techniques, analytical and intelligence capabilities, ability to work with data, big data analytics, big data processing capability, knowledge of big data analytics.	(Akyazi et al., 2022, 2023; Bag et al., 2021a, 2021b; de Miranda et al., 2021; Ghobakhloo et al., 2023; Luo and Qiao, 2023)
	Programming skills	Programming, optimize relevant algorithms and digital models through computers.	(Bag et al., 2021a; Burger et al., 2019; Chen, 2022; Isaksson et al., 2018; Luo and Qiao, 2023)
	Design digital services and product-service systems (PSS)	Service-based products, product as a service, product-service systems, design services, service orientation.	(Burger et al., 2019; De los Rios and Charnley, 2017; Ghobakhloo et al., 2023; Giannoccaro et al., 2021; Pinzone and Taisch, 2023; Sumter et al., 2021; Vogt Duberg et al., 2020; Watkins et al., 2021)
Technology Innovation in the CE **refers to skills to adopt digital technologies to improve operations and organizational processes.**	Industry 4.0 technologies application	Artificial intelligence, machine learning, business ict systems, industry 4.0 technologies, digital technologies and i4.0-ce concepts, smart grid systems, smart factory, digital twin, cyber-physical systems, iot, cloud technologies, digital solutions, incorporate digital technology.	(Akyazi et al., 2022, 2023; Alonso-Muñoz et al., 2021; Burger et al., 2019; de Miranda et al., 2021; Dwivedi et al., 2022; Ghobakhloo et al., 2023; Giannoccaro et al., 2021; Pinzone and Taisch, 2023; Watkins et al., 2021)
	Master 3D printing and scanning technology	3D printing, 3d laser scanning, working principle and use process of 3d printing, component printing.	(Akyazi et al., 2022; Chen, 2022; Despeisse et al., 2017; Leal et al., 2020)
	Master virtual, augmented, and mixed (VAM) realities	Virtual reality technologies, virtual manufacturing process, modelling or simulation, augmented reality, virtual reality and augmented reality, advanced	(Akyazi et al., 2022; de Miranda et al., 2021; Reichmanis and Sabahi, 2017; Watkins et al., 2021)

(*continued on next page*)

Table 3 (*continued*)

Sub-category	Skills	Representative codes	Reference
		simulation, vam realities.	
	Robotics and automation	Remote control and smart sensoring, rovs remotely operated vehicles, operate and maintain industrial robots, human–robot collaboration, robotic construction, human machine interfaces.	(Akyazi et al., 2022; Luo and Qiao, 2023)

platforms (Isaksson et al., 2018). This skill is connected with several other digital applications and purposes (Burger et al., 2019), such as the adoption of industrial robots (Luo and Qiao, 2023), artificial intelligence (Bag et al., 2021b), digital models and 3D printing (Chen, 2022).

Data and algorithm knowledge is also crucial for the *design of digital services and product-service systems (PSS)*. Understanding how the service experience is provided and how to enable dematerialization is a key skill in circularity-oriented business model innovation (De los Rios and Charnley, 2017; Ghobakhloo et al., 2023). This skill is not only associated with delivering a product as a service or incorporating additional services into a product offering. It also refers to the possibility of creating multiple lifecycles and increasing resource use efficiency in product-services (Pinzone and Taisch, 2023).

3.2.2.2. Technology innovation in the CE. Knowledge of *Industry 4.0 technology applications* has become vital in the digital age. The existing technologies are vast, such as the Internet of Things, cloud, artificial intelligence, etc. (Akyazi et al., 2022). Therefore, it is necessary to create employee skills to integrate digital technologies into daily activities and the functions performed by workers (Ghobakhloo et al., 2023). Otherwise, the lack of this skill can create a barrier to technological innovation (Dwivedi et al., 2022), making it impossible to exploit digital functions and make real-time decisions (Akyazi et al., 2023).

Another skill within the technological innovation subcategory is *mastery of 3D printing and scanning technology*. According to Chen (2022), this skill also requires designers to understand software and methods and know which materials can be used as consumables for 3D printing, observing the types of products generated depending on the input. Understanding the composition of virgin and recycled materials and the best way to use them (Despeisse et al., 2017) helps minimizing waste and maximize sustainable initiatives.

Mastery of *virtual, augmented, and mixed (VAM) realities* is also a required skill. Virtual and augmented reality can simulate manufacturing environments and allow interaction with the system to perform different types of analyses and even predictive maintenance (de Miranda et al., 2021). Using these technologies to simulate product development (Watkins et al., 2021) and factory environments is also possible.

Finally, a digitalized environment requires engineers to have knowledge of *automation and robotics*. In line with Luo and Qiao (2023, p. 6), "*the adoption of industrial robots increases the demand for skilled labor who have high levels of technical expertise and skills in fields such as engineering, computer science and robotics to operate and maintain these machines*". The individual is expected to develop human-robot collaboration, remote control, and construction and operation skills (Akyazi et al., 2022).

3.2.3. Specialized/technical skills analysis

This category embraces 10 distinct skills, which have been grouped into three categories (see Table 4): *Circular lifecycle management*, *Cleantech and advanced materials*, and *Waste management*. The *Circular lifecycle management* category includes skills that enhance circularity aspects in different phases of product lifecycle (such as product design or (re)manufacturing), as well as skills that enable participants to assess circularity and environmental impact. *Waste management* category covers skills needed to manage the reverse flows of materials, such as waste collection, reverse logistics management, and utilization of resources out of the waste. Finally, the *Cleantech and advanced materials* category includes building competences needed to process the recovered materials, including the energy recovery of the waste, but also developing new materials from the recovered resources, and related product, environment regulatory aspects and certifications.

3.2.3.1. Circular lifecycle management. *Circular product design* is a category of skills addressed in the largest number of the papers (Fig. 10). This is justified by the fact that around 80% of the environmental impact of a product is decided at the early stages of the product development (Watkins et al., 2021). These skills equip students and practitioners (designers, engineers, operators) to consider different sustainable product and process design strategies and methods to reduce the environmental impact of a product (Spreafico and Landi, 2022; Watkins et al., 2021). Some of the skills relate to design for longevity of products from durability perspective (Andrews, 2015) or from timeless design perspective (Spreafico and Landi, 2022). This may include skills to understand product wear as it is used (De los Rios and Charnley, 2017) and material properties (Avadanei et al., 2020), as well as design simplification (Watkins et al., 2021). Other groups of skills are about design and development of products using waste material (Avadanei et al., 2020; Rizzo et al., 2017) which includes developing new (composite) materials to enable composting (Manfredi et al., 2019; Mottese et al., 2021) and biodegradability (Spreafico and Landi, 2022) of the products/packaging. It is also evident from the literature that the skills of designers should embrace knowledge about the effects of the product design on the subsequent phases of the lifecycle, such as recovery and multiple use cycles (Sumter et al., 2021), remanufacturing (Bag et al., 2021b), disassembly process complexity (Burger et al., 2019; Kim and Lee, 2022) and related technology support (Cappelletti et al., 2022).

Circular (re)manufacturing category covers skills needed in the transition and implementation of circular and sustainable production. Students and practitioners should be able to design (Monyaki and Cilliers, 2023), select and develop innovative transformation technologies and circular processes (Knudby and Larsen, 2017; Vogt Duberg et al., 2020) (such as moulding, shredding, 3DP, etc. (Fernandes et al., 2018)) and systems to optimize sustainability impacts (Pinzone and Taisch, 2023). This is challenging since process designers need to work with production using new innovative or waste materials as raw materials (Fernandes et al., 2018) or wide range of quality of return products. Additional skills needed are designing and understanding material flows in remanufacturing (Lanz et al., 2019), remanufacturing facility location (Vogt Duberg et al., 2020), commercial production (Whitehill et al., 2022), but also identifying and understanding skills that are required by remanufacturing processes (Ghobakhloo et al., 2023; Vogt Duberg et al., 2020). In addition, skills related to management of daily operations are necessary to be built (Knudby and Larsen, 2017), including production planning and scheduling skills (Akyazi et al., 2023).

Circularity and environmental impact assessment category covers skills that enable evaluation of the environmental impact of diverse circularity strategies (Sumter et al., 2018) and audit (including energy, CO_2, material circularity indicator, etc.) of circularity scenarios (Pereira and Fredriksson, 2015). This can be done on a system level (considering multiple lifecycles) (Sumter et al., 2018), on a site level (Akyazi et al., 2022) (considering health, safety and hazard aspects of (chemical)

Table 4
Skills regarding the Specialized/Technical category.

Sub-category	Skills	Representative codes	Reference
Circular lifecycle management **refers to skills that improve aspects of circularity at different stages of the product life cycle, as well as skills that allow participants to assess circularity and environmental impact.**	Circular (re) manufacturing	Production planning, Design and management of circular operations and production systems, sustainable biomaterials production, sustainable processes, sustainable manufacturing practices, disassembly and dismantling process, circular production, remanufacturing processes, remanufacturing tasks, Circular Manufacturing, Managing the daily manufacturing processes.	(Akyazi et al., 2022; Avadanei et al., 2021; Burger et al., 2019; Fernandes et al., 2018; Ghobakhloo et al., 2023; Giannoccaro et al., 2021; Knudby and Larsen, 2017; Lanz et al., 2019; Monyaki and Cilliers, 2023; Onpraphai et al., 2021; Pinzone and Taisch, 2023; Sumter et al., 2021; Vogt Duberg et al., 2020; Watkins et al., 2021; Whitehill et al., 2022)
	Circular product design	Design for multiple use cycles, design for recovery, long-lasting products, design for sustainability, recycle, reuse, dissemble, design for remanufacture, eco-design/ sustainable product design, engineering functions of the product, intelligent materials, product functions, design/ component simplification, life cycle design, timeless design, product teardown and sustainable product redesign.	(Akyazi et al., 2022; Andrews, 2015; Avadanei et al., 2021; Bag et al., 2021b; Burger et al., 2019; Cappelletti et al., 2022; De los Rios and Charnley, 2017; de Miranda et al., 2021; Favi et al., 2016; Fernandes et al., 2018; Kim and Lee, 2022; Leal et al., 2020; Llorens et al., 2019; Manfredi et al., 2019; Mottese et al., 2021; Reichmanis and Sabahi, 2017; Rizzo et al., 2017; Sanchez-Romaguera et al., 2016; Spreafico and Landi, 2022; Summerton et al., 2019; Sumter et al., 2021; Vihma and Moora, 2020; Walker et al., 2023; Watkins et al., 2021)
	Circularity and environmental impact assessment	Circular impact assessment, ce indicators, track key performance indicators, assessing health, safety, and hazards of chemical processes, assessment of circularity and environmental, social and economic impact, assess environmental impact, methods and tools to assess environmental impact, life cycle analysis, economic and environmental performance, conduct environmental site assessments, perform environmental investigations.	(Akyazi et al., 2022, 2023; Esparragoza and Mesa-Cogollo, 2019; Giannoccaro et al., 2021; Knudby and Larsen, 2017; Mayer, 2020; Pereira and Fredriksson, 2015; Pinzone and Taisch, 2023; Reichmanis and Sabahi, 2017; Sanchez-Romaguera et al., 2016; Sumter et al., 2018, 2021; Vihma and Moora, 2020; Walker et al., 2023; Watkins et al., 2021)
Clean tech and advanced materials **refers to skills related to the effective and efficient employment and deployment of technologies in organizations' processes to trigger circular economy practices fostering sustainability dynamics.**	Compliance and policy management	Comply with legal regulations, development of ce action plans, develop environmental policies, ensure compliance with safety legislation, apply and monitor company policies, general regulatory awareness, learn about regulations and regulatory processes, understanding legislative and compliance requirements, ensure compliance with environmental legislation, monitor legislation developments.	(Akyazi et al., 2022, 2023; Avadanei et al., 2020; Reichmanis and Sabahi, 2017; Summerton et al., 2019; Vihma and Moora, 2020)
	Maintenance and equipment selection	Equipment selection, understand failure mode and maintenance procedures, preventive and predictive maintenance, equipment maintenance, repairing.	(Akyazi et al., 2023, 2022; Burger et al., 2019; De los Rios and Charnley, 2017; Giannoccaro et al., 2021; Mayer, 2020; Watkins et al., 2021)
	Energy management	Understanding energy use, energy management, monitoring systems of energy consumption, adoption of alternative energy sources, energy conservation and energy efficiency.	(Akyazi et al., 2022, 2023; Avadanei et al., 2020; Lanz et al., 2019; Sanchez-Romaguera et al., 2016)
	Master in quality and safety	Quality control analysis, process analysis, quality	(Akyazi et al., 2022, 2023; Burger et al., 2019; Mayer, 2020)

(continued on next page)

Table 4 (*continued*)

Sub-category	Skills	Representative codes	Reference
		assurance methodologies.	
Waste management **refers to skills needed to manage the reverse flows of materials.**	Reverse logistics and operational management	Environmental knowledge of transporters, understand logistics and distribution processes, understand processes for reverse logistics, design logistical systems that can take back used products, reverse logistics knowledge, reverse logistics & logistics, managing the daily operation of logistical.	(Bag et al., 2021b; Burger et al., 2019; De los Rios and Charnley, 2017; Halfdanarson and Kvadsheim, 2020; Knudby and Larsen, 2017; Mayer, 2020; Watkins et al., 2021)
	Waste collection and recovery	Manage and recover products at the end-of-life, knowledge of waste and sustainability, waste management principles, use waste as a resource.	(Akyazi et al., 2022; Alarcón et al., 2019; Avadanei et al., 2021; Burger et al., 2019; Demartini et al., 2023; Giannoccaro et al., 2021; Leal et al., 2020; Llorens et al., 2019; Mayer, 2020; Mondal et al., 2023; Sanchez-Romaguera et al., 2016; Whitehill et al., 2022)
	Resource utilization	Prioritise regenerative resources, material reutilisation, resource efficiency.	(Akyazi et al., 2022; Alarcón et al., 2019; Avadanei et al., 2020; Burger et al., 2019; Leal et al., 2020)

processes) (Reichmanis and Sabahi, 2017), or on a product level (through the Life Cycle assessment (LCA) method) (Giannoccaro et al., 2021; Mayer, 2020; Sanchez-Romaguera et al., 2016; Vihma and Moora, 2020). Besides the environmental impact, understanding and using economic sustainability indicators in assessing and comparing circular systems and interventions is also important (Esparragoza and Mesa-Cogollo, 2019). To conduct these assessments effectively, specific environmental management methods and tools are employed, such as LCA, ISO 14001 certification, and sustainability reporting frameworks. Mastering these tools is crucial (Giannoccaro et al., 2021; Walker et al., 2023; Watkins et al., 2021). Additional skills in this category relate to tracking relevant key performance indicators (Akyazi et al., 2022; Giannoccaro et al., 2021) and implement environmental protection measures (Giannoccaro et al., 2021).

3.2.3.2. Clean tech and advanced materials. Compliance and policy management category of skills should enable individuals to effectively develop environmental policies, implement environmental action plans, and monitor them (Akyazi et al., 2022). This should be based on having knowledge (Reichmanis and Sabahi, 2017) and appreciation/awareness (Akyazi et al., 2022; Summerton et al., 2019) on regulations and regulatory processes, as well as on ability to monitor and analyse legal developments (Akyazi et al., 2022; Vihma and Moora, 2020). This knowledge and awareness should be related to specific product registration and commercialization (Reichmanis and Sabahi, 2017) but also to overall EU environmental legislation, national action plans and certifications (Avadanei et al., 2020).

Energy management category encompass a wide range of skills and knowledge that allow individuals and organizations to use energy efficiently and sustainably. This includes understanding the use of energy and related costs (Akyazi et al., 2023), knowledge on monitoring systems of energy consumption (Akyazi et al., 2022). It also involves familiarity with different energy sources such as renewable energy (Akyazi et al., 2022; Sanchez-Romaguera et al., 2016), as well as ways of energy conservation (Akyazi et al., 2022). Knowledge on different approaches and technologies to achieve energy efficiency in a production system and/or through industrial symbiosis enables making informed decisions about investments in energy-saving measures (Akyazi et al., 2023; Lanz et al., 2019). Additional skills and knowledge are related to system optimization and process analysis that can be used to improve understanding of how the industrial symbiosis (IS) process operates, and to determine potential targets for IS process improvement and increased efficiency (Akyazi et al., 2023).

Maintenance and equipment selection category relates more to skills needed for implementing CE principles through slowing resource cycles (for example, via maintenance, repair, etc.) (Giannoccaro et al., 2021). This involves understanding different failure modes of products and processes (De los Rios and Charnley, 2017; Watkins et al., 2021) and developing and implementing preventive and predictive maintenance methods and procedures (Akyazi et al., 2022; Burger et al., 2019; De los Rios and Charnley, 2017; Watkins et al., 2021). This should be supported by knowledge on different equipment and procedures for monitoring of operations to make sure machines work properly (Burger et al., 2019; Giannoccaro et al., 2021). Additional skills related to correcting malfunctions of technological systems include capability for equipment selection (Burger et al., 2019) which is about determining needed tools and equipment to perform the work needed, or to support the deconstruction (Mayer, 2020).

Master in quality and safety embraces skills needed due to variable and uncertain quality of return products and materials in CE context and the safety issues these might cause. This category focuses on the application of quality and safety principles to materials, parts, products, processes, and systems within the CE. This includes skills for performing quality control analysis (Burger et al., 2019), knowledge on quality assurance methodologies (Akyazi et al., 2022), but also performing deconstruction processes in a way that maintains salvaged values (Mayer, 2020). Safety-related skills encompass the ability to ensure that products sold are free from health hazards, as well as knowledge of best practices for maintaining safety at deconstruction sites, with a focus on structural stability and handling hazardous materials (Mayer, 2020).

3.2.3.3. Waste management. Eighteen papers deal with the skills required for effective waste management and resource utilization. This category of skills encompasses diverse aspects of the reverse value chain, covering the initial stages of waste collection and recovery, looking into reverse logistics and operations management skills, and ultimately, utilization of resources skills.

The area of *waste collection and recovery skills* enable participants to gain fundamental understanding of waste management principles and sustainability practices for example in textile sector (Whitehill et al., 2022), in manufacturing in general (Akyazi et al., 2022; Sanchez-Romaguera et al., 2016) and at multiple manufacturing industries (steel, ceramic, water, cement, etc.) (Burger et al., 2019). Furthermore, building these skills also covers more specialized knowledge related to location of job site and mapping of supply chain, layout of job site, and key steps and work sequence at a job site with a purpose of maximizing material yield (Mayer, 2020). This work is mainly based on the building sector (Mayer, 2020). Finally, this area of skills encompasses building competences related to ways of waste transformation (Llorens et al., 2019), as well as techniques for identifying, deconstructing, handling of materials suitable for recovery and finding ways of their recovery (Leal et al., 2020; Mayer, 2020) or discovering materials deemed non-recoverable (Mayer, 2020).

The *reverse logistics and operations management* area offers specialized skillset and expertise necessary to design the reverse logistic system (Knudby and Larsen, 2017) that seamlessly integrates with the overall supply chain, ensuring efficient and effective handling (manufacturing and repair) of discarded materials (Watkins et al., 2021). In addition to this, there is a need for skills to manage the complex dynamics of reverse flows, including managing daily operations and control of sites (Burger et al., 2019; Knudby and Larsen, 2017), including understanding the skills needed (Halfdanarson and Kvadsheim, 2020) and the processes to manage reverse flows (De los Rios and Charnley, 2017). Furthermore, this area of skills enables the participants to understand the effect of bidding on the economic viability of dismantling/deconstructing operations (Mayer, 2020).

In terms of *resource* utilization, the expertise required entails knowledge of various waste recovery strategies, such as reuse, recycling, and reduction of waste (Akyazi et al., 2022). Furthermore, identification of types of waste, including organic and industrial waste (Alarcón et al., 2019), are important skills gained. Additional skills in this category involve prioritizing resources (Burger et al., 2019) and selecting (Leal et al., 2020) the most appropriate processes and practices for optimizing resource usage, maximizing resource recovery, and minimizing resource consumption (Avadanei et al., 2020).

3.3. Future research agenda

Based on the analysis of papers from the SLR, a research agenda focused on six promising areas for future studies on skills is proposed (Fig. 11). This agenda was developed to provide theoretical guidance to help future researchers better direct their scientific contributions in the circular and digital domain. It was created by identifying gaps in the existing literature, which are crucial for advancing new research.

The first research avenue focuses on understanding skills and requalification for the implementation of circular manufacturing. Building upon previous work (e.g., Akyazi et al., 2023; De los Rios and Charnley, 2017), we encourage researchers to concentrate on identifying new skills, competencies, and roles in the industry that require qualified professionals.

The second research avenue highlights a gap in the literature regarding the skills, training programs, and educational approaches across multiple geographic regions. As noticed in Figs. 5 and 6, most research in this area is conducted from the perspective of developed nations. Therefore, there is a promising research direction that considers geographical and regional differences in establishing design teaching programs and professional formalization to acquiring both circular and digital skills (in line with Burger et al., 2019; Halfdanarson and Kvadsheim, 2020; Watkins et al., 2021)).

The third research avenue sheds light on the need for further investigation into the impact of digitalization and essential skills aligned with the phenomenon of digital transformation. It suggests conducting studies to identify skills necessary for a smart CE. Additionally, understanding the social implications of digital transformation on the workforce is crucial, including which skills and professions might become obsolete due to technological advances (Ghobakhloo et al., 2023).

The fourth research avenue is directed at developing and identifying methods and tools that can be applied to facilitate teaching in CE. Exploring how digital technologies can be integrated into education represents a promising avenue for scientific contribution. Additionally, it is crucial to investigate teaching methods that foster knowledge exchange among students from different fields (Knudby and Larsen, 2017) and to explore courses offered on MOOC platforms (Giannoccaro et al., 2021) compared to traditional classroom teaching approaches.

The fifth research avenue focuses on the integration between hard and soft skills. As revealed in this study, digital, technical, and resilience

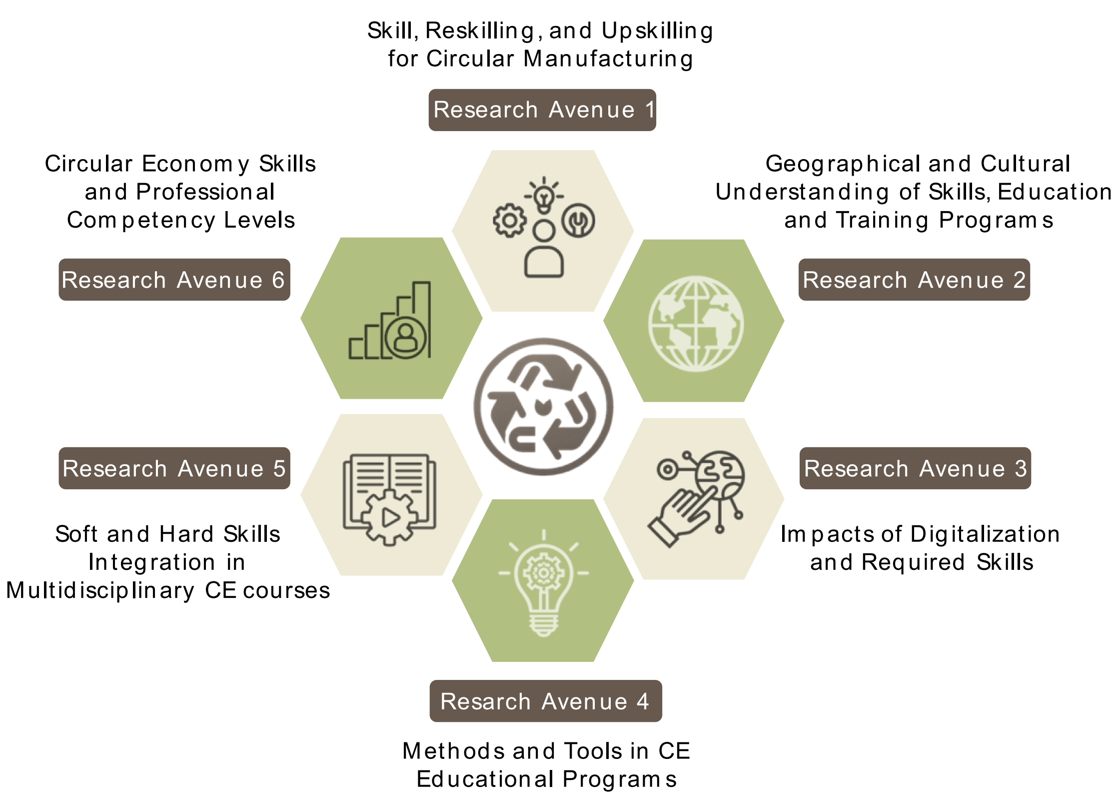

Fig. 11. Future research avenues.

skills are complementary. However, we suggest that future studies provide mechanisms for restructuring educational curricula to incorporate the promotion of these skills. For this, it is necessary to consider the integration of circular principles in courses from various fields of knowledge.

Finally, in addition to understanding this integration, it is relevant to establish levels of professional competence (Pinzone and Taisch, 2023), as evidenced in the sixth research avenue. Therefore, we recommend further work on developing maturity levels based on the categories provided in this paper. As emphasized by (Sumter et al., 2021), the transition may require skills at different stages, making continuous monitoring crucial.

4. Discussion

4.1. Theoretical implications

This study aimed to explore and understand which skills are essential for a CE in the manufacturing sector, including those necessary to leverage DTs for a circular approach. Through a systematic literature analysis, this study revealed 40 skills grouped into three main categories (Technical, Resilience, and Digital Technologies skills). These skills are interdependent, which means that the new generation of professionals should develop not only technical skills but also interpersonal ones, in addition to exploring resources within the digital era. Therefore, the combination and synergy between these skills is crucial for a workforce capable of overcoming the challenges of the twin transition.

Overall, this study offers four main theoretical contributions. These contributions are aimed at scholars who will have access to a systematized knowledge of skills, contributing to the ongoing debate related to CE and industrial digitalization. Possessing this knowledge is essential because without understanding the skills demanded by the job market, academics may struggle to provide high-quality education to improve the inclusion of human intellectual resources and boost employability in the twin transition.

Therefore, the first theoretical contribution is a set of resilience skills. These skills are essential for restructuring current sociotechnical regimes towards more resilient production systems, capable of adapting to disruptions and uncertainties, ensuring long-term sustainability. This study demonstrates a massive demand for labour that knows about establishing circular supply chains and developing new businesses with environmental and social value propositions (in line with Giannoccaro et al., 2021; Walker et al., 2023). Communication skills also prove to be a key factor in the resilience of systems. This includes not only using verbal resources to share information clearly but also visual resources (e.g., project presentations) (Akyazi et al., 2023; Watkins et al., 2021). Indeed, quality communication reduces organizational structure rigidity and increases company departments' integration (Trevisan et al., 2023). This influences the innovation activities for developing circular solutions (Watkins et al., 2021), and allows for greater agility in the recurring changes of industrial systems.

The second theoretical contribution is a systematization of skills associated with business digitalization processes aimed at circularity. Among the skills presented, the application of digital technologies such as the Internet of Things, Cloud, Artificial Intelligence and Big Data are frequently highlighted by scholars. According to previous literature (e.g., Akyazi et al., 2023; Ghobakhloo et al., 2023), it is necessary to train professionals who can include these new technologies in different organizational activities and processes. On the other hand, the literature has not yet explored in depth the skills for automation and robotic development. Automation and robotic development includes not only creating and operationalizing robots (Luo and Qiao, 2023), but also establishing mechanisms for effective human-machine collaboration (Akyazi et al., 2022). In this sense, to foster this type of collaboration, it is also necessary to rely on resilience skills associated with communication, coordination, and decision-making processes. Therefore, this research goes beyond previous literature by showing the synergy between skills in the digital technologies category and those linked to resilience skills, as they intrinsically enable the exploration of the benefits of digital transformation to create new value-delivery approaches and to support industrial automation. Unlike other research that has explored digital skills in the context of startup business models (such as Straub et al., 2023) this study contributes by focusing on digital skills oriented toward the manufacturing sector. In doing so, it enriches the ongoing discussion (see Akyazi et al., 2022; Luo and Qiao, 2023) on essential skills for implementing circular strategies in Industry 4.0.

The third contribution is enriching the theoretical foundation on the specialized/technical skills most critical for circular manufacturing in the twin transition. This study revealed that according to the literature (i.e Leal et al., 2020; Reichmanis and Sabahi, 2017; Sassanelli et al., 2020), the ability to design circular products is the most crucial, requiring professionals to have comprehensive knowledge of design across all lifecycle stages. In particular, this study reinforces the need to integrate eco-design strategies with engineering knowledge. Such strategies encompass a variety of expertise, such as circular design for longevity, design using recyclable and waste materials, design for remanufacturing and multiple-use cycles (Avadanei et al., 2021; De los Rios and Charnley, 2017; Rizzo et al., 2017). This work advances the body of knowledge, showing that in addition to knowing how to idealize and design more circular products, it is also essential to pay fair attention to techniques for assessing environmental impacts and monitoring circular indicators. Professionals should have the skills to understand which tools and methods are best applicable according to the nuances of each business solution (Giannoccaro et al., 2021; Walker et al., 2023). To achieve this, it is possible to rely on digital skills, such as the application of Industry 4.0 technologies. Therefore, this study also emphasizes the intrinsic importance of combining technical skills with technological innovation.

Finally, the fourth theoretical contribution consists of presenting a research agenda encompassing six promising areas for developing new studies. This strategic agenda aims to guide new scientific efforts in research fields integrating CE and Industry 4.0, which require special attention. By providing this agenda, the study acknowledges the continuous need to update skills for an effective twin transition. Specifically, more studies are recommended on the impact of digitalization on the human domain, the multi-geographical and cultural understanding of skills, and the establishment of maturity levels for these skills as industrial systems progress through the transition.

4.2. Practical implications

This study provides valuable insights for practitioners, including industry managers/designers and educational instructors aiming to develop professional courses aligned with market needs.

From an industrial point of view, managers and designers can better understand the skills and training needed to upskill professionals in the manufacturing sector. Considering that competent employees are more likely to develop innovative solutions (Behl et al., 2024), the set of skills mapped in this work can direct the search for new ways of training human intellectual capital. Also, knowing the critical skills allows managers to have greater clarity about which aspects need to be fostered within the organizational team, developing strategies to recruit and train new talent. The study shows that organizational structures require training program implementation skills. Therefore, this work also contributes to the development of internal technical training plans and the development of interpersonal skills.

For educators interested in incorporating knowledge of the CE and digital transformation into their teaching, this study provides valuable insights for designing courses and academic programs to educate both students and professionals. Developing dedicated courses for each identified category or subcategory is feasible. For instance, within the subcategory of cross-cutting, the skills can serve as a foundation for creating specific modules within courses. In this case, modules promoting research and writing skills could be developed, or to teach the creation of organizational training programs that facilitate transitions within companies. The provided skills list can also enable educators to assess their current skills and update them to meet contemporary educational demands. According to Watkins et al. (2021), it is essential for academics to be adequately trained to impart knowledge to students effectively.

4.3. Policy implications

This study also has policy implications. First, standardization of skills needed for CE and digital transition can be triggered by this work. Governments can create mechanisms to promote different skills, such as complementary professional training programs and establishing collaboration networks among the public, industry sector and society. Policymakers can act positively through initiatives that encourage teaching skills from basic educational formation. According to Torreggiani et al. (2021) skills such as communication and creativity are not necessarily inherent to the individual. Therefore, strategies, even in primary education, can support developing soft skills that reduce the gap between technical and interpersonal skills required by the job market. Additionally, Policymakers can use this study as scientific support to guide the development of social policies to reduce the adverse effects of digitalization on job losses. Through the skill set provided in this study, governments can create opportunities through programs, projects, and technical courses for the digital inclusion of individuals while fostering programming, automation, and robotics development skills. Such initiatives can support the inclusion of future workers rather than their replacement as technological innovations progress.

5. Conclusion

Grounding on a systematic literature review, this paper investigated the required professional skills for a successful transition to the CE in the manufacturing sector. The primary contribution of this study is to provide a comprehensive synthesis of skills, acknowledging the current changes resulting from the circular and digital transformations experienced by firms. A set of 40 skills categorized into three dimensions was identified: Resilience skills, Digital technologies skills, and Specialized/technical skills. The literature review confirmed the critical value of resilience skills for a CE, especially related to adapting and designing circular business models and restructuring supply chains to the recent transformations that socio-technical systems are undergoing. However, among all the skills identified, the one that stood out most is in the specialized/technical dimension that corresponds to the design of circular products, including a variety of strategies to allow products to reduce their impacts throughout the whole lifecycle and to return them to production systems. This study also sheds light on skills for implementing digital technologies for circularity, ranging from skills to digitally transform businesses to innovation based on robotic automation.

However, inherently to any scientific study, this research has some limitations that can be converted in future studies directions. First, the findings obtained are exclusively based on a literature review of journal and conference papers. Due to publication selection bias, business reports or data collected directly through interviews with market professionals were not analysed. Future work could include an investigation of practitioners' perspective, through dedicated interviews and surveys, about the skills and job profiles required to ease their path into the twin transition. Therefore, a further step in this research is to compare theoretical insights with empirical data to understand whether the skills required for the CE, as highlighted by both theory and practice, are currently covered by courses available on the market. In addition, case studies in specific manufacturing sectors could be conducted, refining the skill set mapped in this study. Furthermore, this work did not examine the differences and similarities in terms of skills required according to each nation's geographic and economic specificities. Professionals from emerging countries may require different skills from developed countries, which are already more advanced in transitioning to the CE. A market analysis could be also conducted to evaluate whether the already available training programs match practitioners' requirements. Finally, new studies can focus on developing training programs and prioritizing skills according to the nature of current organizational demands.

CRediT authorship contribution statement

Adriana Hofmann Trevisan: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Federica Acerbi:** Writing – review & editing, Methodology, Formal analysis. **Iskra Dukovska-Popovska:** Writing – review & editing, Writing – original draft, Formal analysis. **Sergio Terzi:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Claudio Sassanelli:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization, Writing – original draft.

Declaration of competing interest

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

Data availability

The data that has been used is confidential.

Acknowledgments

This work was supported by the Coordination for the Improvement of Higher Education Personnel – Brazil (CAPES) – Financing Code 001. It was also co-funded by the European Union (CERES project (n.101111684)). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Education and Culture Executive Agency (EACEA). Neither the European Union nor EACEA can be held responsible for them.

Project funded under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.3 - Call for tender No. 341of March 15, 2022 of Italian Ministry of University and Research funded by the European Union– NextGenerationEU. AwardNumber: PE00000004, Concession Decree No. 1551 of October 11, 2022 adopted by the Italian Ministry of University and Research, CUP D93C22000920001, MICS (Made in Italy - Circular and Sustainable).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.143603.

References

Acerbi, F., Rossi, M., Terzi, S., 2022. Identifying and assessing the required I4.0 skills for manufacturing companies' workforce. Front. Manuf. Technol. 2, 1–19. https://doi.org/10.3389/fmtec.2022.921445.

Acerbi, F., Taisch, M., 2020. A literature review on circular economy adoption in the manufacturing sector. J. Clean. Prod. 273, 123086 https://doi.org/10.1016/j.jclepro.2020.123086.

Ada, E., Kazancoglu, Y., Mangla, S.K., Aydin, U., 2023. Barriers to cement industry towards circular economy. Int. J. Math. Eng. Manag. Sci. 8, 612–631. https://doi.org/10.33889/IJMEMS.2023.8.4.035.

Akyazi, T., Goti, A., Bayón, F., Kohlgrüber, M., Schröder, A., 2023. Identifying the skills requirements related to industrial symbiosis and energy efficiency for the European process industry. Environ. Sci. Eur. 35 https://doi.org/10.1186/s12302-023-00762-z.

Akyazi, T., Val, P. Del, Goti, A., Oyarbide, A., 2022. Identifying future skill requirements of the job profiles for a sustainable European manufacturing industry 4.0. Recycling 7. https://doi.org/10.3390/recycling7030032.

Alarcón, J., Palma, M., Navarrete, L., Hernández, G., Llorens, A., 2019. Educating on circular economy and diy materials: how to introduce these concepts in primary school students? EDULEARN19 Proc 1, 10083–10088. https://doi.org/10.21125/edulearn.2019.2523.

Alonso-Muñoz, S., González-Sánchez, R., Siligardi, C., García-Muiña, F.E., 2021. Building exploitation routines in the circular supply chain to obtain radical innovations. Resources 10, 1–18. https://doi.org/10.3390/resources10030022.

Andrews, D., 2015. The circular economy, design thinking and education for sustainability. Local Econ. 30, 305–315. https://doi.org/10.1177/0269094215578226.

Avadanei, M., Belakova, D., Ortega Martínez, R., Souto, R., Sivevska, N., Mouazan, E., 2021. E-learning platform of eco-design in textile and fashion sectors towards a circular textile. In: The 17th International Scientific Conference ELearning and Software for Education, pp. 72–79.

Avadanei, M., Olary, S., Ionescu, I., Ciobanu, L., Alexa, L., Luca, A., Ursache, M., Olmos, M., Aslanidis, T., Belakova, D., Silva, C., 2020. ICT new tools for a sustainable textile and clothing industry. Ind. Textil. 71, 504–512. https://doi.org/10.35530/IT.071.05.1811.

Bag, S., Pretorius, J.H.C., Gupta, S., Dwivedi, Y.K., 2021a. Role of institutional pressures and resources in the adoption of big data analytics powered artificial intelligence, sustainable manufacturing practices and circular economy capabilities. Technol. Forecast. Soc. Change 163, 120420. https://doi.org/10.1016/j.techfore.2020.120420.

Bag, S., Yadav, G., Dhamija, P., Kataria, K.K., 2021b. Key resources for industry 4.0 adoption and its effect on sustainable production and circular economy: an empirical study. J. Clean. Prod. 281, 125233 https://doi.org/10.1016/j.jclepro.2020.125233.

Bai, C., Quayson, M., Sarkis, J., 2021. COVID-19 pandemic digitization lessons for sustainable development of micro-and small- enterprises. Sustain. Prod. Consum. 27, 1989–2001. https://doi.org/10.1016/j.spc.2021.04.035.

Beducci, E., Acerbi, F., Pinzone, M., Taisch, M., 2024. Unleashing the role of skills and job profiles in circular manufacturing. J. Clean. Prod. 141456 https://doi.org/10.1016/j.jclepro.2024.141456.

Behl, A., Sampat, B., Gaur, J., Pereira, V., Laker, B., Shankar, A., Shi, P., Roohanifar, M., 2024. Can gamification help green supply chain management firms achieve sustainable results in servitized ecosystem? An empirical investigation. Technovation 129, 102915. https://doi.org/10.1016/j.technovation.2023.102915.

Burger, M., Stavropoulos, S., Ramkumar, S., Dufourmont, J., van Oort, F., 2019. The heterogeneous skill-base of circular economy employment. Res. Pol. 48, 248–261. https://doi.org/10.1016/j.respol.2018.08.015.

Can Saglam, Y., 2023. Does green intellectual capital matter for reverse logistics competency? The role of regulatory measures. J. Intellect. Cap. 24, 1227–1247. https://doi.org/10.1108/JIC-07-2022-0147.

Cappelletti, F., Rossi, M., Germani, M., 2022. How de-manufacturing supports circular economy linking design and EoL - a literature review. J. Manuf. Syst. 63, 118–133. https://doi.org/10.1016/j.jmsy.2022.03.007.

Cassells, S., Lewis, K.V., 2017. Environmental management training for micro and small enterprises: the missing link? J. Small Bus. Enterprise Dev. 24, 297–312. https://doi.org/10.1108/JSBED-09-2016-0145.

Cavallini, S., Soldi, R., 2023. Europe's Circular Economy and its Pact for Skills: Working Together for an Inclusive and Job-Rich Transition?.

Chen, Y., 2022. Advantages of 3D printing for circular economy and its influence on designers. Proc. Des. Soc. 2, 991–1000. https://doi.org/10.1017/pds.2022.101.

Colangelo, G., Facchini, F., Ranieri, L., Starace, G., Vitti, M., 2023. Assessment of carbon emissions' effects on the investments in conventional and innovative waste-to-energy treatments. J. Clean. Prod. 388, 135849 https://doi.org/10.1016/j.jclepro.2023.135849.

Cozma, P., Smaranda, C., Comăniţă, E.D., Roşca, M., Ghinea, C., Campean, T., Gavrilescu, M., 2020. Knowledge transfer in university-industry research collaboration for extending life cycle of materials in the context of circular economy. Environ. Eng. Manag. J. 19, 2097–2112. https://doi.org/10.30638/eemj.2020.198.

Dąbrowska, J., Almpanopoulou, A., Brem, A., Chesbrough, H., Cucino, V., Di Minin, A., Giones, F., Hakala, H., Marullo, C., Mention, A.L., Mortara, L., Nørskov, S., Nylund, P.A., Oddo, C.M., Radziwon, A., Ritala, P., 2022. Digital transformation, for better or worse: a critical multi-level research agenda. R D Manag. 1–25 https://doi.org/10.1111/radm.12531.

De los Rios, I.C., Charnley, F.J.S., 2017. Skills and capabilities for a sustainable and circular economy: the changing role of design. J. Clean. Prod. 160, 109–122. https://doi.org/10.1016/j.jclepro.2016.10.130.

de Miranda, S.S.F., Córdoba-Roldán, A., Aguayo-González, F., Ávila-Gutiérrez, M.J., 2021. Neuro-competence approach for sustainable engineering. Sustain. Times 13. https://doi.org/10.3390/su13084389.

Demartini, M., Ferrari, M., Govindan, K., Tonelli, F., 2023. The transition to electric vehicles and a net zero economy: a model based on circular economy, stakeholder theory, and system thinking approach. J. Clean. Prod. 410, 137031 https://doi.org/10.1016/j.jclepro.2023.137031.

Despeisse, M., Baumers, M., Brown, P., Charnley, F., Ford, S.J., Garmulewicz, A., Knowles, S., Minshall, T.H.W., Mortara, L., Reed-Tsochas, F.P., Rowley, J., 2017. Unlocking value for a circular economy through 3D printing: a research agenda. Technol. Forecast. Soc. Change 115, 75–84. https://doi.org/10.1016/j.techfore.2016.09.021.

Dwivedi, A., Moktadir, M.A., Chiappetta Jabbour, C.J., de Carvalho, D.E., 2022. Integrating the circular economy and industry 4.0 for sustainable development: implications for responsible footwear production in a big data-driven world. Technol. Forecast. Soc. Change 175. https://doi.org/10.1016/j.techfore.2021.121335.

Elo, S., Kyngäs, H., 2008. The qualitative content analysis process. J. Adv. Nurs. 62, 107–115. https://doi.org/10.1111/j.1365-2648.2007.04569.x.

Esparragoza, I., Mesa-Cogollo, J., 2019. A case study approach to introduce circular economy in sustainable design education. Proc. 21st Int. Conf. Eng. Prod. Des. Educ. Towar. a New Innov. Landscape. https://doi.org/10.35199/epde2019.3. E PDE 2019.

European Commission, 2020. Circular Economy Action Plan.

European Commission, 2019. The European Green Deal. Communication from the commission to the european parliament, the european council, the council, the european economic and social committee and the committee of the regions. Eur. Community.

Favi, C., Germani, M., Mandolini, M., Marconi, M., 2016. Disassembly knowledge classification and potential application: a preliminary analysis on a washing machine. Proc. ASME Des. Eng. Tech. Conf. 4, 1–12. https://doi.org/10.1115/DETC2016-59514.pdf.

Fernandes, A., Cardoso, A., Sousa, A., Buttunoi, C., Silva, G., Cardoso, J., Sá, J., Oliveira, M., Rocha, M., Azevedo, R., Baldaia, R., Leite, R., Pernbert, S., Range, B., Alves, J., 2018. We won ' t waste you , design for social inclusion. Conf. Port. Soc. Eng. Educ.

Findik, D., Tirgil, A., Özbuğday, F.C., 2023. Industry 4.0 as an enabler of circular economy practices: evidence from European SMEs. J. Clean. Prod. 410 https://doi.org/10.1016/j.jclepro.2023.137281.

Ghobakhloo, M., Iranmanesh, M., Foroughi, B., Babaee Tirkolaee, E., Asadi, S., Amran, A., 2023. Industry 5.0 implications for inclusive sustainable manufacturing: an evidence-knowledge-based strategic roadmap. J. Clean. Prod. 417, 138023 https://doi.org/10.1016/j.jclepro.2023.138023.

Giannoccaro, I., Ceccarelli, G., Fraccascia, L., 2021. Features of the higher education for the circular economy: the case of Italy. Sustain. Times 13, 1–26. https://doi.org/10.3390/su132011338.

Halfdanarson, J., Kvadsheim, N.P., 2020. Knowledge and practices towards sustainability and circular economy transitions: a Norwegian manufacturing perspective. IFIP Adv. Inf. Commun. Technol. 591 IFIP, 546–553. https://doi.org/10.1007/978-3-030-57993-7_62.

Isaksson, O., Hallstedt, S.I., Rönnbäck, A.Ö., 2018. Digitalisation, sustainability and servitisation: consequences on product development capabilities in manufacturing firms. Proc. Nord. Des. Era Digit. Nord. 2018.

Kim, J., Lee, J.H., 2022. Development of sustainable fashion design education program. Arch. Des. Res. 35, 149–173. https://doi.org/10.15187/adr.2022.11.35.4.149.

Kinkel, S., Baumgartner, M., Cherubini, E., 2022. Prerequisites for the adoption of AI technologies in manufacturing – evidence from a worldwide sample of manufacturing companies. Technovation 110, 102375. https://doi.org/10.1016/j.technovation.2021.102375.

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005.

Knudby, T., Larsen, S.B., 2017. The circular economy in practice-focused undergraduate engineering education. In: Proceedings of the 45th SEFI Annual Conference 2017, pp. 1268–1275. https://doi.org/10.36661/2596-142x.2019v1i1.10902.

Kopnina, H., 2019. Green-washing or best case practices? Using circular economy and Cradle to Cradle case studies in business education. J. Clean. Prod. 219, 613–621. https://doi.org/10.1016/j.jclepro.2019.02.005.

Kristoffersen, E., Blomsma, F., Mikalef, P., Li, J., 2020. The smart circular economy: a digital-enabled circular strategies framework for manufacturing companies. J. Bus. Res. 120, 241–261. https://doi.org/10.1016/j.jbusres.2020.07.044.

Lanz, M., Nylund, H., Lehtonen, T., Juuti, T., Rattya, K., 2019. Circular economy in integrated product and production development education. Procedia Manuf. 33, 470–476. https://doi.org/10.1016/j.promfg.2019.04.058.

Leal, D., Alves, J.L., Fernandes, A., Rangel, B., 2020. We won't waste you:a research project to introduce waste and social sustainability in design thinking. IEEE Glob. Eng. Educ. Conf. EDUCON 1959–1963. https://doi.org/10.1109/EDUCON45650.2020.9125180, 2020-April.

Liu, Q., Trevisan, A.H., Yang, M., Mascarenhas, J., 2022. A framework of digital technologies for the circular economy: digital functions and mechanisms. Bus. Strat. Environ. 1–22 https://doi.org/10.1002/bse.3015.

Llorens, A., Alarcón, J., Di Bartolo, C., 2019. Teaching for a sustainable awareness, case study. EDULEARN19 Proc 1, 10159–10165. https://doi.org/10.21125/edulearn.2019.2543.

Luo, H., Qiao, H., 2023. Exploring the impact of industrial robots on firm innovation under circular economy umbrella: a human capital perspective. Manag. Decis. https://doi.org/10.1108/MD-02-2023-0285.

Manfredi, L.R., Engineering, M., Design, P., 2019. Board 92 : MAKER : Developing Compostable Composites : A Multi-Disciplinary Approach towards Sustainable Material Adoption WIP/MAKER : Developing Compostable Composites : A Multi-Disciplinary Approach towards Sustainable Material Adoption.

Mayer, M., 2020. Material recovery certification for construction workers. Build. Cities 1, 550–564. https://doi.org/10.5334/bc.58.

Merriam-Webster dictionary, 2024. Skill [WWW Document]. URL. https://www.merriam-webster.com/dictionary/skill. (Accessed 28 February 2024).

Miles, M.B., Huberman, M., Saldaña, J., 2014. Qualitative Data Analysis: a Methods Sourcebook, Third. ed. Sage Publications.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., 2009. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. BMJ 339, 332–336. https://doi.org/10.1136/bmj.b2535.

Mondal, S., Singh, S., Gupta, H., 2023. Green entrepreneurship and digitalization enabling the circular economy through sustainable waste management - an exploratory study of emerging economy. J. Clean. Prod. 422, 138433 https://doi.org/10.1016/j.jclepro.2023.138433.

Monyaki, N.C., Cilliers, R., 2023. Defining drivers and barriers of sustainable fashion manufacturing: perceptions in the global South. Sustain. Times 15. https://doi.org/10.3390/su151310715.

Mottese, A.F., Parisi, F., Marciano, G., Giacobello, F., Franzone, M., Sabatino, G., Di Bella, M., Italiano, F., Tripodo, A., 2021. A flipped classroom experience: towards the knowledge of new ecofriendly materials named "geopolymers.". AAPP - Atti della Accad. Peloritana dei Pericolanti Cl. Sci. Fis. Mat. Nat. 99, 1–18. https://doi.org/10.1478/AAPP.99S1A35.

Nobre, G.C., Tavares, E., 2020. Assessing the role of big data and the internet of things on the transition to circular economy: Part I an extension of the ReSOLVE framework proposal through a literature review. Johnson Matthey Technol. Rev. 64, 19–31. https://doi.org/10.1595/205651319x15643932870488.

Onpraphai, T., Jintrawet, A., Keoboualapha, B., Khuenjai, S., Guo, R., Wang, J., Fan, J., 2021. Sustaining biomaterials in bioeconomy: roles of education and learning in mekong river basin. Forests 12, 1–12. https://doi.org/10.3390/f12121670.

Pereira, A., Fredriksson, C., 2015. Teaching circularity using CES EduPack. Proc. 43rd SEFI Annu. Conf. 2015 - Divers. Eng. Educ. An Oppor. to Face New Trends Eng. SEFI 2015, 1–8.

Pinzone, M., Taisch, M., 2023. Key competencies for circular manufacturing. Hum. Asp. Adv. Manuf. 80, 120–125. https://doi.org/10.54941/ahfe1003514.

Raeva, A., Usenyuk-Kravchuk, S., Raev, A., Surina, I., Fionova, M., 2021. Augmenting design education for sustainability through field exploration: an experience of learning from DIY practices in a rural community. Sustain. Times 13. https://doi.org/10.3390/su132313017.

Ranjbari, M., Saidani, M., Shams Esfandabadi, Z., Peng, W., Lam, S.S., Aghbashlo, M., Quatraro, F., Tabatabaei, M., 2021. Two decades of research on waste management in the circular economy: insights from bibliometric, text mining, and content analyses. J. Clean. Prod. 314, 128009 https://doi.org/10.1016/j.jclepro.2021.128009.

Rehman, S.U., Giordino, D., Zhang, Q., Alam, G.M., 2023. Twin transitions & industry 4.0: unpacking the relationship between digital and green factors to determine green competitive advantage. Technol. Soc. 73, 102227 https://doi.org/10.1016/j.techsoc.2023.102227.

Reichmanis, E., Sabahi, M., 2017. Life cycle inventory assessment as a sustainable chemistry and engineering education tool. ACS Sustain. Chem. Eng. 5, 9603–9613. https://doi.org/10.1021/acssuschemeng.7b03144.

Rizzo, S., Cappellaro, F., Accorsi, M., Orsini, F., Gianquinto, G., Bonoli, A., 2017. Co-design for a circular approach in green technologies: adaptation of reused building material as growing substrate for soilless cultivation of lettuce. Environ. Eng. Manag. J. 16, 1775–1780. https://doi.org/10.30638/eemj.2017.193.

Rosa, P., Sassanelli, C., Urbinati, A., Chiaroni, D., Terzi, S., 2020. Assessing relations between Circular Economy and Industry 4.0: a systematic literature review. Int. J. Prod. Res. 58, 1662–1687. https://doi.org/10.1080/00207543.2019.1680896.

Sanchez-Romaguera, V., Dobson, H.E., Bland Tomkinson, C., 2016. Educating engineers for the circular economy. 9th Int. Conf. Eng. Educ. Sustain. Dev. Bruges. Belgium.

Sassanelli, C., Garza-Reyes, J.A., Liu, Y., de Jesus Pacheco, D.A., Luthra, S., 2023. The disruptive action of Industry 4.0 technologies cross-fertilizing Circular Economy throughout society. Comput. Ind. Eng. 183 https://doi.org/10.1016/j.cie.2023.109548.

Sassanelli, C., Urbinati, A., Rosa, P., Chiaroni, D., Terzi, S., 2020. Addressing circular economy through design for X approaches: a systematic literature review. Comput. Ind. 120, 103245 https://doi.org/10.1016/j.compind.2020.103245.

Spreafico, C., Landi, D., 2022. Using product design strategies to implement circular economy: differences between students and professional designers. Sustain. Times 14. https://doi.org/10.3390/su14031122.

Straub, L., Hartley, K., Dyakonov, I., Gupta, H., van Vuuren, D., Kirchherr, J., 2023. Employee skills for circular business model implementation: a taxonomy. J. Clean. Prod. 410, 137027 https://doi.org/10.1016/j.jclepro.2023.137027.

Summerton, L., Clark, J.H., Hurst, G.A., Ball, P.D., Rylott, E.L., Carslaw, N., Creasey, J., Murray, J., Whitford, J., Dobson, B., Sneddon, H.F., Ross, J., Metcalf, P., McElroy, C. R., 2019. Industry-informed workshops to develop graduate skill sets in the circular economy using systems thinking. J. Chem. Educ. 2959–2967. https://doi.org/10.1021/acs.jchemed.9b00257.

Sumter, D., Bakker, C., Balkenende, R., 2018. The role of product design in creating circular business models: a case study on the lease and refurbishment of baby strollers. Sustain. Times 10. https://doi.org/10.3390/su10072415.

Sumter, D., de Koning, J., Bakker, C., Balkenende, R., 2021. Key competencies for design in a circular economy: exploring gaps in design knowledge and skills for a circular economy. Sustain. Times 13, 1–15. https://doi.org/10.3390/su13020776.

The Ellen MacArthur Foundation, 2013. Towards the Circular Economy Economic and Business Rationale for an Accelerated Transition.

Torreggiani, A., Zanelli, A., Degli Esposti, A., Polo, E., Dambruoso, P., Lapinska-Viola, R., Forsberg, K., Benvenuti, E., 2021. How to prepare future generations for the challenges in the raw materials sector, minerals. Metals and Materials Series. Springer International Publishing. https://doi.org/10.1007/978-3-030-65489-4_27.

Tranfield, D., Denyer, D., Smart, P., 2003. Towards a methodology for developing evidence-informed management knowledge by means of systematic review. Br. J. Manag. 14, 207–222. https://doi.org/10.2307/249689.

Trevisan, A.H., Lobo, A., Guzzo, D., Gomes, L.A. de V., Mascarenhas, J., 2023. Barriers to employing digital technologies for a circular economy: a multi-level perspective. J. Environ. Manag. 332, 117437 https://doi.org/10.1016/j.jenvman.2023.117437.

Uhrenholt, J.N., Kristenses, J.H., Adamsen, S., Jensen, S.F., Colli, M., Waehrens, B.V., 2022. Twin transition: synergies between circular economy and internet of things – a study of Danish manufacturers. J. Circ. Econ. 1, 1–19. https://doi.org/10.55845/hrgw4040.

Ul-Durar, S., Awan, U., Varma, A., Memon, S., Mention, A.L., 2023. Integrating knowledge management and orientation dynamics for organization transition from eco-innovation to circular economy. J. Knowl. Manag. 27, 2217–2248. https://doi.org/10.1108/JKM-05-2022-0424.

Vihma, M., Moora, H., 2020. Potential of circular design in Estonian SMEs and their capacity to push it. Environ. Clim. Technol. 24, 94–103. https://doi.org/10.2478/rtuect-2020-0088.

Vitti, M., Facchini, F., Mummolo, G., 2024. Assessing the decarbonisation potential of waste-to-hydrogen routes in the energy transition phase: an environmental analytical model. J. Clean. Prod. 457, 142345 https://doi.org/10.1016/j.jclepro.2024.142345.

Vogt Duberg, J., Johansson, G., Sundin, E., Kurilova-Palisaitiene, J., 2020. Prerequisite factors for original equipment manufacturer remanufacturing. J. Clean. Prod. 270, 122309 https://doi.org/10.1016/j.jclepro.2020.122309.

Walker, A.M., Simboli, A., Vermeulen, W.J.V., Raggi, A., 2023. A dynamic capabilities perspective on implementing the Circular Transition Indicators: a case study of a multi-national packaging company. Corp. Soc. Responsib. Environ. Manag. 30, 2679–2692. https://doi.org/10.1002/csr.2487.

Watkins, M., Casamayor, J.L., Ramirez, M., Moreno, M., Faludi, J., Pigosso, D.C.A., 2021. Sustainable product design education: current practice. She Ji 7, 611–637. https://doi.org/10.1016/j.sheji.2021.11.003.

Weick, M., Ray, N., 2022. EY: Regulatory Landscape of the Circular Economy.

Whitehill, S., Hayles, C.S., Jenkins, S., Taylour, J., 2022. Engagement with higher education surface pattern design students as a catalyst for circular economy action. Sustain. Times 14. https://doi.org/10.3390/su14031146.

Wohlin, C., 2014. Guidelines for snowballing in systematic literature studies and a replication in software engineering. ACM Int. Conf. Proceeding Ser. https://doi.org/10.1145/2601248.2601268.