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What digital-enabled dynamic capabilities support the circular economy? A multiple case study approach

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Abstract

Circular economy and digital technologies are crucial topics in the current academic and managerial debates. It is largely recognised that - although related to different paradigms - digital technologies could support the industrial circular transition, fostering the adoption of circular economy practices. So far, the relationship has been studied by directly linking the adoption of digital technologies to the implementation of circular economy practices; however, indications for practitioners are unclear. There is thus the need to investigate the relationship at a deeper level. This paper aims at contributing to the debate by adopting a dynamic capabilities theory perspective. By employing an explorative multiple case study methodology and based on an abductive logic, this study investigates 11 Northern-Italy industrial firms in order to understand the transformations that occurred following the adoption of digital technologies and how these transformations supported the adoption of circular economy practices. The results shed preliminary light on which dynamic capabilities – sensing, seizing, and transforming, and their related microfoundations – can be enabled by the different digital technologies and how these capabilities and microfoundations support the circular transition. The study thus provides a first-of-a-kind investigation and suggests propositions for further research to better deepen the knowledge of digital-enabled dynamic capabilities supporting industrial circular economy.

Keywords: Circular Economy; Sustainability; Practices; Industry 4.0; Digital Technologies; Digitalisation; Dynamic Capabilities; Case Study

1. Introduction

The challenges posed by rapid economic and technological development, climate change, and resource depletion are deeply shaping society (Govindan & Hasanagic, 2018). These transformations create new needs and opportunities in the industrial sector (V. Kumar et al., 2019). In this scenario, Circular Economy (CE) represents a fundamental approach thanks to its ability to shape a positive vision of the future of the industrial sector and bridge the gap between economic and environmental sustainability and social aspects (Cagno et al., 2023; Helander et al., 2019). CE is an economic system replacing 'the "end-of-life" concept by reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes' (Kirchherr et al., 2017); the implementation of CE requires operations at the nano, micro, meso and macro levels (de Oliveira et al., 2021), and it should go beyond the single firm and focus at least on the industrial system in which the firm operates (Figge et al., 2022), such as the supply chain or the industrial district (Cagno et al., 2023). In this context, CE practices are crucial because actions and interventions focused on CE aspects enable firms to improve the related performance (Elf et al., 2022; Garza-Reyes et al., 2019).

A second current pivotal macro-topic in the industrial sector is the adoption of digital technologies (DTs), key pillars of the fourth industrial (I4.0) revolution (Brunelli et al., 2017). The revolution is based on integrated, adapted, optimised and interoperable production processes and on the facilitation of connections with suppliers, customers, and stakeholders, thanks to the exploitation of the latest technological innovations (Lopes de Sousa Jabbour et al., 2018; Upadhyay et al., 2021). The largest shared classification for DTs is the one proposed by Rüßmann et al. (2015). This classification identifies the following main families of DTs: the Internet of Things (IoT); big data and data analytics; cloud technologies; cybersecurity and blockchain; horizontal and vertical systems integration; simulation; augmented reality; autonomous robots; additive manufacturing.

Based on recent managerial and academic debates, the integration between CE and DTs can support firms willing to be more competitive and sustainable (Khatami et al., 2023; P. Kumar et al., 2021). As both CE and DTs are relatively new topics, there is no mature or exhaustive discussion yet on their relationship, particularly the overall guidance on how DTs can support the circular transition of industrial firms is limited (Kristoffersen et al., 2020; Neri et al., 2023).

The discussion is mainly conducted from an operative perspective, trying to understand what DT(s) can directly support the implementation of actions addressing specific aspects of CE. However, the latest developments (Chari et al., 2022; Kristoffersen et al., 2020; Vacchi et al., 2021) hint a non-direct relationship between DTs adoption and CE practices implementation. Particularly, it has been suggested that the supporting role of DTs could derive from - and thus be mediated by - the generation of dynamic capabilities (DCs) enabled by the adoption of DTs. Indeed, the presence and adoption of a single DT or a set of DTs seems insufficient to durably modify a firm's competencies (Mohammadian et al., 2022; F. Yu et al., 2021). Rather, the transformation allowed and supported by DTs appears to be led by the enhancement and development of DCs (Vial, 2019), of which DTs are recognised as enablers (Owoseni et al., 2022; Savastano et al., 2022). On the other hand, the presence and leverage of DCs are key to the adoption of CE practices (Chari et al., 2022; Elf et al., 2022; Santa-Maria et al., 2021). It is thus evident that the investigation of the relationship between DTs adoption and CE practices implementation from a direct perspective, although interesting, might pose severe limitations to the understanding of the digital-enabled transformation happening within firms and leading to the adoption of CE practices. To the best of the authors' knowledge, the extant literature is missing such a perspective. This research thus aims at addressing the identified gap by investigating the following research question:

What DCs, enabled by DTs, support the adoption of CE practices in industrial firms?

The remainder of the paper is structured as follows. The theoretical frame and the background for the research are offered (Section 2 and Section 3, respectively). After the presentation of the methodology being employed (Section 4), the results of the study are illustrated (Section 5). Results are then discussed and compared with the extant knowledge, leading to the suggestion of propositions for future research (Section 6). Lastly, conclusions are offered (Section 7).

2. Theoretical Framing: Dynamic Capabilities Theory

A capability is the ability to perform an activity (Helfat et al., 2007). Capabilities are divided between operational and dynamic ones (Collis, 1994; Winter, 2003). DCs are defined as 'the capacity of an organization to create, extend, or modify its resource base' (Helfat et al., 2007) - that is, routines, processes, tangible, intangible, human assets, and capabilities themselves (Eisenhardt & Martin, 2000; Helfat et al., 2007), in a repeatable manner (Helfat & Peteraf, 2003). DCs allow firms to constantly reconfigure and renew operational capabilities (Ambrosini et al., 2009; Protogerou et al., 2012). The renovation of capabilities is necessary so as to keep pace with a constantly evolving scenario, particularly by 'adapting, integrating, and reconfiguring internal and external organizational skills' (Teece et al., 1997), through technological, organizational, and strategic innovation (Helfat et al., 2007).

Therefore, firms should be able to detect the opportunity to transform their organisation. In this regard, Teece (2007) defined three steps: *sensing* the opportunity; *seizing* the opportunity by designing and refining the business model and committing resources; *transforming* aspects of the organisation, and realigning the structure and the culture (Teece, 2018). DCs are bolstered by microfoundations, defined as 'skills, processes, procedures, organizational structures, decision rules, and discipline' (Teece, 2007). In order not to treat capabilities as a black box, Felin et al. (2012) strongly recommend focusing on the origin of capabilities going through microfoundations, namely studying the sub-elements of DCs. Indeed, only the study of microfoundations can provide an appropriate nuanced overview of what constitutes different DCs (Dixon et al., 2014).

3. Background

3.1. The relationship between Digital Technologies and Circular Economy

Both DTs and CE are emerging and pivotal topics in the current debate, and more guidance is needed to understand how DTs can support the circular transition in industrial firms (Neligan et al., 2022). The increasing number of contributions addressing the topic proves the growing interest in it (Agrawal et al., 2022). The literature remarkably agrees that the relationship between CE and DTs is critical for achieving the transition from a linear to a circular production model (Ertz et al., 2022; Patyal et al., 2022). So far, the studies have analysed the relationship from an operative perspective, trying to understand how DTs - in general or only focusing on a limited set of them - directly impact the implementation of selected strategies of CE, such as recycling (Kintscher et al., 2020) or remanufacturing (Bag, Dhamija, et al., 2021), or the management of sustainable and circular products (Pinheiro et al., 2022; Rusch et al., 2022). Nonetheless, it is not clear how DTs impact the implementation of selected CE practices – for a complete overview of previous literature please refer to Cagno et al. (2021). As proof, Okorie et al. (2021) clarify the role of DTs for incentivising and supporting the adoption of circular business models, noting a relevant role of DTs as factors influencing the value creation on value delivery steps, yet no specific DTs are considered. Subramoniam et al. (2021) focus only on the relevance of data and their analysis, underlying that the integration of a digitised product life cycle into the business model improves both product returns and remanufacturing processes. The relevance of smart data is also underlined by Vacchi et al. (2021), who empirically investigate their potential in the re-engineering of ceramic products in the Italian tile industry. Furthermore, Ghoreishi & Happonen (2022) focus on the adoption of IoT in the textile sector for data exchange among the different actors of the industrial system, raising awareness on circular opportunities. Z. Yu et al. (2022) focus on the automotive sector and assert that I4.0 technologies can improve the adoption of circular purchase and design practices, opening new horizons for CE; nonetheless, they do not investigate any specific DT and approach CE practices from an aggregated perspective. Neri et al. (2023), focusing on small and medium enterprises, underline the relevance of, IoT, big data analytics and robots in supporting the implementation of a variety of CE practices. Additionally, they also provide preliminary insights on the support towards circular transition offered by the joint adoption of multiple DTs.

All things considered, despite the great interest in the topic among academics, the discussion results in an unclear picture for practitioners (Q. Liu et al., 2022; Z. Liu et al., 2021; Massaro et al., 2021). Many indications, in fact, remain at an early conceptual stage, with empirical evidence overall missing (Gebhardt et al., 2021; Ghoreishi & Happonen, 2022). Deepening the knowledge of the role of specific DTs in supporting the implementation of CE practices is necessary to allow the industrial circular transition (Cagno et al., 2021); it is particularly important to understand which transformations enabled by DTs can support CE practices implementation.

3.2. The Role of Digital-enabled Capabilities in supporting Circular Economy

An interesting perspective on the role of DTs in enabling CE in the industrial sector has arisen recently. Vacchi et al. (2021) empirically show that the benefits of I4.0 in supporting CE, besides operational efficiency, are due to the organisational innovation allowed by DTs; DTs are thus not directly impacting the CE transition, rather they support product innovation and consequently the re-engineering of the raw material sourcing system, ultimately impacting on the circular transition. Additionally, although their work remains at a conceptual stage, Kristoffersen et al. (2020) focus on business analytics capabilities related to the adoption of IoT and big data and analytics to support the implementation of CE, thus suggesting that their supporting role could be actually fostered by the development of capabilities. Chari et al. (2022) emphasise the role of I4.0 as a microfoundation of DCs that can favour the implementation of CE practices, focusing especially on data analytics capabilities, advanced manufacturing, and skills and knowledge. Di Maria et al. (2022) suggest that supply chain integration is a relevant capability linking smart manufacturing technologies – such as robots, cyber-physical systems, additive manufacturing and augmented reality, and superior CE performance.

Therefore, it is generally recognised that DTs can support the transformation of the industrial sector, influencing business models and operating modes (Gökalp & Martinez, 2021) and enabling and enhancing the DCs (Roscoe et al., 2019; Savastano et al., 2022; Teece, 2018). For instance, Garbellano & Da Veiga (2019) observe how the introduction of I4.0 in Italian small-medium enterprises helped them renew capabilities, especially allowing the improvement of economic and production-related performance in a continuum with their traditional strategy and helping to further DCs (Gupta et al., 2020). Witschel et al. (2019) give relevance to the relational capabilities that support inter- and intra-organisational collaborations for a more efficient and effective implementation of digitisation initiatives. Mrugalska & Ahmed (2021) stress the relevance of DTs in supporting operational agility. Felsberger et al. (2022) also show that DCs deriving from the adoption of DTs can support the improvement of sustainability-related performance, with a focus on capabilities in the data analytics segment.

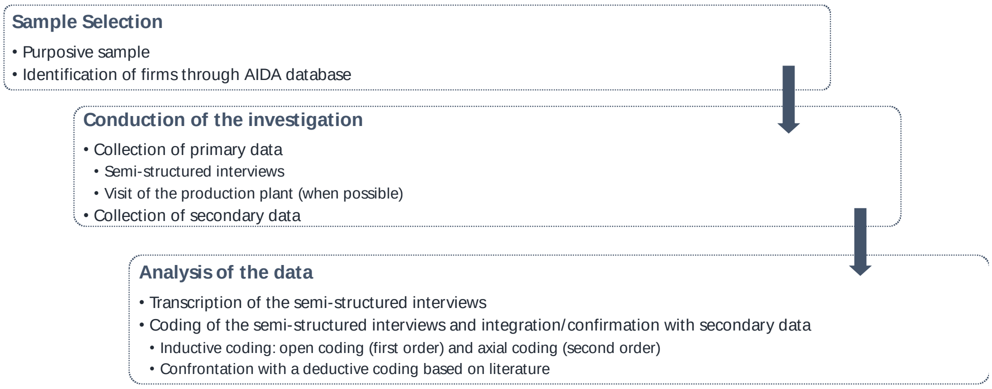
On the other hand, DCs are needed to accelerate CE transition (de Angelis et al., 2023; Köhler et al., 2022; Seles et al., 2022), as they can support the implementation of CE practices (Chari et al., 2022; Elf et al., 2022). Part of the literature focuses on specific strategies for CE. As proof, Fernandez de Arroyabe et al. (2021) concentrate on the DCs needed for the development of new products aligned with the circular business model. Marín-Vinuesa et al. (2021) investigate eight capabilities applied by firms to waste-related patents, as an indicator of circular innovation, underlying the role of persistent and collaborative innovation. Ritola et al. (2021) focus on the DCs to exploit the opportunity deriving from the information related to product return, concentrating on incremental and continuous learning. Wade et al. (2022) address the capabilities to create products from waste, evaluating their development over time. Another portion of literature addresses different aspects of and strategies for CE. For instance, Prieto-Sandoval et al. (2019) identify nine DCs among the internal factors that can support small and medium enterprises in their circular transition. Marrucci et al. (2022) consider DCs as a strategy to foster CE and focus on capabilities leading to the internalisation of the environmental management system. Elf et al. (2022) aim their attention at DCs needed by micro, small and medium enterprises operating in the fashion industry for advancing CE, underlining the relevance of close interaction with customers. Some of the DCs fostering the CE transition are enabled by innovation and technology. From this standpoint, Khan et al. (2020a) document the crucial impact of technological upgrades and research and development on transforming and sensing capabilities, an impact which was later confirmed by Santa-Maria et al. (2021). Khan et al. (2020b) propose a list of DCs where technological advancement and knowledge are central aspects that provide huge opportunities for CE. Coppola et al. (2023), focusing on the textile sector, investigate the

DCs needed for properly implement strategies of pollution prevention, product stewardship, and sustainable development.
It is thus evident that i) DTs allow the development and upgrade of dynamic capabilities; ii) CE needs DCs to be implemented; iii) DCs might arise from the adoption of technologies. The relationship between DTs and CE appears thus more complex than the direct one addressed by the extant literature (Chari et al., 2022). The literature has only recently started dealing with the topic. As proof, Bag et al. (2020) focus on the information process capability deriving from the adoption of Procurement 4.0.Bag, Gupta, et al. (2021) analyse how I4.0 can support the development of capabilities necessary for the adoption of the 10R framework for CE; despite providing a comprehensive perspective on CE, I4.0 is analysed from a general point of view, without focusing on specific DTs. Belhadi et al. (2022) explore the role of a large set of DTs in the development of capabilities regarding the implementation of CE practices in closed-loop supply chains. Quayson et al. (2023) identify some blockchain-driven capabilities needed for properly develop a circular supply chain. These valuable efforts are nonetheless centred only on selected aspects for both DTs and CE. On the one hand, focusing only on selected DTs might prevent the understanding of synergies among different DTs (Almeida et al., 2022); indeed, there is more than one configuration allowing the generation of DCs (Van De Wetering et al., 2019) or fostering the CE transition (Neri et al., 2023), and different DTs can contribute in different ways (Demeter et al., 2021). On the other hand, CE as well should be investigated in a holistic manner, taking into consideration the different strategies and levels of adoption (Fehrer & Wieland, 2021), as this is the only way to properly explicate it (Negri et al., 2021).
So far, the literature has not extensively explored how the digital-enabled DCs can support the CE transition; in other words, to the best of the authors' knowledge, there is no study dealing with all the different DTs families and CE practices and analysing the relationship between the two from the perspective of DCs.
In addressing the identified gap, we respond to the call of several authors. We want to contribute by providing an understanding of the digital-enabled DCs that can leverage the circular transition (Kristoffersen et al., 2020), and by offering empirical evidence which could prove useful to develop and complement theoretical arguments (Protogerou et al., 2012). Empirical evidence will also provide additional knowledge regarding the application of DTs aimed at fostering the CE transition (Agrawal et al., 2022; Q. Liu et al., 2022) by investigating the role of specific DTs supporting the transition thanks to their impact on specific CE practices (Cagno et al., 2021).

4. Methodology

To address the research question and considering the lack of preliminary research on the topic, we employed an explorative multiple case study approach (Streb, 2013). An abductive logic was applied to generate a theory based on the analysis of the case studies (Timmermans & Tavory, 2012). An abductive analysis allows for the generation of new concepts and the development of theoretical models, leading to the development of a theory (Dubois & Gadde, 2002). Rather than setting preconceived theories, in the abductive approach theories are generated through the continuous interaction and confrontation between real-life observations and existing theories (Kovács & Spens, 2005), directing the researcher back and forth from theory to practice (Timmermans & Tavory, 2012), matching theoretical framework, empirical observation, and analytical discussion (Dubois & Gadde, 2002). The abductive research is considered appropriate for the investigation of topics with limited previous exploration (Timmermans & Tavory, 2012). The research process for the methodology is reported in Figure 1.

Figure 1. The research process.



4.1. Case Selection

Cases were selected through purposive sampling (Moser & Korstjens, 2018), aiming at a theoretical replication (Schreier, 2014), with a single manufacturing firm as the unit of analysis. We focused on Northern Italy manufacturing firms. The manufacturing sector plays a central role in the European industrial sector and economy (Eurostat, 2020); it has pivotal implications for environmental impacts, but it also leads the way in terms of CE adoption (Zamfir et al., 2017) and digitalisation (Zangiacomi et al., 2020). Among the main European economies, Italy ranks first in the circularity index implementation (Circular Economy Network & ENEA, 2020) and plays a decent but constantly more relevant role in the European panorama regarding the digitalisation level (European Commission, 2021). The Italian manufacturing sector shows encouraging and interesting steps toward both CE and DTs adoption (Ghisellini & Ulgiati, 2020; Zangiacomi et al., 2020). Northern Italy represents one of the most important manufacturing districts at a national and European level (European Union, 2017).

A list of manufacturing firms operating in Northern Italy was retrieved from the database AIDA (https://aida.bvdinfo.com). Firms were contacted preliminary via e-mail or phone. Upon their acceptance to participate in the research, interviews were scheduled with knowledgeable employees, identified as key informants (Voss et al., 2002). 11 firms were included in the final sample. The number was deemed adequate: it is aligned with the literature's suggestion for multiple case studies (Voss et al., 2002) and similar research (Santa-Maria et al., 2021); it allowed us to achieve sound empirical grounding reach (Ellegaard et al., 2022), and it is in line with the researchers' process capacity (Pagell & Wu, 2009); it provided a good representation of manufacturing firms in Northern Italy in terms of sector, size, awareness, and level of CE and digitalisation. Table 1 provides an overview of the investigated sample.

Table 1. Characteristics of the sample investigated in terms of sector, size and key informants interviewed.

Firm	Sector	Employees (number)	Key informants interviewed
Firm 1	Production of rubber and plastic goods	238	Sustainability Manager Production Manager Assistant
Firm 2	Manufacture of paper and paperboard	494	Marketing Manager Executive Assistant
Firm 3	Manufacture of soft drinks; production of mineral waters	84	CEO Operations Manager Assistant
Firm 4	Work on milling and trade of products	174	Owner Production Plant Manager
Firm 5	Manufacture of other metal items and metal smallware	214	CEO Control and Quality Manager Production Manager Marketing Manager
Firm 6	Manufacture of steel welded tubes, ferrous materials, and iron metallurgical products	139	Industrial Manager Executive Assistant
Firm 7	Finishing of textiles	106	Environment, Quality and Safety Manager Digital Production Manager
Firm 8	Manufacture of other textile items	108	Manager for foreign sales and events Production, quality, and control manager
Firm 9	The manufacturing of household linen, mainly sheets, towels and related items	42	Owner Operations Manager Assistant
Firm 10	Manufacture of non-wovens and articles made from non-wovens, except apparel	49	Owner Assistant Production Manager
Firm 11	Manufacture of soft drinks; production of mineral waters	159	CEO Executive Assistant

4.2. Data Collection

The primary source of data is represented by twelve semi-structured interviews, conducted with a total of 22 interviewees from October to December 2020 – the informants of each firm were interviewed at the same time (the only exception is Firm 4). The interview protocol was designed to be flexible, allowing the collection of free comments and the emergence of additional questions during the conversation (Dicicco-Bloom & Crabtree, 2006); as a fundamental feature of abductive research, the use of a semi-structured protocol allows the informants to naturally address the peculiar aspects of each case, providing informative empirical evidence (Timmermans & Tavory, 2012). Before the interviews, the researchers reviewed publicly available documents about the firms (e.g. websites and company reports). The semi-structured interviews lasted on average about 2h.

Interviewees were first asked to provide general information about the firm, i.e. characteristics, products, and production process. Informants were then required to provide a definition of CE and to report how CE is implemented in their firms by citing practices and explaining the decision-making and adoption processes. Later, interviewees were asked to provide information regarding DTs adopted within their firm, their impact on production processes and the adoption of CE practices. Lastly, the interview focused on the microfoundations enabled by the adoption of DTs and connected to the implementation of CE practices and the overall firm's circular transition. A relevant aspect at this stage was the operationalisation of the concept of dynamic capabilities and the related microfoundations. In this regard, we decided to allow for an easy understanding of the concepts by the respondents, asking them to recall skills, processes, and procedures that were enabled by the adoption of DTs and that possibly supported the implementation of CE practices, leveraging on Elf et al. (2022) and Santa-Maria et al. (2021).

Seven interviews were conducted in person - Firms 3, 4, 5, 7, 8, 9, and 10 - whereas the remaining five were conducted on Skype or MS Teams, due to the Covid-19 emergency. All the interviews were recorded upon participants' expressed consent, and during their conduction the researchers took notes. The face-to-face interviews were complemented by on-site observation at facilities, during which the researchers took notes as well. An overview of the different sources of primary and secondary data is available in Appendix A. Methodological rigour was ensured by assessing the four design tests suggested by Yin, (2009) against tactics suggested by the literature – please refer to (Barratt et al., 2011; Baškarada, 2014; Benbasat et al., 1987; Beverland & Lindgreen, 2010; Eisenhardt, 1989; Hays, 2004; Meredith & Vineyard, 1993; Rowley, 2002; Voss et al., 2002; Yin, 2009). As for construct validity, we developed a chain of evidence also by creating an organised electronic folder containing all the data for each case, and triangulated evidence from different sources; thanks to the multiple sources of evidence and the matching process (Mousavi et al., 2019), we could guarantee the internal validity, while the external validity was assessed through the specification of the population and the multiple case studies; reliability was assured by the multiple case studies and the use of a case study protocol, whereas the presence of multiple interviewers (at least 2 for each interview) mitigated the risk of research bias.

4.3. Data Analysis

Interviews were transcribed (verbatim), resulting in 123 pages of transcripts. They were subsequently manually coded together with field notes and secondary collected documents. The software NVivo 12® was used to compile the data into a case study database facilitating the coding and ensuring additional rigour (Yin, 2009).
The abductive research approach for theory generation and development requires continuous and cyclic interaction between the data from empirical evidence and the extant literature (Eisenhardt & Graebner, 2007). For first-order coding, we applied an open coding with themes emerging inductively from the data and permitting the identification of the main aspects in the general content; for second-order coding, axial coding was applied to combine related codes and identify relevant categories. The selected coding methods are appropriate for a rigorous process of theory development (Fontana et al., 2022; Santa-Maria et al., 2021). The inductive coding was then compared with a coding system developed based on the extant literature, trying to find a conciliation with literature concepts (Silva et al., 2018). For this step, we used the frameworks proposed by several authors (Garza-Reyes et al., 2019; Rüßmann et al., 2015; Santa-Maria et al., 2021; Teece, 2007; Witschel et al., 2019) as a base.

The coding was performed independently by at least 2 different researchers, and the final coding structure was revised and approved by all the authors. The data structuration and the analysis process are reported in Figure 2 and

Figure ***3***, respectively. Considering the obtained results, we developed a series of propositions, following Eisenhardt & Graebner (2007)

Figure 2. Data structuration and analysis process – details on Digitalization and Dynamic Capabilities.

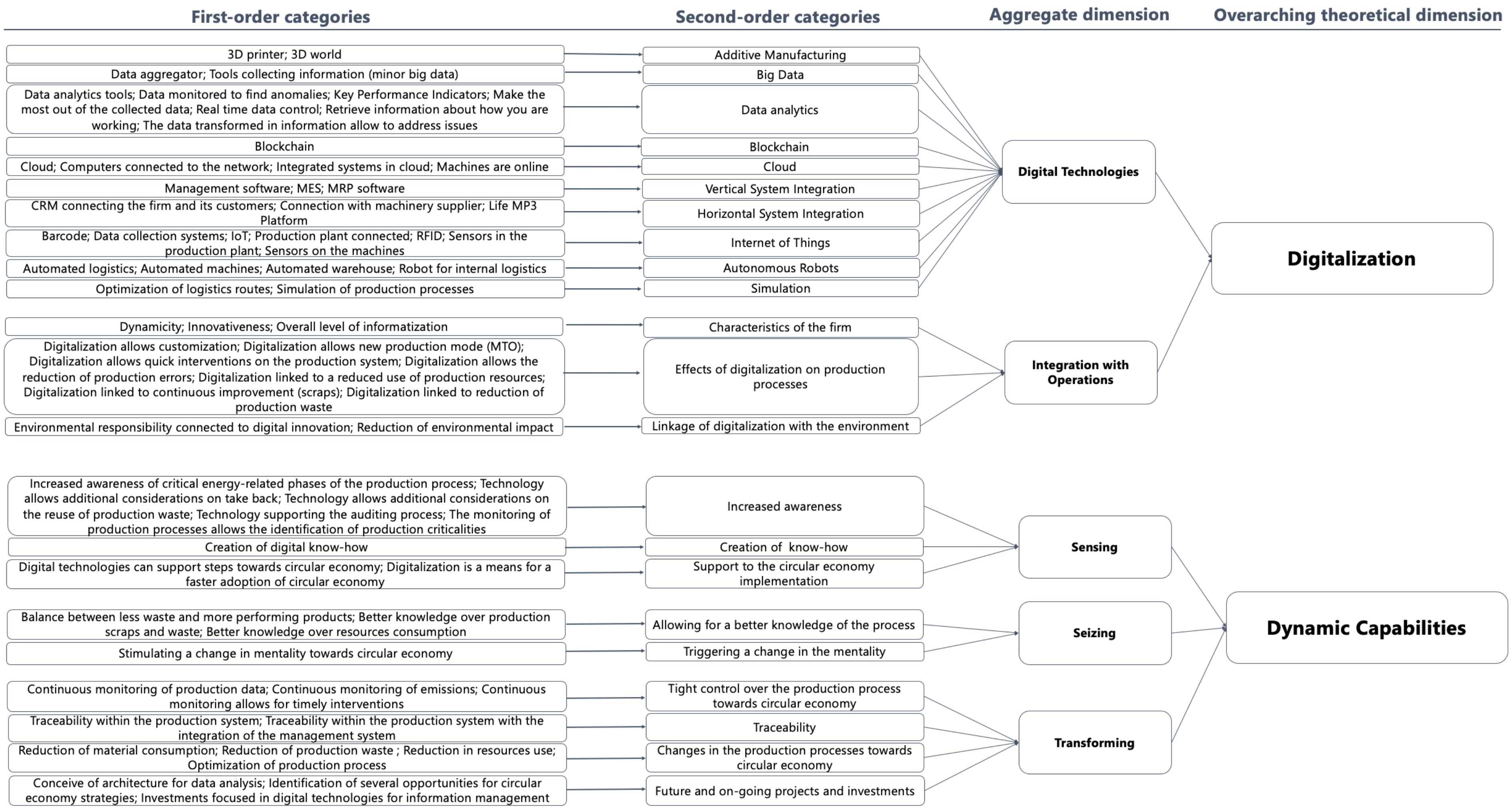
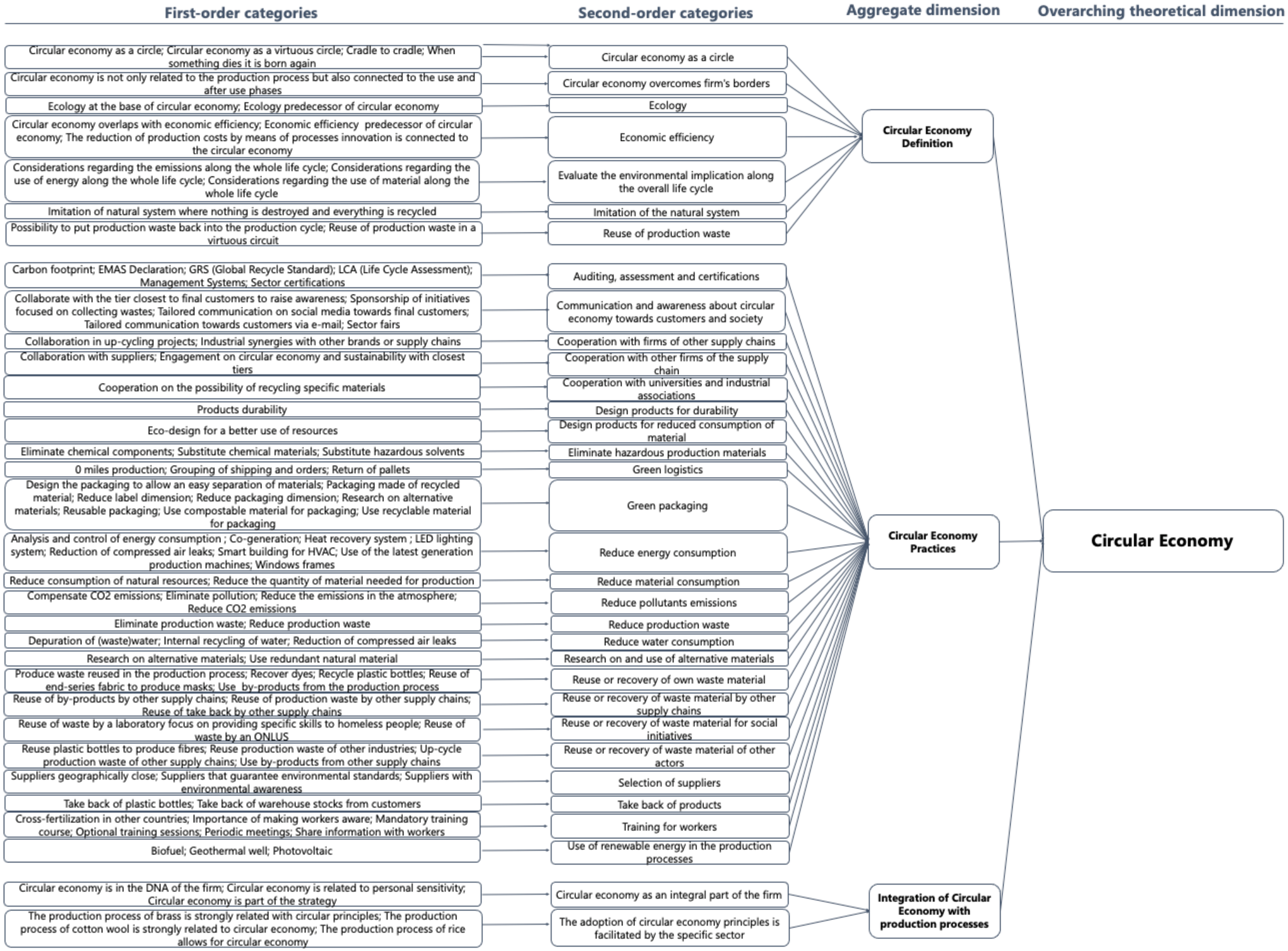


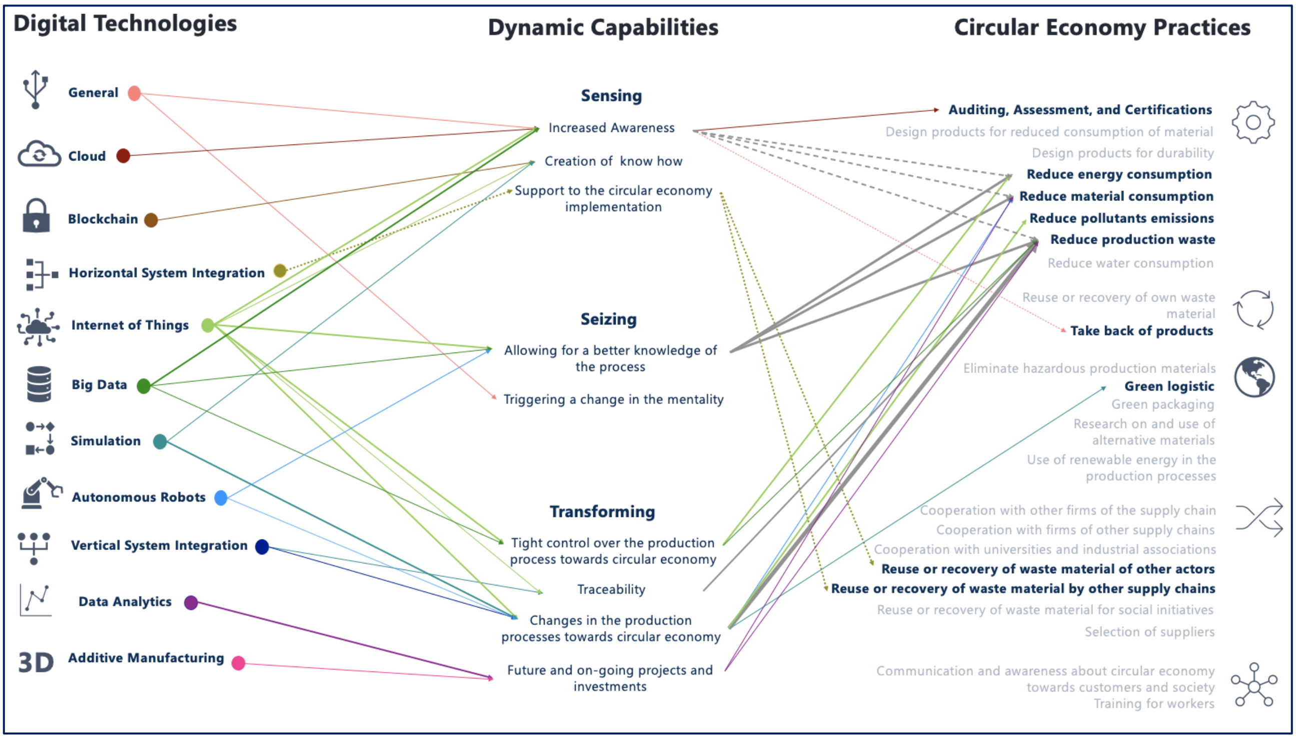
Figure 3. Data structuration and analysis process – details on Circular Economy.



5. Results

The results obtained in terms of DTs, DCs and CE practices characterising the investigated sample, as well as the links among the three, are reported in Figure 4. Then we provide the following: i) the overview of the sample investigated in terms of adopted DTs and implemented CE practices, compared with previous research aimed at characterising the sample being investigated; ii) the presentation of the DCs that emerged and of the links in terms of DTs supporting or enhancing each specific capability and microfoundations, and in terms of CE practices supported by each specific capability. The overall presentation of the results is reinforced by exemplary quotes as emerged from the empirical investigation.

Figure 4. Relationships among DTs adopted, DCs enabled, and CE practices implemented. On the left side of the picture, the DTs adopted by the investigated sample are reported. To each DT, a colour is assigned. The arrows departing from the DTs towards the DCs indicate that the specific DT has a role in enabling the specific capability. The arrows' thickness indicates the frequency of observation (a thicker arrow indicates a higher number of evidence). On the left side of the picture, the full list of CE practices implemented in the sample investigated is reported. The arrows departing from the DCs indicate that the specific capability is relevant for the adoption of the selected practice. The arrows connecting the DCs to the practices are characterized by different colours and thicknesses. The colours are related to the specific DT supporting the relationship; a grey arrow means the relationship is supported by more than one DT. The arrows' thickness indicates the frequency of observation. A dotted arrow indicates that the relationship is identified by the informants, but not exploited.



5.1. *Characterisation of the investigated sample.*

The investigated sample adopted DTs related to all the families proposed by Rüßmann et al. (2015) (Figure 4) - for a complete overview of the DTs adopted by each firm please refer to Appendix B. The most adopted DTs relate to the informatisation of firms and production lines, e.g. IoT, vertical systems integration and cloud infrastructure. To make the most out of the data collected through IoT, quite many firms adopted DTs for the management and analysis of data in line with Alcayaga et al. (2019).

‘The state of data processing, that was previously lacking, now actually allows us to do more activities [...] this type of data transformed into information allows me to direct the technical interventions primarily aimed at resolving major issues’ – Firm 5, CEO

Horizontal systems integration emerged as relevant as well due to its implications, for example, on the management of maintenance and the relationship with customers.

‘Machines are directly connected with the manufacturer, who tells me when it is time to do preventive maintenance because I reached the maximum operating hours [...] our 3D printer is connected with B., in Spain, and they know when it is going to stop before we do’ – Firm 5, CEO

‘We would like the customers to be able to draw on, go and see the situations, and have the information they need without physical interaction’ - Firm 9, Owner

The sampled firms linked DTs with several production-related improvements, among which reduction of production inputs and continuous improvement.

‘ [Technology] *led to a different mentality towards continuous improvement. Not only do we calculate and measure the waste, but we also try to understand where they come from. This allows us to detect sources of problems’ - Firm 11, CEO*

The sampled firms mainly addressed CE from an internal perspective (Figure 4) – for a complete overview of the CE practices implemented by each firm please refer to Appendix B. The definitions of CE provided by the firms mainly link CE to economic efficiency, evaluation of environmental impacts and the overall production process, as well as to the reuse of production waste within the production process.

‘Many things that are done and addressed as circular economy and sustainability, they are economic efficiency’ - Firm 10, Owner

‘Circular economy means using waste materials as secondary raw materials within a virtuous circuit that allows zeroing or limiting waste’ - Firm 1, Sustainability Manager

Moreover, the idea of CE as a virtuous circle imitating the natural system emerged.

‘When I think about circular economy, I have the shape of a circle in mind’ - Firm 5, Control and Quality Manager

‘If we can commit to implementing technologies, systems, and practices aimed at minimising the use of resources and recycling as much as possible, we are getting closer to what the natural system does’ - Firm 2, Marketing Manager

Focusing on the implemented CE practices, the largest share relates to resource consumption and efficiency, and to reduction of production waste. A considerable effort emerged for the application of CE principles for packaging, spanning from the research and use of different and alternative materials to the design of new packaging to changes in the labels.

'Cardboard is recoverable, while plastics rarely are because they are not mono-polymers and in the reuse supply chain they are not well received. We are therefore trying to find alternative plastics' - Firm 4, Production Plant Manager

'These materials cannot be replaced because if, on the one hand, paper is already biodegradable, on the other hand, there are no bioplastic shrink wraps that can perform the same task yet... wooden pallets are recyclable... so what we have worked on is the separation of materials, to make the shrink wrap easily separable from the sack and the paper wrapping" – Firm 2, Marketing Manager

Another set of largely implemented practices relates to reuse and recycling. They take place in three manners: the firm reuses its production waste; the firm reuses the production waste of other firms; other firms reuse the production waste.

'I try to make waste a resource, reusing my trimming' - Firm 10, Owner

'Ferrous sulphate comes from drawing mills, we use it as a raw material in the production process; the sulfuric acid we use is an acid derived from pharmaceutical waste' - Firm 7, Environment, Quality, and Safety Manager

'There are specialised companies that deal with the recovering of the waste yarn that comes from weaving, they process it and create by-products such as anti-noise material for cars, or the mats that go under pavements' – Firm 9, Owner

'The ash, a combustion residue, is sold to steel mills' - Firm 4, Production Plant Manager

The introduction of a cycle for resources, providing a more systemic implementation of CE (Garza-Reyes et al., 2019), is also connected, although to a limited extent, to collaboration and cooperation with partners operating in the same or in other supply chains.

'We asked the supplier for an alternative to virgin plastic. They proposed an alternative containing up to 50% recycled sources that costs even less' - Firm 5, CEO

'They asked us to activate an up-cycling project by converting the bran from a by-product to a raw material for the production of paper for packaging and communication' - Firm 2, Marketing Manager

The overall scenario might underline that firms are conscious of the potential of DTs, but still not ready for a systemic transition (Gökalp & Martinez, 2021); applications in fact are mainly related to information and technology and still limited in terms of digital processes transformation. The level of DTs adoption and the type of DTs adopted by our sample are in line with previous research in similar contexts – see (Brodny & Tutak, 2021; Małkowska et al., 2021; Pirola et al., 2020; Zheng et al., 2020).

As for CE, research showed a focus on the micro-level of application and a missing link between CE and social aspects for the sustainability-related domains. Findings in terms of implemented practices appear aligned with previous evidence – see Antonioli et al., 2022; Bjørnbet et al., 2021; Franzò et al., 2021; Masi et al., 2018; Mura et al., 2020.

Globally, the sampled firms adopted DTs in order to support specific aspects of operations and production processes, only later realising the possibilities deriving from the exploitation of DTs to foster the implementation of CE practices.

> *'This is the goal of technology. There is the emotional part linked to ecology, respect for the environment, less plastic, emissions, then there is the real part, not having waste, increasing productivity, managing batches of production' - Firm 3, CEO*

> *'Circular economy is the aim, digitalisation might be a means to achieve it' - Firm 5, Production Manager*

It is thus reasonable to support the idea that DTs might not act directly on the implementation of CE practices, rather they can enable firms' capability, fostering, in turn, the adoption of CE practices.

5.2. Dynamic Capabilities supporting the adoption of Circular Economy Practices

5.2.1. Sensing

DTs allow sensing new opportunities for CE, with 3 microfoundations emerging (Figure 4). The first microfoundation relates to *increased awareness*, especially on the production process. The microfoundation is linked to digitalisation in general, with evidence connecting it with the cloud and particularly with IoT and big data (Figure 4).

> *'As for waste optimisation, [DTs] allow us to make some considerations, we are still trying to understand how to manage and reuse waste, but it is already a step forward' - Firm 8, Production, Quality, and Control Manager*

A specific link in terms of increased awareness emerged between cloud and auditing as well.

> *'The cloud is extremely helpful for auditing, also because everything is recorded' - Firm 5, CEO*

> *'There is no control of the returnable… there is no need... but thinking about it, it could be useful for having a statistic of took-back or shattered ones' - Firm 3, CEO*

The second microfoundation concerns the *creation of know-how*, as the adoption of DTs can support improvements in terms of know-how related to DTs and processes. Based on data, the microfoundation is linked to the adoption of blockchain, IoT and simulation.

> *'The simulation of different production scenarios allowed us to immediately optimise the production plan, it's a structured process for sharing know-how' - Firm 1, Sustainability Manager*

The *creation of know-how* is not directly related to selected CE practices, rather it is recognised as useful for fostering the CE transition in general, also in view of better identification of the market's needs.

> *'We started a process of sharing digital know-how that will allow the development of new products to respond to the market's changing needs' - Firm 1, Sustainability Manager*

The third microfoundation relates to the *support to the CE implementation*. This is the case of the horizontal systems integration, recognised by several sampled firms as important to support the exchange of waste within the same supply chains or among different supply chains (Figure 4).

> ' [Name of the system] *creates a bridge between the need for potential secondary raw materials and the availability of waste' – Firm 1, Sustainability Manager*

> *'It is an online platform where companies from different sectors make their waste available to those interested in using it' - Firm 8, Manager for foreign sales and events*

5.2.2. Seizing

DTs allow seizing new opportunities for CE, thus designing and refining the business model and committing resources, and 2 microfoundations emerged (Figure 4).
The first one is *allowing for a better knowledge of the process*, as more in-depth knowledge of the process led a considerable number of firms to modify their processes and procedures. The microfoundation is linked to different DTs such as big data and robots, and IoT (Figure 4).

> *'The control on the activity is continuous... we have a tool that collects all the information, a small big data, we are not talking about billions of operations, but hundreds of thousands of operations: 30,000 customers, having to deliver bowls, glasses, maintenance, breakdowns, are hundreds of thousands of operations' - Firm 3, CEO*

Better knowledge of processes is also linked to reorganisation and improvement of processes, particularly concerning the reduction of energy and material consumption and the minimisation of production waste, as confirmed by several informants (Figure 4).

> *'Not only do we calculate and measure waste, but we also try to understand where it comes from' - Firm 11, CEO*

The second microfoundation is *triggering a change in the mentality*. Informants suggested that digitalisation is driving a shift in the top management mentality that could allow an advancement of the CE transition.

> *'It is a tool we need to stimulate a mentality change in favour of circularity' - Firm 10, Owner*

5.2.3. Transforming

DTs support the transformation of the organisation towards the adoption of CE practices, and 4 microfoundations emerged (Figure 4).

The first microfoundation relates to *tight control over the production process towards CE*. Thanks to DTs, firms transformed their activity and implemented stricter controls over their production processes, particularly thanks to IoT and additive manufacturing (Figure 4).

> *'We have sensors throughout the system detecting the emissions produced by fumes and system stability parameters, such as temperature, steam, pressures' - Firm 4, Production Plant Manager*

The *tight control over the production process towards CE* significantly benefits the reduction of production waste, emissions, and energy consumption (Figure 4).

> *'They are fundamental systems, not because they make you reduce waste by producing better, but because they tell you where the material is. In this way, you do not lose it, you do not reproduce it, and above all, you produce the right quantity' - Firm 6, Industrial Manager*

> *'The timeliness of intervention prevents the waste of time that could impact the system's efficiency, above all from an environmental point of view' - Firm 5, Production Manager*

The second microfoundation is *traceability*. DTs support the firms in tracing materials, products, and processes along the overall production chain. Traceability emerged as supported by vertical systems integration and IoT (Figure 4).

> *'The traceability is guaranteed by the manufacturing execution system, which tells you, step by step, where the material is' - Firm 6, Industrial Manager*

Based on our investigation, *traceability* is strongly connected to the implementation of practices concerning the reduction of production waste (Figure 4).

> *'It allowed us to reduce wasted time, e.g. to search or remember where a roll was or if and why it stopped at a certain stage' - Firm 7, Environment, Quality and Safety Manager*

The third microfoundation concerns *changes in the production processes towards CE*. DTs as IoT, robots, and simulation support the emergence of the capability. In the investigated sample, the changes in the processes are strongly related to the reduction of production waste and material consumption (Figure 4).

> *'The introduction of the robot has reduced the plastic use by 40%' - Firm 11, CEO*

> *'Until a few years ago we used to send the samples from one place to another to understand if they were functional. Today, we have 3D, we print them here and tell them to make certain changes, avoiding waste, pollution, and environmental impact' – Firm 1, Sustainability Manager*

Interestingly, simulation, allowing process changes, also led to the implementation of practices related to green logistics.

> *'We decided that each operation takes a certain time; the programme takes the activities in the evening at 6 p.m., takes 1,000 activities to do, goes to the*

management system, checks the characteristics, and divides activities by regional area' - Firm 3, CEO

The last microfoundation relates to *future and ongoing projects and investments* carried out by sampled firms at the time of the investigation. Projects and investments related to big data and analytics are aimed at reducing material consumption and production waste (Figure 4).

'Luckily, we have no waste from the production of rice. With innovation we maximised the different productions in alternative manners' - Firm 4, Production Plant Manager

'Recently we have made more investments in areas like the organisation and management of information rather than production capacity: it is not a matter of producing more, but of producing better' - Firm 9, Owner

Table 2 shows the details of the DCs and microfoundations identified in each firm under investigation.

Table 2. DCs and microfoundations emerged during the investigation.

Dynamic capability	Microfoundation	Detailed Microfoundation	Firm										
			1	2	3	4	5	6	7	8	9	10	11
Sensing	Increased awareness	Increased awareness of critical energy-related phases of the production process					■						
		Technology allows additional considerations on take back			■								
		Technology allows additional considerations on the reuse of production waste								■			
		Technology supporting the auditing process					■						
		The monitoring of production processes allows the identification of production criticalities					■		■				
	Creation of know-how	Creation of digital know-how	■										
	Support to the circular economy implementation	Digital technologies can support steps towards circular economy			■		■			■			
		Digitalization is a means for a faster adoption of circular economy					■						
Seizing	Allowing for a better knowledge of the process	Balance between less waste and more performing products	■										
		Better knowledge over production scraps and waste										■	■
		Better knowledge over resources consumption			■	■							
	Triggering a change in mentality	Stimulating a change in mentality toward the circular economy										■	
Transforming	Tight control over the production process towards circular economy	Continuous monitoring of production data		■		■		■					
		Continuous monitoring of emissions				■							
		Continuous monitoring allows for timely interventions					■						
	Traceability	Traceability within the production system							■				
		Traceability within the production system with the integration of the management system						■					
	Changes in the production processes towards circular economy	Reduction of material consumption							■				■
		Reduction of production waste	■	■				■	■				
		Reduction in resources use	■	■									
		Optimization of production process	■		■								
	Future and ongoing projects and investments	Conceive architecture for data analysis					■						
		Identification of several opportunities for circular economy strategies				■							
		Investments focused on digital technologies for information management									■		

6. Discussion and propositions for future research

Our results confirm that DTs can be a strong ally for the circular transition in industrial firms. However, said results also show that DTs are not acting on the CE practices implementation through a direct relationship, rather it is the enabled transformation of skills, procedures, and processes that supports the implementation of the circular transition, through what Vial (2019) defined as a digital-enabled transformation. This study provides an overview of digital-enabled DCs for CE implementation: newly compared to previous literature, we tried to establish a connection between the single DTs enabling and generating the capabilities and the single CE practices being adopted.

Considering the intrinsic novelty, the discussion on the role of DCs in fostering the support of DTs to the implementation of CE practices is far from being complete and completed. Reasoning on the results obtained, we hereby suggest a series of propositions to be

further investigated for a complete understanding of the dynamics linking together DTs, DCs, and CE practices implementation.
DTs enable capabilities related to sensing, seizing, and transforming. A higher number of microfoundations is detected for sensing and transforming capabilities. The relevance of sensing and transforming capabilities might underline the presence of two different scenarios. On the one hand, there are firms still perceiving – i.e. sensing - the possible opportunities deriving from the adoption of DTs and in the process of understanding how the capabilities can support the implementation of CE practices. On the other hand, some firms already grasped the opportunities provided by DTs and reconfigured and transformed their processes. Anyanwu (2016) suggested the existence of dynamic entrepreneurial and dynamic managerial capabilities, with the former needed primarily for sensing and the latter for seizing and transforming. Leveraging also on the distinction provided by Busenitz & Barney (1997), entrepreneurs are founders of their firms and face rapidly changing and highly uncertain environments, while managers are people with middle to upper-level responsibilities with substantial oversight in the organisation that renew competencies to achieve congruence with the changing business environment. From our investigation, no specific patterns emerged in this regard, considering the size and the sector of the firms or the type and mix of DTs adopted. This might confirm the viewpoint of Khan et al. (2020a), according to whom capabilities should be intended as a sequential process through which firms accomplish CE. Overall, it emerged that DTs could support the industrial circular transition by transforming skills, procedures, and processes. From this standpoint, we suggest the following proposition:
Proposition no. 1. The adoption of DTs enables an enhanced sensing, seizing, and transforming of DCs that, in turn, can support the implementation of CE practices in industrial firms.

In terms of microfoundations enabled, evidence pinpointed a predominance of increased awareness, better knowledge and thigh control on processes and changes in them (Figure 4), overall in line with previous research (Jafari-Sadeghi et al., 2022). Specific microfoundations and DCs emerged as possibly enabled by different DTs. From this standpoint, although specific DTs could be related to specific aspects – as proof, blockchain to flexibility, cloud to collaboration (Chari et al., 2022) -, our evidence suggests that DTs can contribute in different manners and by means of different combinations to enabling DCs. We thus suggest the following proposition:
Proposition no. 2. DTs contribute in different manners and by means of different combinations to enabling the enhancement of sensing, seizing, and transforming DCs.

A set of DTs related to information exchange (Cimini et al., 2021) arose as the most promising one, enabling different capabilities. DTs for the collection of big data and particularly IoT are included in the set (Figure 4). The result might not surprise, as these are pervasive technologies (Nadkarni & Prügl, 2021), allowing the transferring of information and data, also for improved CE (Gebhardt et al., 2021; Ghoreishi & Happonen, 2022; Mikalef et al., 2021). Other DTs emerging as relevant are simulation, robots, and vertical systems integration (Figure 4). In contrast to previous literature (Gebhardt et al.,

2021), blockchain is not included in the most promising DTs. Despite the numerous benefits related to the adoption of the blockchain (Upadhyay et al., 2021), the sampled firms are still lagging in terms of its adoption, in line with the insights provided by Kayikci et al. (2022) as for the limited presence of circular supply chain. The reason might be found in the overall low commitment at an industrial system-level observed in the sample firms both in terms of DTs adoption and CE practices, leaving ample space for improvements in this regard. Based on the above discussion, we suggest the following proposition:
Proposition no. 3. Information exchange-related DTs are pivotal for enabling the enhancement of sensing, seizing, and transforming DCs.

Focusing on the digital-enabled microfoundations of DCs supporting the implementation of CE practices, those emerging as the most promising relate to knowledge, changes in processes, and traceability (Figure 4). Based on our evidence, these microfoundations are relevant for the implementation of different CE practices. From this standpoint, the relevance of creating knowledge and adopting new business practices and processes for fostering CE supports the results of Khan et al. (2020b) and Santa-Maria et al. (2021). Previous studies also recognised traceability as an important aspect enabled by DTs (Huynh, 2022). Differently from previous research (Kouhizadeh et al., 2020), in our investigation the microfoundation is connected only with traceability within the firm and not along the supply chain, therefore a significant opportunity for the CE transition is missing. Overall, apart from specific cases such as auditing or green logistics, the adoption of CE practices can be supported by different microfoundations and DCs, that can act alone or in a synergic manner. From this standpoint, we suggest the following proposition:
Proposition no. 4. Digital-enabled sensing, seizing, and transforming DCs support the implementation of CE in different manners and by means of different combinations.

According to results, unfortunately most capabilities are mainly supporting an implementation of internal CE practices strongly related to production efficiency (Sawe et al., 2021). This situation however doesn’t seem attributable to DTs or enabled DCs per se. An example can support this statement. Referring to the microfoundation of sensing capabilities *support to the CE implementation*, the use of horizontal systems integration is recognised to potentially support CE implementation beyond the single firm’s boundaries; however, the adoption and ongoing integration of horizontal systems faced some difficulties, so that the CE practice is implemented anyhow, but it is less common than it could have potentially been and above all not supported by the DT.

> *‘We registered and put all kinds of scraps, but they never contacted us […] Brilliant idea, but it doesn't work. However, we anyhow recover up to 90% of the scrap’ - Firm 10, Owner*

There is thus a missed opportunity and, in general, the results underline that more effort is needed to foster capabilities connected to collaboration through the adoption of DTs. This might also explain why no DCs related to collaboration emerged, contrary to previous literature which underlined the strategic role of DTs in creating collaboration related DCs

(Chi et al., 2018; Warner & Wäger, 2019). Collaboration is crucial to seize opportunities (Khan et al., 2020a; Sandberg & Hultberg, 2021) and it is largely recognised that for proper CE implementation collaboration and efforts at the industrial system level are necessary (Mishra et al., 2019; Tavera Romero et al., 2021).

The importance of managers' mentality in terms of enhancement and generation of digital-enabled DCs emerged as an interesting point during the investigation, confirming the findings of Khan et al. (2020a).

> *'Between words and deeds, there are individuals with their dynamics. Sometimes you can be sure about the validity of an instrument, but its implementation is influenced by individuals who must believe in it' - Firm 10, Owner*

A role in the generation or enhancement and then exploitation of digital-enabled DCs seems thus to derive from how the digitalisation process is managed and accounted for within the firm. The management of DTs and digitalisation can be inserted in the broader concept of contextual factors influencing the firm's strategy (Neri et al., 2021). Based on this, we suggest the following proposition:

Proposition no. 5. The generation or enhancement of digital-enabled DCs and their exploitation to support the implementation of CE practices in industrial firms can be moderated by contextual factors.

Looking at the obtained results and at the above discussion, it is clear that different DTs – alone or in combination - can enable specific DCs, that in turn - alone or in combination - can support the implementation of CE practices. Overall, here we imply that the main role in supporting the industrial circular transition is not directly related to the number or type of DTs adopted, but rather to the set of DCs enabled by the DTs, with a moderating effect of contextual factors. Different factors might influence the capacity of DTs to enable DCs. Besides the abovementioned contextual factors, previous literature also underlined the role of absorptive capacity to benefit from the adoption of DTs (Lorenz et al., 2020) and of digital maturity to enable superior capabilities (Lin et al., 2018). From this standpoint we suggest the following propositions:

Proposition no. 6. A widespread adoption of DTs that enable the enhancement of sensing, seizing, and transforming DCs can successfully support the implementation of CE practices in industrial firms.

Proposition no. 7. A widespread adoption of DTs that do not enable the enhancement of sensing, seizing, and transforming DCs cannot successfully support the implementation of CE practices in industrial firms.

Proposition no. 8. A limited adoption of DTs that enable the enhancement of sensing, seizing, and transforming DCs can successfully support the implementation of CE practices in industrial firms.

Three cases can be cited to support the suggested propositions. Firm 1 is characterised by a widespread adoption of DTs, enabling sensing, seizing, and transforming capabilities; these capabilities supported Firm 1 in the implementation of several CE practices, among which the reduction in production waste, lower emissions, and auditing. Firm 9 presented a good set of DTs, including both vertical and horizontal systems integration; nonetheless, only one microfoundation related to transforming capabilities is enabled, leading to an increase in investments for properly managing information from a circular perspective rather than to an actual transformation process. On the contrary, Firm 2 adopted a limited set of DTs, only IoT; nonetheless, the IoT enabled transformation capabilities thanks to a good set of related microfoundations that supported Firm 2 in implementing CE practices related to the reduction of material consumption, the production, and the design of the product so as to minimise material consumption.

7. Conclusions

The study provides a first-of-a-kind investigation of the relationship between DTs adoption and CE practices implementation and analysed the role of digital-enabled DCs. By advancing the knowledge, we demonstrated that the relationship between DTs and CE might not be direct but could depend on the generation and enhancement of DCs enabled by the adoption of DTs, which can be necessary for fostering and supporting the implementation of CE practices. Specifically, we identified capabilities in terms of sensing, seizing, and transforming, with a prominent role of the first and the latter. The most interesting capabilities are evaluated in terms of increased knowledge, traceability, and changes in processes. These capabilities demonstrated the potential to support the adoption of CE practices both at a micro and at a meso level. Additionally, they appeared generated and enhanced by several DTs, with an interesting role played by knowledge exchange technologies.

7.1. Contributions to theory and practice

From a theoretical perspective, we contributed to the discussion about DCs, specifically providing an understanding of the DCs enabled by the adoption of DTs that can leverage the circular transition, offering empirical evidence to develop and complement theoretical arguments. Considering the explorative nature of our study, we offered interesting propositions to better shape the relationship among DTs, DCs and CE, and paving the way for future research. From an academic perspective, the study offers an interesting base for explanatory and descriptive qualitative research, so as to properly assess the provided propositions against applications characterised by different features, and to conduct quantitative research aimed at providing a stronger generalisation of the results. From a managerial standpoint, the study gives professionals the possibility to understand how to exploit DCs enabled by DTs to foster their circular transition, with the suggestion to invest in those DTs that potentially generate or enhance different capabilities at diverse levels of opportunity's exploitation. The results are even more interesting in unprecedented times as the current ones, when a resilient integration between the different parts of industrial systems is particularly strategic for the industry. A robust point in favour of our work is that DTs and CE practices have been analysed from a specific perspective in order to understand the role of specific DTs and their impacts on specific practices.

7.2. *Limitations and future research*

As for research caveats, the sample is limited only to Italian firms and to manufacturing firms – thus excluding other industrial sectors and countries and limiting the generalisation of the results. The sample might also pose risks of biases, as the firms autonomously decided to take part in the research. Additional caveats relate to the lack of measurement of the strength of the generated capabilities and to the lack of investigation of possible factors moderating the relationships. Further research is encouraged to tackle the abovementioned caveats and also to investigate the suggested propositions. We deem it appropriate to develop a quantitative study to confront correlations among the different variables involved. Such a study would be of considerable interest to generalise the co-presence of different variables and to understand the strongest relationships among them. Once they have been identified, we think it is important to delve into the specific transformation dynamics taking place within firms. Besides, based on the results, some specific links between DTs, DCs and CE practices implementation were interrupted at some point, e.g. for the horizontal systems integration. An interesting stream for future research thus lies in the evaluation of factors, as barriers and drivers, influencing and impacting the relationship.

Appendix A

Details of the protocol used for the conduction of the semi-structured interviews and of the different multiple sources of evidence.

Source of Evidence 1. Semi-structured interview	
General questions	• Interviewee/s introduction (role within the firm, interests, background, experience) • Firm's description (turnover, employees, sector)
Products and processes	• What products do you produce? • What production process activities do you perform?
Circular Economy	• How do you define circular economy within your firm? • What practices have you implemented towards a more circular business model?
Digital Technologies	• What digital technologies have you adopted? • How digital technologies can influence/have influenced production processes? • How digital technologies can influence/have influenced the adoption of circular economy practices? • What skills, processes, procedures, organizational structures, decision rules, and disciplines derived from the adoption of digital technologies that can influence/have influenced the adoption of circular economy practices?
Source of Evidence 2. Direct observation	
Plant tour	Direct observation of the production plant during working hours, with the possibility to contextually ask additional questions to interviewees
Source of Evidence 3. Field notes	
Field notes – semi-structured interview	Field notes collected during the conduction of the semi-structured interview within the firms (descriptive and reflective).
Field notes – Plant tour	Field notes collected during the production plant tour (descriptive and reflective)
Source of Evidence 4. Secondary data	
Firm's website	General firm's information; certifications; sustainability reports and initiatives.
News and press	News related to the firm, also in terms of initiatives toward enhanced sustainability

Appendix B

Details on DTs adopted and CE practices implemented in each investigated firm.

Digital Technologies Adopted	Firm										
	1	2	3	4	5	6	7	8	9	10	11
Additive manufacturing	■				■						
Big data			■	■							
Data analytics	■		■		■	■	■	■			
Blockchain	■										
Cloud	■		■	■	■	■	■		■		
Vertical systems integration						■			■	■	
Horizontal systems integration	■				■			■	■	■	
Internet of Things	■	■		■	■	■	■		■	■	
Robot							■				■
Simulation	■		■								

Circular Economy Practices Implemented	Firm										
	1	2	3	4	5	6	7	8	9	10	11
Auditing, assessment, and certifications	■	■			■				■	■	
Design product for reduced consumption of material		■									
Design product for durability								■			
Reduce energy consumption			■	■	■		■	■		■	
Reduce material consumption		■	■								
Reduce pollutants emissions	■		■	■				■	■		
Reduce production waste	■						■				
Reduce water consumption		■		■	■		■	■			
Reuse or recovery of own waste material	■			■	■	■	■		■	■	■
Take back of products			■			■					
Eliminate hazardous production materials				■	■	■				■	
Green logistics	■				■			■			
Green packaging	■	■		■	■	■		■	■	■	■
Research on and use of alternative materials	■	■					■				
Use of renewable energy in the production processes			■	■	■			■	■		
Cooperation with other firms of the supply chain	■	■	■	■	■					■	■
Cooperation with firms of other supply chains		■									
Cooperation with universities and industrial associations							■				
Reuse or recovery of waste material by other supply chains	■		■	■		■			■	■	■
Reuse or recovery of waste material of other actors		■			■		■			■	
Reuse or recovery of waste material for social initiatives	■										
Selection of suppliers		■			■		■	■			
Communication and awareness about circular economy towards customers and society	■	■	■					■			
Training for workers	■	■						■		■	

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