Received: 7 November 2022 | Revised: 13 January 2023 | Accepted: 7 February 2023
DOI: 10.1002/bse.3388

RESEARCH ARTICLE

Business Strategy and the Environment WILEY

The role of digital technologies in supporting the implementation of circular economy practices by industrial small and medium enterprises

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Funding information
T.I.M.E. Association

Abstract

The adoption of Industry 4.0's digital technologies can enable the implementation of circular economy practices. Nonetheless, current indications for industrial practitioners on how to exploit the broad set of technologies for circular transition appear unclear. This issue is even more challenging for small and medium enterprises, which are typically endowed with more limited resources than larger firms and are characterised by both a digital and circular divide. This present study contributes to the academic debate by offering an exploratory empirical analysis—based on semi-structured interviews—that involved 10 Italian industrial small and medium enterprises to deepen the knowledge of the supporting role played by digital technologies in implementing circular economy practices by small and medium enterprises, also considering the potential synergies among such technologies. Results are of interest also to industrial decision-makers, allowing them to exploit their firms' resources towards the adoption of those digital technologies that could be more effective to foster the circular transition.

KEYWORDS
circular economy, digital technologies, industry 4.0, practices, SMEs

1 | INTRODUCTION

Challenges such as climate change and resource depletion are deeply shaping society (Cagno et al., 2023; Govindan & Hasanagic, 2018), favoring the emergence of new needs and evolutionary trends in the industry (Kumar et al., 2019). Among them, Circular Economy (CE) and Industry 4.0 have emerged as crucial transitions that are currently under discussion among scholars, practitioners, and policymakers (Gupta et al., 2021).

The CE concept entails a shift from the traditional linear production and consumption mode to a circular one, by closing the material loop to decrease material extraction and waste disposal (Moreno et al., 2019). It also replaces the "end-of-life" concept with reducing, alternatively reusing, recycling, and recovering materials in

Abbreviations: AM, additive manufacturing; AR, augmented reality; BDA, big data analytics; CE, circular economy; CEO, chief executive officer; CLOUD, Cloud technologies; CYB, cybersecurity and blockchain; DTs, digital technologies; ERP, enterprise resource planning; HSI, horizontal systems integration; HVSYS, horizontal and vertical systems integration; IoT, internet of things; MES, manufacturing execution system; PMS, production management systems; ROBs, autonomous robots; SIM, simulation; SMEs, small and medium enterprises; VSI, vertical systems integration.

production/distribution and consumption processes. CE principles can be addressed at different levels, namely, microlevel (single firm), mesolevel (industrial systems and networks), and macrolevel (society or country) (Kirchherr et al., 2017). At the microlevel, to foster the transition towards CE, firms have to rethink the logics through which they create, deliver, and capture value within their business model (Franzò et al., 2021) by implementing a set of CE practices (Elf et al., 2022; Masi et al., 2018). The implementation of such practices is affected by several factors, working as enablers or barriers (Urbinati et al., 2021).

Industry 4.0 focuses on developing intelligent factories and products, entailing opportunities for enhanced performance for production activities, organizational strategies, business models, and skills (Massaro et al., 2021), also facilitating interactions among different stakeholders (Upadhyay et al., 2021). In this domain, digital technologies (DTs), such as the Internet of Things (IoT), big data analytics (BDA), and additive manufacturing (AM), have been recognised as fundamental tools for the Industry 4.0 transition (Ardito et al., 2019).

The CE and DTs topics have been largely investigated as standing alone; nonetheless, they recently started to be simultaneously addressed (Cagno et al., 2021), specifically trying to understand the support that DTs can offer to the circular transition (Khatami et al., 2023), with a specific focus on the implementation of CE practices (di Maria et al., 2022; Laskurain-Iturbe et al., 2021). In particular, there is an overall agreement that DTs are crucial for enabling the implementation of CE practices in the industry (Ertz et al., 2022; Patyal et al., 2022). The extant literature addresses such a relationship from both a conceptual and an empirical perspective. Efforts are indeed dedicated to trying to understand how DTs—in general (Nascimento et al., 2019; Rosa et al., 2020; Uçar et al., 2020) or with reference to specific DTs (Hettiarachchi, Brandenburg, & Seuring, 2022; Rejeb et al., 2022; Wilson et al., 2022)—can support the implementation of specific CE practices, such as recycling (Kintscher et al., 2020) or remanufacturing (Bag, Dhamija, et al., 2021). Nonetheless, indications for practitioners on how to exploit the broad set of available DTs for the industrial circular transition remain unclear (Massaro et al., 2021), leading to blurred implications on the relationship between DTs and CE for proper environmental management (Gebhardt et al., 2022; Ghoreishi & Happonen, 2022). Therefore, more guidance is needed to understand how DTs can support industrial firms in their circular transition, by favoring the implementation of CE practices (Centobelli et al., 2020; Neligan et al., 2022).

Clear indications and guidance are even more relevant to foster the circular transition by small and medium enterprises (SMEs). Indeed, even though the circular transition can be pivotal for SMEs' survival and growth (Zhu et al., 2022), many SMEs are lagging (Takacs et al., 2022), leading to a *circular divide*. Furthermore, SMEs are usually more resource-constrained than larger firms, e.g. in terms of managerial competences and financial resources (Micheli et al., 2021), and they often lack appropriate know-how and support towards innovation (Albats et al., 2019; Mitchell et al., 2020; Spithoven et al., 2013). Accordingly, they tend to adopt and use fewer DTs than large firms (Stentoft et al., 2021; Tamvada et al., 2022), leading to a *digital divide* (Sommer, 2015).

The extant literature provides some indications of how DTs can support the circular transition by industrial SMEs, but efforts appear rare and scattered. In particular, valuable contributions only consider selected DTs or CE practices. However, for a proper understanding of the role that DTs can play in supporting the circular transition by industrial SMEs, there is the need to investigate such a relationship from an integrated and holistic perspective (Cagno et al., 2021) and, above all, from an empirical viewpoint (Awan, Sroufe, & Shahbaz, 2021). This means that the investigation should encompass as many as possible, DTs and CE practices, rather than focusing on a limited set of DTs or CE practices (holistic perspective), also considering the possible synergies among different DTs in supporting the circular transition (integrated perspective). Moreover, to the best of the authors' knowledge, contributions that empirically investigate the role of DTs in supporting the implementation of CE practices by industrial SMEs from both a holistic and integrated perspective are still lacking. Therefore, this study aims to contribute to this direction by answering the following research question:

> RQ. What is the role of DTs in supporting the implementation of CE practices by industrial SMEs?

To answer the research question, an exploratory empirical investigation involving 10 Italian manufacturing SMEs has been carried out, through the conduction of semi-structured interviews, which sheds light on the supporting role played by DTs in the implementation of CE practices by industrial SMEs, also providing preliminary evidence on the support offered by the concurrent adoption (i.e. integration) of different DTs for the circular transition.

The remainder of the paper is as follows. A literature background for the study is offered (Section 2), along with the methods employed for the empirical analysis (Section 3). The results of the empirical analysis are then presented and extensively discussed against the extant literature (Section 4). Finally, conclusions as well as limitations and avenues for future research are offered in the last section (Section 5).

2 | LITERATURE BACKGROUND

2.1 | Digital technologies supporting the implementation of circular economy practices

DTs have emerged as an interesting tool, or even a pivotal one (Chauhan et al., 2022), to enable the circular transition by industrial firms (Agrawal et al., 2022; Ciliberto et al., 2021; Rusch et al., 2022; Sahu et al., 2022). The main benefits DTs can bring include (Wynn & Jones, 2022) increased transparency and visibility (Ivanov et al., 2022; Lu et al., 2022), improved collection of data (Bag, Pretorius, et al., 2021), increased efficiency in the use of resources (Khan, Ponce, et al., 2021; Khan, Umar, et al., 2022), enabling circular design (Khan, Piprani, & Yu, 2022; Pinheiro et al., 2022), and servitisation (Atif et al., 2021). Accordingly, the relevance of DTs in supporting the circular transition by industrial firms has been proven in different sectors, such as electronic equipment (Magrini et al., 2021;

Pinheiro et al., 2022), electric motors (Tiwari et al., 2021), waste management (Mastos et al., 2021), and construction (Elghaish et al., 2022).

However, the current debate on the topic is characterised by the fact that both DTs and CE practices are addressed from a general perspective, i.e., without detail on specific DTs or CE practices (Hettiarachchi, Seuring, & Brandenburg, 2022; Lei et al., 2022; Taddei et al., 2022). Interestingly, efforts considering the specificity of DTs or CE practices are present and are increasing in number, yet they mainly focus on selected DTs or CE practices (Bressanelli et al., 2022; Ertz et al., 2022; Gebhardt et al., 2022; Patyal et al., 2022; Rusch et al., 2022).

2.1.1 | The role of specific digital technologies in supporting the implementation of circular economy practices

Deepening the discussion on the role of DTs in supporting the circular transition, interesting insights can be grasped by focusing on the support offered by specific DTs.

IoT is one of the most widely adopted DTs to enable the circular transition by firms, given the many opportunities it offers by allowing the interaction, cooperation, collection, and exchange of data through wireless telecommunications (Rejeb et al., 2022; Rusch et al., 2022). IoT can support different CE strategies (Laskurain-Iturbe et al., 2021; Massaro et al., 2021; Trevisan, Zacharias, Castro, & Mascarenhas, 2021), such as a reduction of resources consumption (Awan, Sroufe, & Shahbaz, 2021; Lopes de Sousa et al., 2021). IoT is also acknowledged to help to raise industrial firms' awareness of circular opportunities, e.g. in the textile sector (Ghoreishi & Happonen, 2022), also thanks to the enabled connection among different stakeholders (de Oliveira Neto et al., 2022; Rizvi et al., 2021).

BDA can facilitate and support the decision-making process in a circular perspective (Spaltini et al., 2021; Voulgaridis et al., 2022), thanks to the provided data-driven insights (Awan, Shamim, et al., 2021). Such insights have been connected to the possibility of performing remanufacturing and disassembly activities in a more efficient manner (Agrawal et al., 2022), as well as reuse and recycling (Hallioui et al., 2022), also fostering resource efficiency (Hettiarachchi, Seuring, & Brandenburg, 2022; Laskurain-Iturbe et al., 2021).

Cybersecurity and blockchain (CYB) are of interest for the circular transition due to their ability to assure transparency as well as the protection of the cyber environment, which may foster internal and external communication that allows collaboration among different stakeholders within industrial systems (Bekrar et al., 2021; Chauhan et al., 2022; Mastos et al., 2021; Nandi et al., 2021). This ability has been empirically proved, for example, in the automotive sector (Rizvi et al., 2022). Moreover, CYB can support circular purchasing and design (Khan, Razzaq, et al., 2021; Khan, Zia-ul-haq, et al., 2021), as well as waste management (Upadhyay et al., 2021) and material recovery, refurbishing, and recycling activities (Hallioui et al., 2022; Hennemann Hilario da Silva & Sehnem, 2022).

AM and especially 3D printing are considered strong enablers for the circular transition (Hettiarachchi, Brandenburg, & Seuring, 2022), due to their ability to build parts with geometrical and material complexity, not feasible with traditional manufacturing processes (Garza-Reyes et al., 2019). AM can be adopted at different stages of the supply chain (Patyal et al., 2022; Ponis et al., 2021; Tavares-Lehmann & Varum, 2021), and it helps reduce waste (Burmaoglu et al., 2022) and favor the use of recovered materials instead of virgin raw materials (de Mattos Nascimento et al., 2022; Kayikci, Gozacan-Chase, et al., 2022).

Artificial intelligence (AI) is often connected to the identification of new routes for CE activities and increased process quality (Chauhan et al., 2022), thanks to the offered predictions based on data analysis (Khan, Piprani, & Yu, 2022; Rizvi et al., 2021). Specifically, AI can support circular design (Awan et al., 2022; Kayikci, Gozacan-Chase, et al., 2022) and procurement (Hallioui et al., 2022), as well as resource efficiency (Laskurain-Iturbe et al., 2021), waste management (Hennemann Hilario da Silva & Sehnem, 2022; Talla & McIlwaine, 2022) and reverse logistics (Wilson et al., 2022).

Simulation (SIM) shows potential for tracing and predicting the material flow along the supply chain (Tiwari et al., 2021), and it is considered crucial for disassembly activities (Sassanelli et al., 2021).

Automated robots (ROBs), which help with the automation of the production process (Kamble & Gunasekaran, 2021), are mainly associated to disassembly (Kayikci, Gozacan-Chase, et al., 2022; Kintscher et al., 2021) and repairing activities (Wynn & Jones, 2022), with insights from different industries (Tiwari et al., 2021; Trevisan, Zacharias, Liu, et al., 2021). Additionally, evidence proved the suitability of ROBs for activities related to recovery and recycling strategies (Laskurain-Iturbe et al., 2021; Lopes de Sousa Jabbour et al., 2022).

Augmented reality (AR)—by providing an interactive computer simulation—can support the virtualisation strategy promoted within the ReSOLVE Framework (Ellen MacArthur Foundation, 2015) for CE (Bressanelli et al., 2022) and disassembly (Kayikci, Kazancoglu, et al., 2022).

Horizontal and vertical systems integration (HVSYS) can facilitate access to data (Hirota et al., 2022; Trevisan, Zacharias, Castro, & Mascarenhas, 2021), particularly allowing collaboration among different stakeholders (Awan et al., 2022; del Vecchio et al., 2021; Khan, Laalaoui, et al., 2022). This offers great opportunities for recycling activities and the redesign of products and processes (Oyinlola et al., 2022).

Finally, Cloud computing (CLOUD) allows the storage and sharing of data between stakeholders along the supply chain (Filho et al., 2022). Specifically, CLOUD shows great potential in different industries to promote collaboration (Gebhardt et al., 2022), whereas no specific CE practices enabled by this DT have been discussed within the extant literature.

2.1.2 | The integration of digital technologies in supporting the implementation of circular economy practices

Despite the discussion on the topic has been mainly focused on single DTs at a time, the scholarly debate is nonetheless starting to address digital ecosystems, i.e. the integration of different DTs to support the implementation of CE practices (Ertz et al., 2022), which are associated to different benefits (Rusch et al., 2022).

Most of the contributions focus on the integration between IoT and other DTs, as the ability of IoT of collecting and exchanging data is recognised as the basis for the adoption of other DTs (Schöggl et al., 2023). As a way of example, Agrawal et al. (2022) suggest that coupling IoT and AI can lead to improved manufacturing performance and better analysis of product usage, leading to optimised disassembly and remanufacturing processes (Järvenpää et al., 2021; Spaltini et al., 2021). Moreover, when coupled with IoT and AI, BDA can support data analysis and the identification of possible improvements for CE (Bag, Pretorius, et al., 2021; Liu et al., 2022). IoT, AI, and SIM can support the traceability of products and materials along the supply chain. Positive effects for traceability can be also obtained by concurrently adopting IoT, CYB, and HVSYS (de Oliveira Neto et al., 2022; Huynh, 2022; Magrini et al., 2021).

CYB can ensure the safety of the use of other DTs (Caterino et al., 2022; Ivanov et al., 2022), such as IoT or AM (Laskurain-Iturbe et al., 2021; Upadhyay et al., 2021). Furthermore, the integration of ROB and AI has been perceived as particularly beneficial for recycling activities (Elghaish et al., 2022). Moreover, AM, BDA, IoT, AI, and ROBs can work synergically for improved efficiency of activities and processes. As a way of example, they can collect and analyse real-time data supporting the decision-making process (Ghoreishi & Happonen, 2022; Patyal et al., 2022).

2.1.3 | A focus on SMEs

The adoption of DTs, and especially the integration of different DTs, might prove challenging for industrial SMEs (Lei et al., 2022), as they are usually characterised by a limited availability of resources (Micheli et al., 2021) such as financial resources and managerial competences. This might lead SMEs to adopt fewer DTs than larger firms (Aldrighetti et al., 2022; Schöggl et al., 2023). Given the industrial SMEs' relevance in the overall industrial economy from economic, environmental, and social viewpoints (e.g., in the European economy) (Chatzistamoulou & Tyllianakis, 2022; Journeault et al., 2021) as well as their idiosyncratic characteristics (Cagno et al., 2023; Negri et al., 2021), relevant contributions address the relationship between DTs and CE practices by these firms. For example, Bressanelli et al. (2018a, 2018b) analyse the coupled adoption of IoT and BDA supporting the development of servitised business models, such as Product-Service Systems. They find that IoT and BDA can also help overcome specific challenges, such as operational risks, technology improvements, and return flow uncertainty, yet recognising the limited generalisability of the results based on a single case study in the household appliances sector in Italy. De Marchi and di Maria (2020) consider a larger set of DTs while focusing on the support they offer to Italian SMEs for implementing resource efficiency and recycling CE strategies. As they underline the role of DTs as enablers for CE, they do recommend understanding the specific role played by each DT. Chaudhuri et al. (2022) discuss the support that CYB and AM can offer to SMEs involved in recycling plastic waste, particularly addressing the processes of sorting and managing such waste, underlying the necessity to tailor the two DTs to each specific SME's features. The contribution also provides insights into the business transformations required to properly exploit DTs for the circular transition, yet it appears limited due to the number of DTs and CE practices being considered. Di Maria et al. (2022) address both DTs and CE practices from a general perspective. Indeed, they mainly focus on recycling practices and the reduction of resource consumption but consider the empirical results obtained from an aggregated viewpoint. Attention is nonetheless drawn to the role of supply chain integration in mediating the relationship between DTs and CE practices.

2.2 | Emerging gaps

Although the discussion over the relationship between DTs and CE practices is getting momentum, several gaps can be identified within the extant literature.

On the one hand, many studies address the two concepts of DTs and CE practices from a general perspective, thus neither underlying nor investigating the peculiarities of different DTs and CE practices; on the other hand, many studies only focus on selected DTs or CE practices, thus missing a comprehensive perspective on the topic (Cagno et al., 2021). A more holistic perspective on the relationship is thus needed (Lei et al., 2022), considering not only a large set of DTs and CE practices but also the possible integration (i.e. synergies) among DTs in supporting the implementation of CE practices (de Felice & Petrillo, 2021; Ertz et al., 2022; Trevisan, Zacharias, Castro, & Mascarenhas, 2021).

Furthermore, apart from specific notably valuable contributions, e.g. (de Mattos Nascimento et al., 2022; Tang et al., 2022), the debate is still mainly carried out at a theoretical and conceptual level, thus lacking an empirical analysis of the relationships between DTs and CE practices. For this reason, empirical applications and validations of the proposed relationships between the two have been called out (Bekrar et al., 2021; Ghoreishi & Happonen, 2022; Taddei et al., 2022). Among the possible research methods, previous literature underlines the strategic role of qualitative research, such as semi-structured interviews or case studies (Aldrighetti et al., 2022; Cagno et al., 2021).

On top of this, despite their relevance in the industrial context, the investigation of the relationship between DTs and CE practices in supporting circular transition by industrial SMEs has been only partially addressed so far, and considerable room for further development remains (Cagno et al., 2021).

3 | METHODS

To tackle the abovementioned gaps and provide empirical evidence on the role that DTs can play in supporting the implementation of CE practices by industrial SMEs, we performed an explorative empirical investigation that relied on the conduction of semi-structured interviews, complemented by the collection of secondary data.

Semi-structured interviews are an appropriate method for complementing extant knowledge when the related empirical literature seems fragmented (Cagno et al., 2023; Kallio et al., 2016). Semi-structured interviews are indeed the right method to embrace to shed preliminary and exploratory light on a limited addressed topic (Cotta et al., 2022; Negri et al., 2022). Moreover, they allow asking immediate follow-up questions when issues arise (Adams, 2015), thus benefitting from the emerging free dialog (Dicicco-Bloom & Crabtree, 2006).

3.1 | Sample selection

To select firms to be involved in the empirical analysis, we adopted purposive sampling (Acharya et al., 2013; Hibberts et al., 2012). In particular, we designed a heterogeneous sample in terms of industrial sectors (manufacturing ones) (Trianni et al., 2019), with the intention of improving external validity and the robustness of the results (Baškarada, 2014), as detailed in the following.

The manufacturing sector plays a central role in the European industrial sector and economy (Eurostat, 2020); moreover, it has crucial repercussions for environmental impacts, also leading the way in the circular transition (Zamfir et al., 2017). In this domain, SMEs are key contributors to European economic growth, innovation, job creation, and social integration (Eurostat, 2018), representing more than 99% of firms in Europe (European Commission, 2019; OECD, 2022). SMEs are commonly identified in the European context as firms with less than 250 employees and an annual turnover not exceeding 50 million euros (European Union, 2003). These firms have a significant environmental impact, with still considerable room for improvement (Marrucci et al., 2022; Sáez-Martínez et al., 2016).

We specifically focused on Italian manufacturing SMEs. Italy ranks first for the circularity index implementation among the main European economies (Circular Economy Network & ENEA, 2020) and plays an increasingly relevant role in the European panorama regarding the digitalisation level (European Commission, 2022). The Italian manufacturing sector shows encouraging and interesting steps towards both CE and DTs adoption (Ghisellini & Ulgiati, 2020; Zangiacomi et al., 2020), as also demonstrated by the interest accrued in the extant debate (di Maria et al., 2022; Roos Lindgreen et al., 2020; Tiscini et al., 2022).

We identified possible firms to be included in the empirical analysis through the AIDA database (aida.bvdinfo.com/), also pre-screening them by looking at secondary information on their CE and digital-related strategies or activities in place. Firms were then contacted by e-mail or phone, asking for their willingness to voluntarily take part in the research. All in all, 10 Italian manufacturing SMEs have been selected, whose main characteristics are summarised in Table 1 (while additional information on such firms is available in Appendix A).

3.2 | Data collection

To collect data from the selected SMEs, semi-structured interviews were carried out. Interviews were conducted with interviewees holding managerial roles within the firms (in addition to ownership, in just two cases, as shown in Table 1), which ensures their accountability for digitalisation and circular transition within their firm, thus being the most suitable and knowledgeable source of information to address all questions.

Overall, we conducted 15 interviews with the 10 identified firms. The number of conducted interviews is in line with previous works adopting the same methodology (Villamil & Hallstedt, 2021; von Kolpinski et al., 2022). Each interview lasted approximately 1 h and was conducted in person when allowed by each firm, due to the Covid-19 emergency—see details in Table 1. The interviews were conducted by following an interview guide (DeJonckheere & Vaughn, 2019), ensuring reliability (Baškarada, 2014), as shown in Appendix B.

TABLE 1 Investigated sample.

Firm	NACE Sector	Role of the key informants interviewed	Interview(s) modality
1	C22.19	Sustainability manager	Online
2	C11.07	CEO	In person
3	C10.61	Production plant manager	In person
4	C25.99	CEO; control and quality manager; production manager; marketing manager	In person
5	C24.20	Industrial manager	Online
6	C13.30	Environment, quality and safety manager; digital production manager	In person
7	C13.99	Sales manager; production, quality, and control manager	In person
8	C13.92	Owner	In person
9	C13.95	Owner	In person
10	C11.07	CEO	Online

Note: The table reports the details of the sampled firms in terms of NACE Sector's code, role of the key informants interviewed, and how the interviews took place (online or in person).

The interview guide was developed with the aim of understanding (i) the CE practices being implemented; (ii) the DTs being adopted; and (iii) if and to what extent the adopted DTs helped in the implementation of the CE practices. The structure of the interview guide is aligned with previous research adopting semi-structured interviews as the research method (Cagno et al., 2023; von Kolpinski et al., 2022). In particular, the interview guide includes four parts, also following also the indication provided by DeJonckheere and Vaughn (2019). The first part focuses on a general description of the firm, products, and processes. The second part concentrates on CE, where interviewees were asked to provide an understanding of CE and an overview of the CE practices implemented by their firms, recalling the implementation process, and providing an indication of each practice's implementation level (Zhu et al., 2008). For the indication of the level of implementation, we relied on the following 4-point Likert-like scale: 1, *We are currently evaluating its implementation*; 2, *We are currently implementing it*; 3, *We have implemented it for less than 3 years*; and 4, *We have implemented it for more than 3 years*. The respondents were then asked to elaborate on the identified level. The third part focuses on DTs. Interviewees were asked to provide an understanding of DTs and an overview of the DTs adopted by their firms, recalling the adoption process, and providing an indication of each DT's use level. For the indication of the level of use, we relied on the following 4-point Likert-like scale: 1, *We are currently evaluating its adoption*; 2, *We are currently adopting it*; 3, *We are starting using it*; and 4, *We use it in an advanced manner*. The respondents were then asked to elaborate on the identified level. The fourth and last part is centred on the relationship between DTs and CE practices. We asked the respondents whether each of the adopted and used DTs was of any support in the implementation of each CE practice previously discussed and to what extent. For the indication of the level of support offered, we relied on the following 4-point Likert-like scale: 1, *From no to very limited support*; 2, *Quite significant support that nonetheless did not completely change the implementation process and/or outcome of the CE practice*; 3, *Significant but not pivotal support that changed the implementation process and/or outcome of the CE practice*; and 4, *Pivotal support for the implementation process and/or outcome of the CE practice*. The respondents were then asked to elaborate on the identified level.

Finally, secondary data and field notes were used to integrate and corroborate primary data collected through the interviews (Cannas et al., 2019; Silva et al., 2022). The overall protocol for the empirical investigation is available in Appendix B.

3.3 | Data analysis

As far as data analysis is concerned, interviews were recorded (upon interviewees' agreement) and transcribed (Kohlbacher, 2006). They were subsequently manually coded together with field notes and secondary data. We first applied open coding, with themes emerging inductively from the data and enabling the identification of main aspects and general contents. The coding was performed by at least three different researchers independently, reducing bias. To have a common reference for the categorisation of CE practices and DTs (Trianni et al., 2019), we compared our inductive open coding with a coding system developed based on the extant literature, trying to find a conciliation with literature concepts (Neri, Cagno, & Trianni, 2021; Silva et al., 2018). Concerning CE practices, we referred to the list of micro level (internal and external) practices for SMEs offered by Garza-Reyes et al. (2019). As for DTs, we referred to the classification by Rüßmann et al. (2015) and to the descriptions by Cagno et al. (2021). These classifications (which are reported in Appendix C) were used as a reference model for the analysis and discussion of the obtained results, considering their straightforwardness and ease of applicability in the industrial SMEs' context. Following the suggestions by Adams (2015) and Meredith (1998), results related to CE practices implemented, DTs adopted, and the relationship between the two were analysed by considering their frequency and reported using graphs and supplemented by illustrative examples. The choice is in line with previous works adopting semi-structured interviews as the research method, and it is an interesting approach to allow grasping a snapshot of the overall results (Fallahi et al., 2022; Julkovski et al., 2022; Neri, Cagno, & Trianni, 2021).

4 | RESULTS AND DISCUSSION

This section shows the results of the empirical investigation and discusses them against the extant literature. First, a characterisation of the investigated firms is offered, in terms of CE practices being implemented and DTs being adopted and used (Sections 4.1 and 4.2, respectively). Second, a detailed analysis of the role of DTs in supporting the implementation of CE practices is offered (Section 4.3), with reference to both single DTs and bundles of them.

4.1 | Circular economy practices implementation

An overview of the CE practices implemented by the investigated SMEs, together with their level of implementation, is shown in Figure 1 (for a more detailed view, please refer to Appendix D). Interestingly, all the investigated firms have implemented at least one CE practice, but none of them has implemented all the CE practices suggested by Garza-Reyes et al. (2019). Furthermore, some CE practices have been very poorly implemented by the sampled firms, especially those related to external practices for longevity (category "E" in Figure 1). As far as implemented CE practices are concerned, the average level of implementation is equal to 2.7, with most of the SMEs that have implemented such practices for less than 3 years (i.e. level 3) or are still in the implementation process (i.e., level 2).

Results overall underline that efforts towards the circular transition by SMEs mainly address internal practices for resource efficiency (category "A" in Figure 1), thus confirming Mura et al. (2020) and Nudurupati et al. (2022), but also in line with other studies that are not focused on SMEs (Elia et al., 2020; Masi et al., 2018). As proof, the Sustainability Manager from Firm 1 stated:

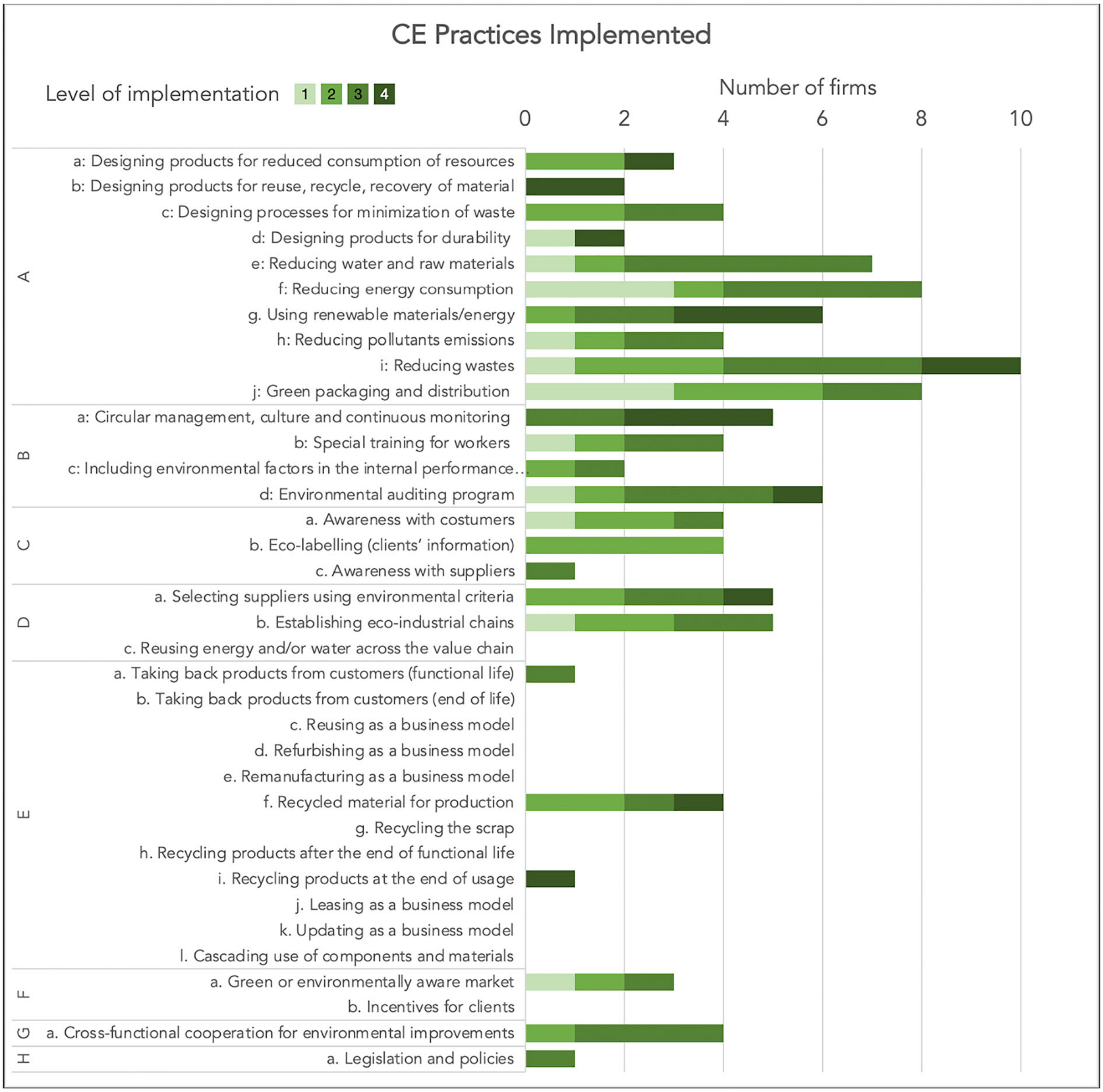

FIGURE 1 CE practices implemented. The figure reports the detail of the CE practices implemented by the investigated firms, in terms of number of occurrences. The CE practices implemented are classified according to Garza-Reyes et al. (2019) list of CE practices. Moreover, the figure offers a detail on the level of implementation (legend—1, we are currently evaluating its implementation; 2, we are currently implementing it; 3, we have implemented it for less than 3 years; 4, we have implemented it for more than 3 years).

> The external part is still under development, not because we are not doing anything but because it is still very unstructured. Often there are initiatives from single departments but without an overarching objective.

Among the internal practices, the most frequently implemented ones refer to reducing resources, energy consumption, and waste, as well as green packaging and distribution, thus corroborating previous research (Guerra et al., 2021; Stumpf et al., 2021). Reducing resources and waste is also characterised by a relatively high level of implementation, in line with Antonioli et al. (2022) and Dey et al. (2022), while the others are still in the process of being implemented. The result supports the considerations brought by Afif et al. (2022) for the implementation of resource efficiency practices by SMEs. These practices are perceived by the sampled firms as bringing economic advantages, as stated for example by Firm 4's CEO:

> Any mistake in dosing raw materials is a higher cost for the firm.

Also, practices related to internal awareness (category "B" in Figure 1) show quite an interesting rate of implementation, especially for the conduction of auditing and continuous monitoring, supporting Kamble and Gunasekaran (2021) and Zhu et al. (2010).

Conversely, external practices, which require the involvement of stakeholders beyond a firm's boundaries (Antonioli et al., 2022) through collaborations along the supply chain (Negri et al., 2021; Neri, Cagno, Lepri, & Trianni, 2021), seem less implemented, in line with Calzolari et al. (2021). Moreover, such practices are characterised by a lower level of implementation compared to internal practices for resource efficiency. Nonetheless, half of the investigated firms particularly focus on the selection of suppliers by using environmental criteria, in line with Nudurupati et al. (2022), although this can be biased due to the number of textile firms included in the investigated sample (Saha et al., 2021). Similarly, although the same number of firms claimed to collaborate with external partners on circular solutions and to promote joint initiatives with other firms by establishing eco-industrial chains, most of them are still predominantly implementing linear business models, as shown by the limited number of CE practices being implemented.

4.2 | Digital technologies adoption and use

An overview of the DTs adopted by the investigated firms and their level of use is offered in Figure 2. The adoption and the use of DTs by the investigated firms are rather limited—with an average level of 2.7, following previous insights on the level of digitalization among Italian manufacturing firms (Cimini et al., 2021; Zheng et al., 2020), and SMEs in particular (European Investment Bank, 2021).

CLOUD, HVSYS, and IoT are among the most adopted DTs, thus supporting Filho et al. (2022), Marcon et al. (2022), and Ruggero et al. (2020). These DTs are largely recognised as a catalyst for further digitalisation (Pirola et al., 2020). They are characterised by different levels of use, with most of the SMEs still in the initial phase of adoption and use, in line with European Investment Bank (2021).

Conversely, the investigated firms are not making a diffused use of BDA, contrasting some previous research (Marcon et al., 2022) but supporting others (Chauhan et al., 2021). Moreover, when used, BDA is often coupled with other DTs for data collection, such as IoT (Firm 3) or HVSYS—with reference to Manufacturing Execution System (MES) or Enterprise Resource Planning (ERP) (Firm 2), thus confirming Bressanelli et al. (2018a, 2018b) and Kamble and Gunasekaran (2021).

ROBs are not largely adopted, contrasting Zheng et al. (2020) but supporting Cimini et al. (2021), whereas firms adopting them show a medium-high level of use. AM and SIM show an even lower adoption by the sampled firms, while their relatively high level of use seems to be driven by a specific activity carried out by related firms, such as using moulds within the production process (Firm 1) or the management of logistics activities (Firm 2). Finally, CBY and AR show very limited or even no use. The result is consistent with previous literature (Cimini et al., 2021; Toufaily et al., 2021; Zheng et al., 2020), and it might underline the presence of significant challenges in the adoption of these DTs.

4.3 | Discussion on the role of digital technologies in supporting the implementation of circular economy practices

Table 2 offers an overview of the relationship between DTs adoption and CE practices implementation, as emerged from the empirical investigation, i.e. the role played by DTs in supporting CE practices implementation.

A considerable relationship seems to emerge between some DTs and CE internal practices for resource efficiency (Category "A"), while it appears to be very sporadic for the other CE practices. Overall, specific DTs (i.e. ROBs, AM, BDA, SIM, and CLOUD) seem to support only internal practices, while others (i.e. HVSYS, CYB, and IoT) extend their backing to external practices, although to a limited extent.

These results confirm previous research from various standpoints. First, DTs show a strong potential to reduce the material loop by enabling more efficient use of resources (de Marchi & di Maria, 2020), by acting on internal processes (Rajput & Singh, 2019). From this perspective, the role of automated control, computing, and connecting technologies is fundamental (Kamble & Gunasekaran, 2021; Lorenz et al., 2020; Marcon et al., 2022). Second, HVSYS, CYB, and IoT can

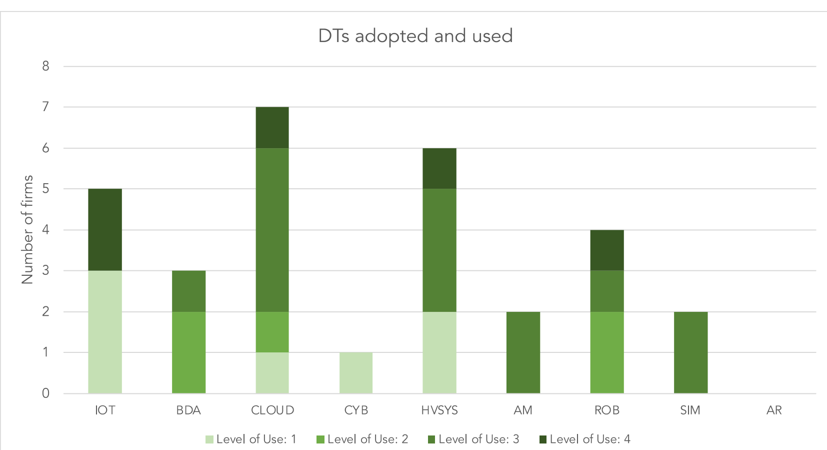

FIGURE 2 DTs adopted and used. The figure reports the detail of the DTs adopted by the investigated firms, in terms of the number of occurrences. DTs are classified according to Rüßmann et al. (2015)'s classification. Abbreviations: AM, additive manufacturing; AR, augmented reality; BDA, big data analytics; CLOUD, cloud technologies; CYB, cybersecurity and blockchain; HVSYS, horizontal and vertical systems integration; IoT, internet of things; ROBs, autonomous robots; SIM, simulation. Moreover, the figure offers a detail of the level of usage (legend—1, we are currently evaluating its adoption; 2, we are currently adopting it; 3, we are starting using it; 4, we use it in an advanced manner).

TABLE 2 Overview of the results on the relationship between the adoption of DTs and the implementation of CE practices.

			DTs								
			IOT	BDA	CLOUD	CYB	HVSYS	AM	ROB	SIM	AR
CE practices implemented	A	a: Designing products for reduced consumption of resources						3			
		b: Designing products for reuse, recycle, recovery of material									
		c: Designing processes for minimization of waste						3	3		
		d: Designing products for durability									
		e: Reducing water and raw materials		1			3	2.5	3		
		f: Reducing energy consumption	2.5	2			2		3		
		g: Using renewable materials/energy	4	4							
		h: Reducing pollutant emissions	4	3							
		i: Reducing wastes	3.5	3	2	1	1.8	3	3		
		j: Green packaging and distribution						1	4	2.5	
	B	a: Circular management, culture, and continuous monitoring									
		b: Special training for workers									
		c: Including environmental factors in the internal performance evaluation system			3		2				
		d: Environmental auditing program			1						
	C	a. Awareness with costumers	1			1					
		b. Eco-labeling (clients' information)									
		c. Awareness with suppliers									
	D	a. Selecting suppliers using environmental criteria									
		b. Establishing eco-industrial chains					1				
	E	a. Taking back products from customers (functional life)									
		f. Recycled material for production									
		i. Recycling products at the end of usage									
	F	a. Green or environmentally aware market									
	G	a. Cross-functional cooperation for environmental improvements									
	H	a. Legislation and policies									

Note: The rows report only the CE practices implemented by the firms as offered by Garza-Reyes et al. (2019), while the columns report the list of DTs as offered by Rüßmann et al. (2015). The number in the colored boxes indicates the average level of support offered by a specific DT to the adoption of a specific CE practice (legend—1, from no to very limited support; 2, quite significant support that nonetheless did not completely change the implementation process and/or outcome of the CE practice; 3, significant but not pivotal support that changed the implementation process and/or outcome of the CE practice; 4, pivotal support for the implementation process and/or outcome of the CE practice). The color of each box indicates the number of occurrences among the sampled firms, according to the legend below.

Legend: 1 occurrence
2 occurrences
3 or more occurrences

Abbreviations: AM, additive manufacturing; AR, augmented reality; BDA, big data analytics; CLOUD, cloud technologies; CYB, cybersecurity and blockchain; HVSYS, horizontal and vertical systems integration; IoT, internet of things; ROBs, autonomous robots; SIM, simulation.

foster integration among stakeholders (Dev et al., 2020), although still applied to a limited extent (Pirola et al., 2020).

The following sub-sections deepen the understanding of the relationship between DTs adoption and CE practices implementation (Almeida et al., 2022). First, the supporting role played by each DT alone is discussed; second, the integrated support offered by combinations of DTs is addressed.

4.3.1 | The role of the single digital technologies in supporting the implementation of circular economy practices

As shown by Table 2, a single DT can support the implementation of different CE practices, even with a different level of support. From this line, in the following, we propose a discussion on the role that each DT plays in supporting the implementation of the different CE practices, comparing the empirical evidence with extant knowledge.

Internet of Things

IoT is adopted in different ways and with different aims, underlining its versatility (Atzori et al., 2017). In particular, the most widespread adoption that emerges from the empirical investigation, consistent with the extant literature (Kamble & Gunasekaran, 2021), refers to the use of interconnected sensors for collecting and communicating real-time production and process-related data. These data can help support the monitoring of working environment parameters, such as humidity (Firm 7) and temperature (Firm 8) or air emissions (Firm 3), also tracking the product over the supply chain (Firm 1). Bringing the example of Firm 8, the owner stated:

> These sensors are instrumental for measuring process parameters, which must be constant over time.

IoT also offers possibilities for sectorial-specific applications, such as the monitoring and optimisation of fertiliser use (Firm 3). Overall, IoT seems to strongly and significantly support internal CE practices for resource efficiency, as previously noted by Ingemarsdotter et al. (2019). Despite the potential for IoT to support CE practices that involve stakeholders along the supply chain, such as reverse logistics actions (Dev et al., 2020), this aspect does not emerge from our investigation. Nonetheless, it might be attributed to the specific features of the sampled firms, which are characterised by a limited implementation of CE practices at the supply chain level.

Big data analytics

BDA supports some of the sampled firms in implementing internal CE practices for resource efficiency, as it allows for better control over the production processes. As the CEO of Firm 4 stated:

> We have conceived the architecture of analysis to optimize the availability of machines.

BDA—especially if coupled with IoT, as discussed in Section 4.3.2—is crucial for controlling fundamental parameters for energy production and helping reduce related emissions (Firm 3). Collecting and analysing data on the production processes also support the implementation of preventive maintenance, thus extending the equipments' life (Firm 4). Interestingly, firms in the sample typically adopt BDA to improve the performance of a specific process, only later recognising its valuable role to foster the CE transition.

Previous studies also underline the potential role played by BDA in facilitating information exchange among stakeholders along the supply chain (Chiappetta Jabbour et al., 2019). However, the empirical analysis does not support this, yet results might be influenced by the characteristics of the investigated firms, where the adoption of BDA and the implementation of CE practices at the supply chain level are limited.

Cloud technologies

Despite CLOUD being the most widespread DT among the sampled firms, also providing the infrastructure to support the adoption of other DTs, as discussed in Section 4.3.2, a very limited role of this DT in supporting the implementation of CE practices emerges from the empirical investigation, consistent with previous studies that have not tackled this specific relationship. In particular, CLOUD helps raise firms' internal awareness of their performance, thus facilitating the process of obtaining certifications (Firm 4) or setting environmental targets (Firm 6). Indeed, CLOUD makes data always accessible from any place, allowing prompt resolution of possible issues, and constant alignment with internal goals and targets. Bringing as an example the words of Firm 6's Digital Production Manager:

> Having this technology has brought us to cooperate with some suppliers who had more [environmental] certifications, or more sensitive on those [environmental] matters. They have given us different products we could use [...] to reach environmental goals.

Cybersecurity and blockchain

CYB is exploited by the sampled firms to a very limited extent, as only one firm (Firm 1) adopts it, with a twofold aim. On the one hand, it helps exchange product information with final customers, thus increasing their knowledge of the production process, yet not focusing on specific environmental or sustainable-related information. On the other hand, it helps control the different production stages over the supply chain to spot possible quality problems, to identify the faulty batch without the need to extensively check or eliminate all the production. The empirical evidence does not support previous studies addressing CYB, which show that it is crucial for product traceability and recycling (Huynh, 2022). Moreover, it is acknowledged as an enabler for the adoption of CE practices at the mesolevel by facilitating data sharing among the stakeholders along the supply chain (Kouhizadeh et al., 2020; Upadhyay et al., 2021).

Horizontal and vertical systems integration

The integration of horizontal and vertical systems is often addressed by considering them together (Paschou et al., 2020), yet they entail different levels of complexity (Narula et al., 2020), offering different possibilities (Blichfeldt & Faullant, 2021; Brodny & Tutak, 2021; Usai et al., 2021) and reflecting in different adoption rates (Pirola et al., 2020). The results of the empirical investigation support this argument and will be thus discussed for Vertical Systems Integration (VSI) and Horizontal Systems Integration (HSI) in a separated manner.

VSI is fairly widespread among the sampled firms. It allows better control of production-related issues, such as production progress, work in process, machine blocks, or real-time delays, as it is also supported by the extant literature (Dev et al., 2020). The most adopted systems refer to Production Management Systems (PMS) (Firm 9) and MES (Firm 5), with the latter also allowing horizontal integration with the customers' systems to control the status of the orders. The better processes control enabled by VSI can help reduce the overproduction and loss of resources and materials, thus backing the implementation of CE practices in terms of reduced energy and material consumption and waste production, while also supporting the setting of strategic environmental goals. Interestingly, firms adopting VSI introduced it to increase the control on production processes, only later acknowledging the entailed possibilities for supporting the CE transition. As put by the owner of Firm 9:

> We can monitor almost in real-time what is happening in the production. This technology has allowed us to see the cost of not being circular because you get a precise number of how much the scraps and waste are costing you.

The adoption of HSI is quite widespread too. Three of the sampled SMEs participated in an online platform for exchanging industrial scraps/waste among firms supported by the European Commission, aiming at increasing the efficiency of industrial processes and reducing waste by establishing eco-industrial chains. Despite the expectations, at the time of the investigation, the platform had not enabled the creation of partnerships or collaboration among firms and its potential remained unexploited.

Additive manufacturing

Despite the limited number of firms adopting this DT, the empirical analysis confirms the role of AM in supporting the production process, as in Kamble and Gunasekaran (2021) and Lorenz et al. (2020), also leading to better product management (Rosa et al., 2020), reduced resources use, and reduced waste generation (Despeisse et al., 2017). In particular, from the investigation, AM emerges as a valid support to implement CE practices related to resource efficiency and eco-design. AM also allows for reducing the use of material and the emissions related to the shipping of components, and as an enabler of a make-to-order production system (Firm 1), strongly backing Huynh (2022). AM also shows great potential for supporting the testing activities, thus reducing the needed time and the generated waste (Firm 4).

Interestingly, firms adopting AM introduced it to increase the efficiency of the testing phases and allow higher production flexibility, only later recognising the role it may play in fostering the circular transition. The words of the sustainability manager from Firm 1 exemplify this evidence:

> We use AM in a project to produce personalized products directly in the shops. This allows increasing production speed and customizing for single clients. [...] But then it has allowed us to reduce the stock and the related waste.

Autonomous robots

ROBs are adopted by some of the sampled firms to manage the product during the overall production phases to increase resource efficiency, in particular by enabling the design of processes to minimise waste, reducing resources and energy consumption as well as waste generation, confirming Kamble and Gunasekaran (2021). Some sectorial specificities emerge, such as the reduction of waste from the dyeing process (Firm 6) or the reduced consumption of plastic (Firm 10) or glue (Firm 5). ROBs are also introduced in terms of human–machine interface, again leading to reduced waste generation and energy consumption (Firm 7).

Interestingly, firms adopting ROBs introduced them to increase efficiency and reduce resource consumption and associated costs, only later acknowledging their entailed possibilities to foster the CE transition, as stated by Firm 10's CEO:

> ROBs and related innovations are more expensive, but they make our life simpler. We took the idea from different sectors, but now we also recognize they foster a continuous improvement approach, as we quantify waste, where it originates and where the problems arise. [...] We want to improve, and there are several ways to do so.

ROBs thus emerge as a crucial DT for supporting the adoption of resource-efficiency or eco-design-related CE practices, backing de Marchi and di Maria (2020). Contrasting previous literature (Sarc et al., 2019), the relationship between ROBs and disassembly practices does not arise. Although aligned with Masi et al. (2018), results might be influenced by the characteristics of the sampled firms.

Simulation

Despite the potential of SIM to contribute to the CE transition (Sassanelli et al., 2020), the sampled firms exploit it only to optimise logistics-related activities, such as delivery activities (Firm 2) or the overall distribution chain (Firm 10). Observed benefits refer to reduced time, cost, and emissions. Interestingly, SIM is adopted in the first instance for cost and time-related benefits, with environmental benefits considered only later. Firm 2's CEO highlighted the fact that SIM allows easier management of production:

> We have a program that does this. […] The production world is very peculiar, every day there are new problems. […] The important thing is to understand if these problems are repetitive or not.

Moreover, previous studies underline the support that SIM could offer to reverse logistics activities (Rosa et al., 2020) and the determination of product quality to assist in disassembly or maintenance activities (Charnley et al., 2019). However, the two aspects were not detected from the empirical analysis. Regarding the latter, such activities are rather advanced and require specific capabilities and know-how, resulting in difficult implementation by a sample of firms characterised by an overall limited adoption and use of DTs.

Augmented reality

Augmented (and virtual) reality is crucial for fostering CE (Katika et al., 2022), yet the extant literature mainly focuses on the potential support for firms as operators enhancement (Lorenz et al., 2020) and learning of manual processes by workers employed in disassembly or remanufacturing activities (Kerin & Pham, 2019). However, no firms in our sample adopt AR. Therefore, we cannot delve into that.

4.3.2 | The role of digital technologies integration in supporting the implementation of circular economy practices

As shown by Table 2, the implementation of a CE practice can be supported by different DTs. Therefore, it is interesting to shed light on the role that can be played by the concurrent adoption of different DTs in supporting the implementation of CE practices. From this line, in the following, we propose a discussion according to specific CE practices, by providing an overview of the different DTs that can support their implementation—alone or in an integrated manner, as well as their level of support, based on the results of the empirical analysis.

Designing process for minimisation of waste

Half of the firms implementing this CE practice (2 out of 4) are considerably supported by DTs. In particular, Firm 4 implements tests and simulations on new products by exploiting 3D printing, thus limiting both time and resource waste, whereas Firm 6 adopts ROBs to enable a more efficient design of the printing process, especially on digital printing, thus limiting the waste of dyes.

The concurrent adoption of AM and ROBs is considered within previous studies. Cimini et al. (2021) include them under the term "automation." Lorenz et al. (2020) consider them important for "shop floor connectivity." Huynh (2022) includes them in the "pull demand model" for CE transition. However, the empirical analysis shows that the two DTs do not seem to act in a synergic manner (i.e., leveraging one on the other), rather they seem to act independently.

Reducing water and raw materials

About half of the firms implementing this CE practice (3 out of 7) are supported by different DTs, specifically, BDA, HVSYS, ROBs, and AM, although with different levels of support. These DTs act in two different manners.

On the one hand, some DTs help reduce the use of input resources standalone. For example, by exploiting ROBs Firm 10 reduced the consumption of production material by 40%, whereas AM helps Firm 5 in reducing material consumption.

On the other hand, other DTs are synergically adopted. For example, the joint adoption of BDA and HVSYS helps Firm 2 in controlling the process and quantitatively intervening in a targeted way. A strong synergic action between ROBs and HVSYS (MES in particular) emerges from Firm 4, where MES supports the planning of the production according to customers' orders, whereas ROBs automatically and adaptively dose the amount of material based on the specific order.

Reducing energy consumption

Almost half of the firms implementing this CE practice (**three** out of **eight**) are supported by different DTs, specifically IoT, BDA, HVSYS, and ROBs. Also in this case as well, these DTs act in different manners.

IoT, BDA, and HVSYS appear to all offer quite good support in a standalone manner, by allowing the control of energy consumption and the exploitation of optimisation techniques for its reduction. The three DTs can thus be linked to the concept of "automated control" offered by Marcon et al. (2022). As proof, Firm 5 considers MES crucial to control the production process, thanks to the analysis of data collected from the plant through sensors.

As for ROBs, their use (not coupled with other DTs) considerably supports Firm 7 to optimise the energy consumption associated with the production process.

Using renewable materials/energy and reducing pollutant emissions

IoT and BDA strongly support both practices. The empirical evidence shows the synergic support that both DTs offer. As proof, Firm 3 controls the efficiency and emissions of the biomass energy production plant by collecting data through IoT and exploiting them through BDA.

Reducing waste

The practice is largely implemented by the sampled firms (8 out of 10) and largely supported by a considerable set of DTs, i.e., IoT, BDA, CLOUD, CYB, HVSYS, AM, and ROBs (6 out of 10).

On the one hand, some DTs help reduce waste standalone. AM shows the potential to considerably support waste reduction by allowing the conduction of tests and simulations of 3D printed products (Firm 4). HVSYS can strongly support keeping track of and control on production and logistics-related aspects (Firm 5). CLOUD can offer quite a good support for the dematerialisation of processes, as the conversion to digital of active and passive invoices, active bubbles, registers of purchases and sales, and documents of transport;

however, the impact of CLOUD has been identified only as for the administrative process (Firm 10).

On the other hand, other DTs are synergically adopted. IoT and ROBs can act in a synergic manner, allowing tighter control over the production process, and thus over the generation of waste (Firm 7). HVSYS and BDA can act in a synergic manner too, as the data collection and analysis enabled by both DTs strongly support the reduction of waste along the supply chain, by limiting errors, excess production, and distribution waste, as well as the loss of shipments and deliveries (Firm 2).

Green packaging and distribution

The practice is widely implemented by the sampled firms (8 out of 10), but it is supported by DTs (i.e., ROBs, AM, and SIM) only in a few cases. The adopted DTs emerge as acting standalone. ROBs act on the packaging side, by allowing a reduction of the material used for the packaging (Firm 10). SIM strongly enables efficient logistics, especially concerning the delivery process (Firm 2) and the distribution chain (Firm 10). As for AM, as tests and trials can be produced via 3D printing by the firm itself, logistics activities from and to suppliers are reduced (Firm 2).

Including environmental factors in the internal performance evaluation system

HVSYS and CLOUD considerably support the implementation of this CE practice by only one firm (Firm 6) among the two implementing it. The concurrent adoption of both DTs helps monitor parameters such as energy and material consumption or downtimes to support the setting of quantitative and realistic environmental targets. The possibility to collect and manage data is thus seen as an opportunity to understand the potentialities of improved CE-related performance and act accordingly.

Awareness with customers

This CE practice is implemented by only one firm (Firm 1). The joint adoption of IoT and CYB emerges as an enabler of this practice for having a direct link with customers. Particularly, Firm 1 exploits near-field communication to trace the product, thus allowing the customer to be aware of the different stages of the production process followed by the product. At the time of the interview, the support offered by the two DTs was nonetheless limited due to their low level of adoption.

Establishing eco-industrial chains

The practice is implemented by half of the sampled firms (5 out of 10) but supported by a DT, namely, HVSYS, only in limited cases and with a very limited level of support. As anticipated in Section 4.3.1, three of the sampled firms have joined an online platform to promote the exchange of industrial scraps and waste among industrial districts. So far, however, the platform so far offered very limited support to the establishment of eco-industrial supply chains.

Based on the obtained results, two different types of support provided by DTs to foster the circular transition seem to emerge (Figure 3), and each one can help achieve different objectives.

The first type of support leverages a synergic interaction among DTs, which are concurrently adopted to achieve a specific objective. First, DTs can act synergically to allow better control over production processes, in terms of parameters and emissions, as well as waste generation. For example, IoT and BDA are often coupled, as BDA allows proper exploitation of data collected through IoT. BDA can also act synergically with HVSYS, as the analysis of the collected data can greatly help the effective use of HVSYS. Last, the combination of IoT and ROBs allows effective control over the production process inputs. Second, DTs can support production planning activities. This is the case, for example, of the joint adoption of ROBs and HVSYS. Third, DTs can support the exploitation of data and information for performance monitoring and continuous improvements. From this perspective, the combination between HVSYS and CLOUD emerges as beneficial. Fourth, DTs can also support communication and collaboration between a firm and the other stakeholders along the supply chain. From our analysis, it emerges that the integration of IoT and CYB can offer synergic support in this direction.

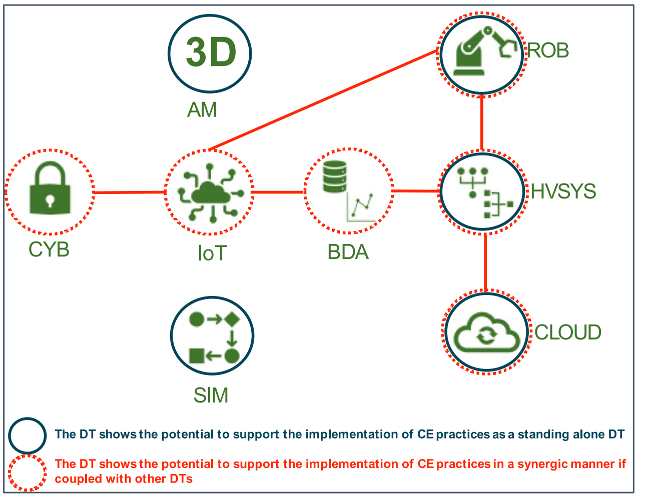

FIGURE 3 Integration among different DTs supporting the implementation of CE practices. The figure reports the relationships among different DTs in terms of integrated and synergic support offered to the implementation of CE practices.

The second type of support is based on the adoption of a single DT in a stand-alone manner. Indeed, some of the analysed DTs show the potentiality to act alone to foster the circular transition. AM and SIM emerge as contributing only as standalone DTs to support the circular transition, as no synergies with other DTs emerged from our empirical investigation. Interestingly, some DTs (i.e., ROBs, HVSYS, and CLOUD) seem to support the implementation of different CE practices both alone and coupled with other DTs. On the contrary, IoT, BDA, and CYB are never adopted alone; rather, they are always coupled with other DTs.

5 | CONCLUSIONS

Our preliminary investigation sheds light on the role that DTs may have in supporting the implementation of CE practices by industrial SMEs. The results suggest that DTs are an enabler of CE practices, yet to different extents. Despite this, SMEs seem to adopt DTs mainly for production-related reasons, looking for efficiency, cost savings, and better quality. Only in a second stage do they recognise the opportunities offered by DTs to foster their circular transition. Among DTs, IoT, BDA, and ROB emerge as the most promising ones, as they strongly support the implementation of a variety of CE practices.

Besides a holistic perspective on the relationship between DTs and CE practices, we provide some preliminary insights on the support towards circular transition offered by the integrated and synergic adoption of different DTs. Particularly, the integration among IoT, BDA, HVSYS, CLOUD, and ROBs is of great interest to foster the circular transition by SMEs.

By performing our analysis, we respond to the call for a holistic and integrated empirical investigation of the relationship between DTs and CE practices in SMEs, thus providing interesting insights into the relationships' characterisation and tackling the digital and circular divides. Newly compared to previous literature, the level of detail offered by our analysis allows for deepening the knowledge of the supporting role played by each DT on the implementation of specific CE practices, thus offering a comprehensive perspective on the relationship between the two pivotal topics. From an academic perspective, we thus contribute to the advancement of the knowledge on the relationship between DTs and CE practices in the SMEs domain, thus offering an interesting starting point for future research.

The provided knowledge is of interest from a managerial perspective as well. Industrial-decision makers are indeed provided with an understanding of how and to what extent the adoption of specific DTs could impact the circular transition, possibly allowing them to better organise their resources and concentrate their efforts towards adopting those DTs that could be more effective in achieving CE targets. Indeed, although CE and environmental conservation appear not to be primary objectives, international and national policies for pollution and waste control will make DTs' adoption even more appealing to practitioners.

Finally, we should highlight the caveats of this research that nonetheless pave the way for future research. The investigated sample is appropriate for an exploratory investigation of the topic, yet the findings, being based on 10 firms (15 interviewees), do not allow generalisability. Moreover, the sample is limited to Italian manufacturing SMEs—thus excluding other sectors and countries, posing limitations for the generalisation of the results in other contexts, as the specific region entails unique characteristics. The sample might also pose risks for biases, as SMEs autonomously decided to take part in the research.

Future research is encouraged to replicate or expand the sample size, as well as perform empirical analyses in other contexts. For a broader understanding of the topic, we suggest including more firms characterised by different contextual factors, such as size, geographical area, and sector. As for the size, we think that interesting insights might arise from comparing SMEs with larger enterprises, but also confronting small with medium enterprises, as previous research showed significant differences between the two of them.

Such a broader understanding could also benefit the deployment of quantitative research. Specifically, we encourage future research to perform quantitative analysis to investigate co-presences and correlations between DTs and CE practices. The current debate also focuses on possible mediators of the relationship between DTs and CE practices. From our perspective, this topic actually deserves further exploration, as it can offer additional insights into the role that DTs can play in supporting the circular transition by SMEs.

AUTHOR CONTRIBUTIONS

Alessandra Nericonceptualized the idea, collected and analysed the data, wrote the original draft and reviewed and edited the paper; she was also responsible for the project administration, general supervision, and funding acquisition. Marta Negri collected and analysed the data and reviewed and edited the paper. Enrico Cagno conceptualized the idea and reviewed and edited the paper. Simone Franzò and Vikas Kumar reviewed and edited the paper. Tommaso Lampertico and Carlo Andrea Bassani collected and analysed the data.

ACKNOWLEDGMENTS

This paper has been developed based on the work performed for "The role of digitalization in supporting the circular transition" project. We acknowledge the support from the T.I.M.E. Association (Top International Managers in Engineering) within the framework of T.I.M. E. Projects. Open Access Funding provided by Politecnico di Milano within the CRUI-CARE Agreement.

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How to cite this article: Neri, A., Negri, M., Cagno, E., Franzò, S., Kumar, V., Lampertico, T., & Bassani, C. A. (2023). The role of digital technologies in supporting the implementation of circular economy practices by industrial small and medium enterprises. *Business Strategy and the Environment*, 1–26. https://doi.org/10.1002/bse.3388

APPENDIX A: ADDITIONAL INFORMATION ON THE SMES INCLUDED IN THE INVESTIGATED SAMPLE

Additional information on the SMEs included in the investigated sample is here reported. Particularly, the following are provided: NACE Code Rev. 2; number of employees; turnover (last available one); form of business; short description.

Firm 1

NACE Code Rev. 2: 22.19
Number of employees: 238
Turnover: 153,836,017
Form of business: Joint-stock company
Short description: Firm 1 was founded in the 1930s by an alpinist with the aim to produce soles for mountain activities. The main activity of Firm 1 is the production of rubber soles for shoes, particularly to be used outdoors in mountain climbing. The firm started its sustainability journey in the year 1994 through the use of an eco-compound aiming at reducing the amount of virgin material in the soles by 30%. Nowadays, Firm 1 works in three different countries and it is considered the global leader for the production of soles embedded in high-quality shoes.

Firm 2

NACE Code Rev. 2: 11.07
Number of employees: 84
Turnover: 10,486,819 €
Form of business: Limited liability company.
Short description: Firm 2 was founded in the 1990s. Its main business is to supply water in offices or private houses, through the distribution of water bottles and water flagons or by using water purification systems. The firm is a national brand, with two bottling plants that allow bottling freshwater directly at the source by using hygienic eco water coolers. Thanks to 10 branches throughout Italy and a network of distributors, the firm can deliver disposable flagons at homes or offices within a few days after bottling. The empty disposable flagons are collected by Firm 2, returned to the warehouse, and recycled with a patented technology that allows recovering 100% of the used PET.

Firm 3

NACE Code Rev. 2: 10.61
Number of employees: 175
Turnover: 198,567,760 €
Form of business: Joint-stock company
Short description: Firm 3 has over 160 years of history. Its core business is the processing of rice and its derivatives. With a storage capacity of over 6,500 tons of paddy rice and a production capacity of about 500 tons/day of white and parboiled rice, Firm 3 is among the Italian leaders in the sector. Firm 3 also produces beverages and other products derived from rice. Firm 3 is developing a plan for an integrated cycle to exploit resources, paying attention to product quality and environmental protection, through a "green" policy related to energy and water efficiency.

Firm 4

NACE Code Rev. 2: 25.99
Number of employees: 214
Turnover: 62,080,436 €
Form of business: Joint-stock company
Short description: Firm 4 was founded in 1985. It designs, develops, and manufactures heating systems, brass plumbing connectors, and energy-efficient plumbing systems. It has over 10,000 items in its catalog, ranging from standard products to unique pieces. Firm 4 currently has 11 branches in Italy, Europe, the US, and North Africa, yet the Italian headquarters is the heart of the group. The production process is carried out in a high-tech factory. The continuous investments in Industry 4.0 technologies have allowed Firm 4 to exploit them to improve production efficiency.

Firm 5

NACE Code Rev. 2: 24.10
Number of employees: 139
Turnover: 23,943,823 €
Form of business: Limited liability company.
Short description: The group to which the Firm 5 belongs was created in 1935 to produce rubber hoses for the hydraulics and oil & marine sectors. The group has progressively expanded with the acquisition of various production plants and entered the automotive sector. Firm 5 produces metal fittings used to produce hydraulic hoses. The raw material purchased and processed by the company are steel bars, which are processed by chip removal and plastic deformation to produce the finished product, which is sent to a warehouse and is used by other companies of the group to produce hydraulic components.

(Continues)

Firm 6
NACE Code Rev. 2: 13.30 **Number of employees:** 105 **Turnover:** 19,995,432 € **Form of business:** Limited liability company. **Short description:** Firm 6 was founded in the late 1960s and operates in the market of printed natural fabrics for home and clothing. In the 1090s, it opened to the international market thanks to technological investments which allowed improving the quality level. Firm 6 is strongly vertical integrated, and it is thus able to follow the customer from the first stages of bleaching to the final quality control. The work is done on fabrics owned by third parties and there is no textile own production. All production is made on-demand.
Firm 7
NACE Code Rev. 2: 13.92 **Number of employees:** 108 **Turnover:** 30,831,417 € **Form of business:** Joint-stock company **Short description:** Firm 7 was founded in the 1920s. It works in the production of lining and ceremonial fabrics market and its products are present in more than 70 countries. Firm 7 is a partner of many famous Italian and foreign luxury fashion brands. It is specialised in the production of linings in viscose, Cupro-Bemberg, and acetate.
Firm 8
NACE Code Rev. 2: 13.92 **Number of employees:** 42 **Turnover:** 5,906,012 € **Form of business:** Limited liability company. **Short description:** Firm 8 is a family-run business founded in the late 40s that produces household linen. The firm has always invested in the automation of production lines through innovative frames, numeric control, and automatic engines. The raw material being used is cotton, which is a natural, renewable, and biodegradable fibre that guarantees high-quality standards.
Firm 9
NACE Code Rev. 2: 13.95 **Number of employees:** 49 **Turnover:** 11,347,897 € **Form of business:** Limited liability company. **Short description:** Firm 9 is a family-run business founded in the early 1970s that produces wadding and needled felts. The first product serves the sectors of upholstered furniture such as sofas, quilts, and mattresses, whereas the second one is focused on PVC lamination and the automotive industry, which absorbs many types of nonwovens. It operates in the business-to-business market through a "just in time" logic.
Firm 10
NACE Code Rev. 2: 11.07 **Number of employees:** 159 **Turnover:** 253,741,432 € **Form of business:** Joint-stock company **Short description:** Founded in the late 1990s, Firm 10 produces bottles and distributes water throughout Italy, being a leader in the Italian mineral water sector. Aware of the environmental impact of its business model, Firm 11 has worked on several fronts seeking to reduce the environmental impact of its entire production chain. Firm 11 is pioneering in terms of robotisation in the production plant, also with the development of tailor-made technological solutions.

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APPENDIX B: PROTOCOL FOR THE EMPIRICAL INVESTIGATION

The protocol adopted for the empirical investigation is here reported. The protocol highlights the different types of primary and secondary data collected.

Source of evidence 1. Semi-structured interview (interview guide)		
Part I	General questions	• Interviewee/s introduction (role within the firm, interests, background, experience) • Firm's description (turnover, employees, sector, form of business)
	Products and processes	• What products do you produce? • What production process activities do you perform?
Part II	Circular economy	• How do you define circular economy within your firm? • What circular economy practices have you implemented? • To what extent have you implemented each practice? 1: *We are currently evaluating its implementation; 2: We are currently implementing it; 3: We have implemented it for less than 3 years; 4: We have implemented it for more than 3 years*. • Please provide an overview of the implementation of the practice—from design to service phase.
Part III	Digital technologies	• What digital technologies have you adopted? • To what extent are you using each technology? *1: We are currently evaluating its adoption; 2: We are currently adopting it; 3: We are starting using it; 4: We use it in an advance manner*. • Please provide an overview of the adoption of the technology
Part IV	Digital technologies and circular economy	• Are the digital technologies you are using supporting the implementation of circular economy practices? If yes, what type of support do they offer? • To what extent the digital technologies have supported the implementation of circular economy practices (*to be asked with reference to the impact of each used technology, on each implemented practice*)? *1: From no support to very limited support; 2: Quite significant support that nonetheless did not completely change the implementation process and/or outcome of the circular economy practice; 3: Significant but not pivotal support that changed the implementation process and/or outcome of the circular economy practice; 4: Pivotal support for the implementation process and/or outcome of the circular economy practice*.
Source of evidence 2. Field notes		
Field notes—Semi-structured interview		Field notes collected during the conduction of the semi-structured interviews with the firms (descriptive and reflective).
Source of evidence 3. Secondary data		
Firm's website and institutional reports		General firm's information; certifications; sustainability reports and initiatives.
News and press		News related to the firm, also in terms of initiatives towards enhanced sustainability

APPENDIX C: MODELS USED FOR THE ANALYSIS OF COLLECTED DATA AND PRESENTATION OF RESULTS

The models used for the analysis of data and presentation of the results are here reported.

Circular Economy Practices – Based on Garza-Reyes et al. (2019). For additional details, please refer to (Garza-Reyes et al., 2019).

Categories of circular economy practices	Circular economy practices
A. Internal practices—resource utility and efficiency	a: Designing products for reduced consumption of resources
	b: Designing products for reuse, recycle, recovery of material
	c: Designing processes for minimization of waste
	d: Designing products for durability
	e: Reducing water and raw materials
	f: Reducing energy consumption
	g. Using renewable materials/energy
	h: Reducing pollutants emissions
	i: Reducing wastes
	j: Green packaging and distribution
B. Internal awareness	a: Circular management, culture, and continuous monitoring
	b: Special training for workers
	c: Including environmental factors in the internal performance evaluation system
	d: Environmental auditing program
C. External awareness	a. Awareness with costumers
	b. Eco-labeling (clients' information)
	c. Awareness with suppliers
D. Value chain support	a. Selecting suppliers using environmental criteria
	b. Establishing eco-industrial chains
	c. Reusing energy and/or water across the value chain
E. External practices for longevity	a. Taking back products from customers (functional life)
	b. Taking back products from customers (end of life)
	c. Reusing as a business model
	d. Refurbishing as a business model
	e. Remanufacturing as a business model
	f. Recycled material for production
	g. Recycling the scrap
	h. Recycling products after the end of functional life
	i. Recycling products at the end of usage
	j. Leasing as a business model
	k. Updating as a business model
	l. Cascading use of components and materials
F. Green market development	a. Green or environmentally aware market
	b. Incentives for clients
G. Technological R&D	a. Cross-functional cooperation for environmental improvements
H. Legislation development	a. Legislation and policies

Digital Technologies—Based on the classification proposed by Rüßmann et al. (2015) and the description of the digital technologies offered by Cagno et al. (2021).

Digital technologies	Description
Internet of things (IoT)	"Technologies allowing the interaction, cooperation, collection and exchange of data among people, devices, things or objects through the use of modern wireless telecommunications"
Big data analytics (BDA)	"Information assets characterized by high volume, velocity and variety, requiring specific technology and analytical methods for being transformed into value"
Cloud/fog/edge technologies (CLOUD)	"Architectural models enabling pervasive, convenient and on-demand network access to shared resources such as networks or servers"
Cybersecurity and blockchain (CYB)	"Technologies, tools, guidelines and policies guaranteeing the protection of the cyber environment, allowing confidentiality, integrity and availability of data"
Horizontal/vertical system integration (HVSYS)	"Universal data integration network, enabling an automated value chain within or among firms by means of linking products, plants, manufacturers, customers and suppliers"
Additive manufacturing (AM)	"Production of items directly from computer aided design models, with fabrication performed layering the material; AM offers the valuable ability to build parts with geometrical and material complexity, not feasible with traditional manufacturing processes"
Autonomous robots (ROBs)	"Robots able to operate completely autonomously, to interact with each other and to cooperate with human beings; sensors and control units facilitate the autonomous decision-making process and symbiotic work with humans"
Simulation (SIM)	"A real-time reflection of the physical world (products, machines, human beings) in virtual models; it can allow testing and optimizing systems before implementing the physical change"
Augmented reality (AR)	"Technologies providing an interactive computer simulation, immersing the user in a programmed environment, simulating a sense of reality whether in the sight, in the hearing or the tactile sense"

APPENDIX D: DETAILS ON THE LEVEL OF IMPLEMENTATION OF THE CE PRACTICES BY THE INVESTIGATED FIRMS

For each CE practice proposed by Garza-Reyes et al. (2019), the level of implementation by each firm included in the sample is reported. Additionally, a detail on the total number of firms that have implemented each CE practice as well as the average level of implementation is provided too. *"Level of implementation"* legend: 1: We are currently evaluating its implementation; 2: We are currently implementing it; 3: We have implemented it for less than 3 years; 4: We have implemented it for more than 3 years.

		Firms											
Circular economy practices		1	2	3	4	5	6	7	8	9	10	Number of firms implementing the practice	Average implementa-tion level
A	a: Designing products for reduced consumption of resources		2		2						4	3	2,7
	b: Designing products for reuse, recycle, recovery of material		4								4	2	4,0
	c: Designing processes for minimization of waste	2				3	2			3		4	2,5
	d: Designing products for durability	1										2	2,5
	e: Reducing water and raw materials	1	3	3	3	2			3		3	7	2,6
	f: Reducing energy consumption	1	3		3	2	3	3	1	1		8	2,1
	g. Using renewable materials/energy	3	4	4	4			3	2			6	3,3
	h: Reducing pollutants emissions	3		3	2				1			4	2,3
	i: Reducing wastes	4	2	3	3	2	3	1	3	4	2	10	2,7
	j: Green packaging and distribution	1	3	1	3	1			2	2	2	8	1,9

(Continues)

	Circular economy practices	Firms 1	2	3	4	5	6	7	8	9	10	Number of firms implementing the practice	Average implementa-tion level
B	a: Circular management, culture and continuous monitoring	4	3		4		4	3				5	3,6
	b: Special training for workers	3			3			1		2		4	2,3
	c: Including environmental factors in the internal performance evaluation system				3		2					2	2,5
	d: Environmental auditing program	3			3	1		3	2	4		6	2,7
C	a. Awareness with costumers	3	1		2			2				4	2,0
	b. Eco-labeling (clients' information)	2			2			2			2	4	2,0
	c. Awareness with suppliers				3							1	3,0
D	a. Selecting suppliers using environmental criteria	2			2			3		3		5	2,8
	b. Establishing eco-industrial chains	2		3			3	1		2		5	2,2
	c. Reusing energy and/or water across the value chain												
E	a. Taking back products from customers (functional life)		3									1	3,0
	b. Taking back products from customers (end of life)												
	c. Reusing as a business model												
	d. Refurbishing as a business model												
	e. Remanufacturing as a business model												
	f. Recycled material for production				3	2				4	2	4	2,8
	g. Recycling the scrap												
	h. Recycling products after the end of functional life												
	i. Recycling products at the end of usage		4									1	4,0
	j. Leasing as a business model												
	k. Updating as a business model												
	l. Cascading use of components and materials												
F	a. Green or environmentally aware market				3					1	2	3	2,0
	b. Incentives for clients												
G	a. Cross-functional cooperation for environmental improvements	3	3				3	2				4	2,8
H	a. Legislation and policies	3										1	3,0