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Research paper

Transition of Manufacturing Companies towards Circular Economy: The Enabling Role of Digital Technologies for Product Life Cycle Extension

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Abstract

Extending the product life cycle is increasingly seen as a key strategy for manufacturing firms transitioning to a circular economy. This involves redesigning products through practices like design for remanufacturing and product-service systems, which also reshape the value proposition towards customers. Digital technologies have recently emerged as enablers of these circular economy practices, yet research in this area remains limited and largely qualitative. This paper addresses the gap of a more comprehensive view on the enabling role of digital technologies as for product life cycle extension by conducting an exploratory empirical study—using Correspondence Analysis—on 41 Italian manufacturing firms that have adopted circular economy practices supported by digital technologies. The findings reveal that while digital technologies generally support the adoption of circular economy, some are more effective than others in enabling specific practices. The study contributes to academic discourse by confirming the enabling role of digital technologies and highlighting their relative effectiveness in extending product life cycle. The study also offers practical insights for managers and policymakers aiming to foster the adoption of circular economy practices in the manufacturing sector.

Keywords: Circular Economy · Digital Technologies · Manufacturing Sector · Correspondence Analysis · Product Life Cyle Extension.

1. INTRODUCTION

Circular Economy (CE) is a novel industrial approach that has been introduced to overcome the typical issues surrounding the linear 'take-make-dispose' economic model, by minimizing the use of raw materials, exploiting the maximum value of products by extending their life cycle and, once a product reaches end of life, reusing spare parts and components in order to reduce the global demand for raw materials (Kirchherr et al., 2017; Stahel, 2013). Furthermore, CE aims to do so by decoupling the growth of output, i.e., the demand for final products, from the need for input, i.e., resources and materials.

To implement CE principles, companies are required to innovate their business model as well as their strategic positioning into the market. To do so, companies need to adopt different managerial practices, i.e., actions that managers can implement within their companies to make their business model and value propositions consistent with CE principles (Ünal et al., 2019a, 2019b). Among these practices, spanning from designing out waste and pollution to regenerating natural systems, scholars have highlighted that product life cycle extension is crucial for keeping products and materials in use (Geissdoerfer et al., 2018).

The manufacturing sector is of particular interest from the point of view of adopting CE principles (Ahmadov et al., 2025), as this industry represents a significant source of environmental impact, concerning both the massive usage of resources (Schöggl et al., 2023; Kristoffersen et al., 2020) as well as the amount of waste generated (i.e., about 14% of the 2,652 million tons of waste generated in Europe) (European Remanufacturing Network, 2021). Notwithstanding, the penetration rate of CE worldwide is decreasing from 9.1% in 2018 to

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7.2% in 2023, according to the estimates of the Circularity Gap Report of the Circle Economy Foundation, demonstrating that companies in the industrial sectors are still struggling to implement these CE practices.

To increase the possibility of these companies pursuing the transition to this novel industrial approach and to allow for its effectiveness, several scholars have pointed out the exploitation of several enabling factors, spanning from technical and technological, economic and financial, organizational and supply chain-related enablers (Urbinati et al., 2021), and especially in manufacturing companies (Jamwal et al., 2024). Among these, digital technologies (DTs) have been recognised to play an important role for enhancing the effectiveness of the CE transition by manufacturing companies (Nascimento et al., 2019; Uçar et al., 2020; Wilson et al., 2021). Indeed, the use of DTs can support companies in adopting CE practices (Khan et al., 2022; Chiaroni et al., 2020; Ranta et al., 2021; Rosa et al., 2020; de Mattos Nascimento et al., 2022). For example, big data can be used to assess potential pathways for secondary materials (Davis et al., 2017; Jose & Ramakrishna, 2018), or industrial symbiosis (Song et al., 2017), whereas simulation systems can allow optimizing the performance of supply chains and modelling material flows (Schäfers & Walther, 2017).

More specifically, recent studies show that the adoption of CE practices addressing product life cycle extension could really help manufacturing companies in reducing waste generation and maximizing the resources exploitation (Urbinati et al., 2020). The existing research shows that practices enabling product life cycle extension may refer to either the redesign of products, i.e., including all the practices that encourage the use of resources and materials more extensively (e.g., Kręt-Grześkowiak & Baborska-Narożny, 2023; Sassanelli et al., 2020) or the redesign of the interface with customers, i.e., all the practices that allow changing how the value proposition is offered and delivered to the customers (Khitous et al., 2022; Triguero et al., 2022).

Nevertheless, the enabling role played by DTs for the adoption of the CE practices allowing product life cycle extension is an under-researched topic that deserves further investigation (Alcayaga & Hansen, 2025; Chávez et al., 2024; Pagoropoulos et al., 2017). In addition, the existing research at the intersection between DTs and CE is still embryonic and mostly based on qualitative premises (Cagno et al., 2021; Cherrafi et al., 2022; Ranta et al., 2021), especially in the manufacturing sector (Cannas et al., 2025; Khan et al., 2024).

In this paper we take stock of these research gaps with the objective of providing a more comprehensive view on the enabling role of DTs in supporting manufacturing companies to extend products life cycle. We aim to fill these research gaps by answering the following research question: "*How do manufacturing companies exploit DTs to favor the adoption of CE practices enabling product life cycle extension?*"

To answer this research question, the paper carries out an exploratory empirical analysis, based on a Correspondence Analysis (CA) involving 41 Italian companies that have implemented CE practices for product life cycle extension, i.e., redesign of products and redesign of interface with customers, by exploiting DTs. First, the CA is a suitable method to be used for answering the research question, as it leverages a quantitative data analysis that offers a visual understanding of relationships among qualitative variables (Greenacre, 2010; Monteiro et al., 2019), as it is in our case (i.e., with reference to DTs and those CE practices favouring product life cycle extension). Moreover, the data analysis methodology employed in this research closely mirrors the approaches used by several studies (e.g., Holzmann et al., 2017; Cagli et al., 2012), showcasing a parallel in the analytical frameworks and techniques applied. Second, the Italian manufacturing industry has been chosen as the empirical setting since it has been increasingly studied as far as the adoption of CE practices and DTs are concerned (e.g., Ghisellini & Ulgiati, 2020; Zangiacomi et al., 2020). Moreover, Italy ranks first among the main European countries in the circularity index implementation (Circular Economy Network, 2021), also fostered by the scarcity of mineral and raw materials required for production processes that distinguish the country. The country also plays an increasing role in the European landscape with reference to its level of digitization (European Commission, 2012).

The paper contributes to the existing literature at the intersection between CE and DTs by showing that some DTs are more promising than others in supporting manufacturing companies in the adoption of certain CE practices enabling product life cycle extension, although the literature has historically argued that DTs behave rather transversally across the adoption of these practices (Cagno et al., 2021). In addition, the paper reveals that DTs are exploited for both the adoption of CE practices concerning the redesigning of products and those related to the redesigning of the interface with customers. The paper also provides useful insights for managers, by shedding light on the role of DTs in enabling the CE transition of manufacturing companies. Given this evidence, policy makers could also be informed in drafting supporting schemes and other provisions to favour the spread of DTs for CE purposes among manufacturing companies, especially with reference to product life cycle extension.

The remainder of the paper is structured as follows. Section 2 summarises the literature background on the topic and presents the addressed research gap. Section 3 illustrates the methodology for empirical analysis, whereas Section 4 shows the main results of our study. Finally, Section 5 discusses the results against prior research and Section 6 draws conclusions, along with limitations and avenues for future research.

2. LITERATURE BACKGROUND

In this Section, the CE practices enabling product life cycle extension by companies are first presented. Then, the DTs that can help manufacturing companies to implement CE practices are analysed.

2.1 CE Practices Enabling Product Life Cycle Extension

Companies implementing CE principles need to innovate their business model as well as their strategic positioning into the market (Geissdoerfer et al., 2018). It implies that companies, among the other actions, must rethink how their products are designed to turn them into circular products, to address the CE objective of a product life cycle extension (Triguero et al., 2023). Different from linear products, circular products have a value proposition characterised by longer product life cycles (Franzò et al., 2021). Moreover, they may be characterised by other features related to the interface with customers, e.g., coupled with services or virtualised, collaborative consumption and take back systems allowing customers for bringing back used products (Urbinati et al., 2019).

Accordingly, to enable product life cycle extension, existing studies identify two main areas of intervention belonging to the value network and value proposition dimensions of a company's business model (Urbinati et al., 2017): (i) the redesign of products, i.e., all the practices that encourage the use of resources and materials more extensively, such as the Design for Repairing or the Design for Reuse (Kręt-Grześkowiak & Baborska-Narożny, 2023; Sassanelli et al., 2020); and (ii) the redesign of the interface with customers, i.e., all the practices that allow changing how the value proposition is offered and delivered to the customers, such as the adoption of product-service systems (Khitous et al., 2022; Triguero et al., 2022).

Table 1 reports a summary of the areas of intervention for product life cycle extension, along with the CE practices that address each of these areas, which are the basis of our research and derived from the existing research (e.g., Morseletto, 2020; Centobelli et al., 2020).

Table 1. Areas of Intervention for Product Life Cycle Extension and Related CE Practices

Areas of intervention enabling product life cycle extension	CE practices that address the area of intervention	CE practice definition	Relevant references
Redesign of products	Design for Remanufacturing	Design for using parts of discarded products in a new product with the same function	Spreafico, 2022 Morseletto, 2020 Sassanelli et al., 2020 Vanegas et al., 2018 Den Hollander et al., 2017 Mestre & Cooper, 2017
	Design for Refurbishing	Design for restoring an old product and bringing it up to date	
	Design for Repairing	Design for non-invasive ways to implement repairing and cleaning on product, module, component, material	
	Design for Reusing	Design for reusing a discarded product which is	

		still in good condition and fulfils its original function	
Redesign of interface with customers	Product Service System	Tangible product and intangible service designed and combined so that it is jointly able to fulfill specific customer needs (the extent to which service is core to the product allows to discern product-oriented and use-oriented PSS)	Atif, 2023 Katsanakis et al., 2023 Uhrenholt et al., 2022 Khitous et al., 2022 Urbinati et al., 2017 Tukker, 2004
	Take Back System	Operational set of processes including the collection of end-of-life products, […], components or products in the forward supply chain	

The redesign of products can be interpreted as the concurrent design of products and related manufacturing processes, which may enhance competitiveness measures, rationalize product/process/resource design decisions and improve operational efficiency in product development (Sassanelli et al., 2020). Those practices enabling the redesign of products aim at closing, slowing and narrowing resource loops and addressing the sustainable use of resources. Among these practices, particular attention has been devoted in this article on those enabling product life cycle extension (Sassanelli et al., 2020). In particular, Design for Remanufacturing enables the use of parts of discarded products for a new product with the same function; Design for Refurbishing enables to restore an old product and to bring it up to date; Design for Repairing enables either the repair and maintenance of a defective product so as to use it according to its original function; Design for Reusing enables another consumer to reuse discarded products that are still in good condition and fulfil their original function. We believe this classification, built on a synthesis of the framework proposed by Morseletto (2020), allows us to focus on four "design-for-R" strategies that directly slow product flows and thus extend product life. Moreover, because our study investigates how DTs enable product life cycle extension, strategies aimed primarily at material recovery (e.g., Design for Recycling) or resource efficiency fall outside our scope.

As far as the redesign of the interface with customers is concerned, literature suggests adopting particular practices for enhancing customers' engagement in companies' transition towards CE (Franzò et al., 2021), in a way to facilitate the reintroduction of products and related materials within the economic cycle and extend the life cycle of products more effectively. For example, product servitisation is widely discussed on a scholarly level. This aspect is conceived within the Product Service System (PSS) context. PSSs have been proposed to create value no longer from tangible products alone, but also from intangible services. PSSs are mostly aimed at letting both the producer maintain the ownership of the product and the customer act as a user rather than a buyer. PSSs can be defined as 'tangible products and intangible services designed and combined so that they jointly are capable of fulfilling specific customer needs' (Tukker, 2004, p. 246). In particular, product-oriented PSSs are aimed at supplementing products with additional services (e.g., repair services); use-oriented PSSs resolve to maintain the product as central in the offer while staying under the ownership of the producer (e.g., rental or leasing services); result-oriented PSSs work towards allowing the producer to sell results rather than products (e.g., power by the hour) (Khitous et al., 2022). These PSSs allow slowing down resource loops by extending products' service life and intensifying their use (Bocken et al., 2018; Geissdoerfer et al., 2020). Moreover, a second CE practice that can favour the redesign of the interface with customers refers to the Take Back Systems (TBSs), which include initiatives promoted by companies to encourage customers to take back used products to achieve waste elimination and close loops (Ranta et al., 2018).

2.2 Digital Technologies Supporting the Adoption of CE Practices by Manufacturing Companies

A recent stream of research has highlighted the role of DTs in the manufacturing context, and especially as enablers of CE (Cannas et al., 2025; Rosa et al., 2020). Indeed, different DTs are considered useful to enable CE transition in the manufacturing context (e.g., Zheng et al., 2020; Ramanathan & Samaranayake, 2022).

Cloud Computing may help promote collaboration among supply chain actors by allowing data storage and sharing (Gebhardt et al., 2022; Filho et al., 2022). Interestingly, a clear indication on specific CE practices that can be enabled for the redesign of products is missing (Neri et al., 2023).

IoT refers to the set of technologies that allows interaction and cooperation between devices, things, or objects by using modern wireless telecommunications, such as radio frequency identification (RFID), but also sensors, tags, actuators, and cell phones. IoT is functional for monitoring, analysing, and controlling products' data during their life cycle with the purpose of extending their service life and quantifying resource efficiency (Bressanelli et al., 2018; Laskurain-Iturbe et al., 2021).

Big Data Analytics (BDA) refers to the application of advanced data analysis techniques for the management, processing, and storage of large data sets. BDA supports the development of automated approaches aimed at evaluating new pathways for secondary materials or discovering potential industrial symbiosis (Ertz et al., 2022). BDAs can also be used to develop open-source tools, procedures, and services for the promotion of reuse or cloud platforms of services for the collection, analysis, and storage of data. As a result, BDAs can support the collection and management of data along the life cycle of products or the implementation of smart design and production actions (Bahrin et al., 2016).

Autonomous robots have been studied with reference to their ability to favour product recovery (Laskurain-Iturbe et al., 2021; Lopes de Sousa Jabbour et al., 2022), along with disassembly (Kayikci et al., 2022; Kintscher et al., 2021) and repairing activities (Wynn & Jones, 2022). Existing literature provides evidence about their application in different industrial contexts for circular purposes (Tiwari et al., 2021; Trevisan et al., 2021).

Simulation technologies include a wide range of mathematical programming techniques that allow achieving objectives related to both CE and Industry 4.0, such as the modelling of material flows or the regeneration of products or urban areas. Simulation represents a decision-support tool for the optimisation of internal processes and supply chain management performances, which allows modelling material flows, among others (Rönnlund et al., 2016).

Additive Manufacturing (also known as '3D printing') refers to a suite of technologies that allows the production of a growing range of products through the layering or 3D printing of materials. It can be exploited for the implementation of Design for Disassembly practices that allow producing modular and customised products (Urbinati et al., 2023). Moreover, Additive Manufacturing proves useful for the optimisation of reuse and remanufacturing processes, as well as for the redesign and reuse of products and their components (Floren et al., 2021; Ertz et al., 2022).

Augmented Reality (AR) can support the virtualisation strategy of CE initiatives (Bressanelli et al., 2022) as well as product disassembly (Kayikci et al., 2022) and can be used as a tool to raise users' awareness about CE (Lönn, 2019).

Cybersecurity – typically linked with blockchain – can enable collaboration among different supply chain actors by assuring transparency and data protection (Bekrar et al., 2021; Chauhan et al., 2022; Mastos et al., 2021; Nandi et al., 2021). In addition, this technology can promote circular purchasing and design (Khan et al., 2021a; Khan et al., 2021b), as well as waste management (Upadhyay et al., 2021) and material recovery and refurbishing (Hallioui et al., 2022; Hennemann Hilario da Silva & Sehnem, 2022).

Artificial Intelligence (AI) is an overarching term for a collection of technologies dealing with computer models and systems that perform human-like cognitive functions such as reasoning and learning (Sjödin et al., 2023). AI software is capable of learning from experience, and this differentiates it from more conventional software, which is preprogrammed and deterministic in nature. Through machine learning algorithms, AI helps solve problems through performing tasks such as pattern recognition, prediction, optimisation, and recommendation generation based on data from videos, images, audio, text and more. For example, as far as waste management is concerned, the different forms of AI (i.e., mechanical, analytical, intuitive) may provide significant benefits across all functions and tasks in the reverse logistics process (Laskurain-Iturbe et al., 2021). In addition, AI can also be exploited for enabling the implementation of practices for the redesign of customers' interface (Ghoreishi & Happonen, 2020).

RFID is a data collection technology that has been studied in the CE context for its ability to track material flows to enable value recovery through product reuse, repair and remanufacture (Paguropoulos et al., 2017). Moreover, this technology may enable the development of closed-loop systems (Govindan et al., 2014), as well as provide complete information about product life cycle to all the stakeholders within a supply chain.

The existing contributions clearly show that DTs can be a relevant enabler for the adoption of CE practices, such as those related to product life cycle extension, with reference to both the redesign of products and the redesign of the interface with customers (Cagno et al., 2021). However, this research stream is still embryonic and mostly based on qualitative premises, suggesting taking a step forward in the direction of deepening the supporting role of digital technologies as enablers of product life cycle extension, especially in manufacturing companies and from the point of view of methodological design (Soriano-Pinar et al., 2023).

3. METHODOLOGY

An exploratory empirical analysis has been carried out to provide a comprehensive view on the enabling role of DTs in supporting manufacturing companies in the adoption of CE practices for product life cycle extension. In particular, the methodological process followed in this research includes three phases, i.e., survey design, data collection and data analysis, as detailed below.

3.1 Survey Design

A survey questionnaire has been drafted to investigate the supporting role played by DTs for the adoption of CE practices for product life cycle extension that support manufacturing companies in the redesigning of products and interface with customers. The questionnaire – attached as an Appendix – was divided into three parts. The first one includes questions related to the respondents' demographics. The second one includes a question related to the adoption of CE practices for product life cycle extension. This part covers the CE practices identified through the literature review, as detailed in Section 2.1. The third one includes questions on the role of DTs in supporting the adoption of CE practices for redesigning products and the interface with customers. This part covers the DTs identified through the literature review, as detailed in Section 2.2.

3.2 Data Collection

To collect data, an online survey questionnaire was created by using Google Forms and sent to more than one hundred and fifty companies operating according to CE principles in the manufacturing sector. The research followed ethical guidelines to ensure the confidentiality of the respondents. To ensure consensual participation, information on the aim of the research and how the data would be used was shared with participants on the first page of the survey.

The data collection phase lasted approximately 2 months and at the end 93 responses were received. All the respondents work for a manufacturing company and have a managerial role within the company itself. Respondents were contacted via personal networks or the professional networking platform LinkedIn, which has been increasingly perceived as a reliable platform for the fast collection of research data (Masi et al., 2019) as well as appeared to be useful to develop quantitative studies on CE (e.g., Urbinati et al., 2021). Notably, the following data analysis phase (see Section 3.3) was based on the 41 respondents that declared to have adopted at least one CE practice for product life cycle extension by exploiting DTs, which constitutes an argument to support the relevance of our study. Our approach is coherent with the exploratory mixed method analysis, suggested by Stumpf et al. (2021), which enables the use of qualitative analyses as input for quantitative ones. Indeed, we started from an initial qualitative research phase in which participant views are explored through a survey questionnaire, and the information collected was subsequently analysed in a quantitative phase.

In addition, although it is recognized in survey design that sample data should be large enough to provide reliable estimates of means or totals of the whole population (Parker et al., 2023), our paper is mainly qualitative in its premises, given its exploratory nature and the emergence of the phenomenon under investigation. Accordingly, we prioritized the study of diversity (and not distribution) of population, following the suggestion of Jansen (2010) to apply the logic of sample surveys to qualitative analyses to address how the logic and the method of survey research can improve qualitative cases studies. Accordingly, the number of respondents involved is coherent and appropriate with the adopted approach.

Table 2 shows the profile of respondents, belonging to six different manufacturing sectors.

Table 2. Profile of Respondents

Sectors	Number of respondents
Automotive	7
Built environment	10
Consumer electronics	2
Food & Beverage	6
Furniture	4
Machinery	12
TOTAL	***41***

3.3 Data Analysis

The collected data have been analysed by adopting the Correspondence Analysis (CA) methodology, a quantitative data analysis method that provides researchers with a visual understanding of relationships among qualitative (categorical) variables (Greenacre, 2010; Monteiro et al., 2019). This methodology is particularly well-suited to the purpose of our research, as it allows for the exploration of complex relationships between categorical variables in a way that is both intuitive and interpretable. CA is part of the family of multivariate dimension reduction techniques based on Singular Value Decomposition (SVD), enabling the geometric representation of two-way frequency tables for nominal variables (Greenacre, 2017). Like other comparable techniques, such as Principal Component Analysis, CA aims to determine scores that describe the similarity or difference between responses of two or more variables (Beh, 2004). However, what distinguishes CA is its unique ability to handle qualitative data, making it particularly valuable for our study, which involves categorical variables such as DTs and CE practices.

The suitability of CA for this research lies in its capacity to uncover latent structures and relationships within categorical data, which is essential for addressing our research questions: more specifically, CA allows us to visualize and interpret the associations between DTs and CE practices in a low-dimensional space, providing insights that would be difficult to obtain through traditional statistical methods. This is particularly relevant given the exploratory nature of our study, where the goal is to identify patterns and relationships rather than to test predefined hypotheses. This exploratory endeavor is well-supported by the diversity within our sample (representing six distinct manufacturing sectors as detailed in Table 2, which provides a rich categorical dataset enhancing CA's potential to uncover nuanced patterns and associations across varied contexts. Furthermore, CA's ability to handle asymmetric relationships between row and column categories through different normalization techniques (e.g., symmetric normalization) ensures that the analysis is tailored to the specific needs of our research (Greenacre, 2017).

While CA has been widely applied in various fields, as evidenced by Beh & Lombardo (2012), who identified over 270 works using CA across different applications, its relevance to our study is not merely based on its popularity or past successes. Instead, it is grounded in the methodological alignment between CA's capabilities and the specific requirements of our research context. For instance, within the CE field, CA has been effectively used to uncover meaningful patterns and relationships. Stumpf et al. (2021) employed CA to identify correlations between enablers, principles, and sectors, while Dudziak et al. (2022) used it to classify consumer groups based on living conditions and food-wasting tendencies in Poland. Similarly, Huynh Evertsen et al. (2022) applied Multiple CA to explore the connection between academic spin-offs and CE transition. These examples illustrate the versatility of CA, but more importantly, they highlight its applicability to research questions like ours, where the goal is to explore and visualize relationships between categorical variables.

The scores generated by CA represent a form of correlation or dissimilarity matrix, enabling the creation of a plot that illustrates how "row" and "column" variables relate to each other. Depending on the research objectives, different normalization techniques can be applied. For instance, row-normalization or column-normalization is used when comparing categories within rows or columns, respectively, while principal normalization allows for within-row and within-column comparisons on the same plot (Greenacre, 2017). In our case, symmetric normalization is employed to analyse the relationship between DTs (row categories) and CE practices (column categories). Although symmetric normalization may misrepresent differences within rows and columns, this limitation is not relevant to our analysis, as our focus is on the relationships between, rather than within, these categories. Moreover, the robustness of our results is confirmed by the consistency observed across different normalization techniques.

The choice of CA for this study is rooted in its methodological strengths and its alignment with the specific objectives of our research. By providing a visual and interpretable representation of the relationships between DTs and CE practices, CA enables us to address our research questions in a way that is both rigorous and insightful.

4. RESULTS

Figure 1 shows the proximity between the DTs and the areas of intervention of CE practices enabling product life cycle extension, i.e., the redesign of products and the redesign of interface with customers, because of the CA. The concept of proximity refers to the closeness of categories on the biplot, which graphically represents the relationships between row and column categories of a contingency table. Proximity is indicative of a stronger association between the categories. This means that the ones that appear close together on the plot are understood to share similar profiles in terms of their distribution across the other variable's categories, suggesting they respond similarly to the underlying dimensions captured by the analysis and vice versa.

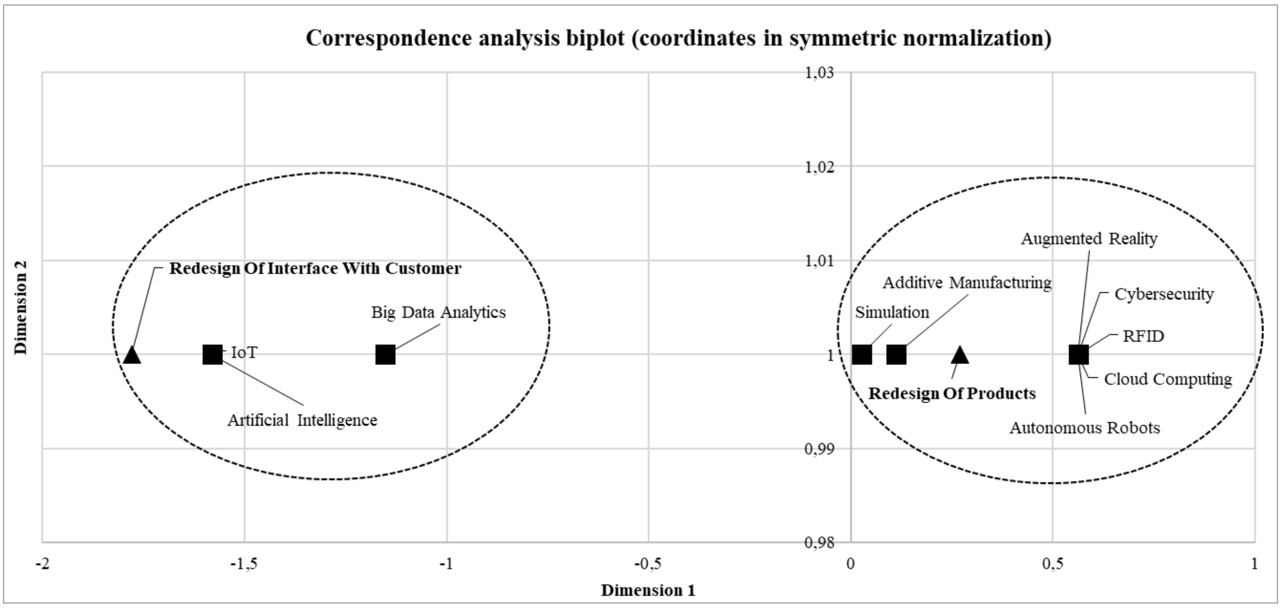

Figure 1. Proximity Between Digital Technologies and Areas of Intervention of CE Practices Enabling Product Life Cycle Extension, Because of the Correspondence Analysis

The empirical analysis shows that, to enable the redesign of products, a pivotal role is played by Simulation and Additive Manufacturing. Simulation is of relevance to carry out life cycle assessment (LCA) and the calculation of the environmental impact of production processes and supply chains, which are needed for supporting the design phase of a new product. Similarly, knowledge on Additive Manufacturing is crucial for allowing companies to properly identify the technical cycles through which the redesigned products can extend their lifecycle and those of their materials and components. Furthermore, the choice of materials for products – one of the key decisions in the product redesign phase – must consider the limits of Additive Manufacturing, those making it even more relevant in this area of intervention.

Augmented Reality, Cybersecurity, Autonomous Robots, Cloud Computing and RFID are also included in intervention related to product redesign – albeit with a greater distance (i.e., with a lower enabling impact).

As far as the redesign of interface with customers is concerned, a pivotal role as enablers is played by Artificial Intelligence (AI) and IoT. The adoption of AI aims at properly understanding the behavior of users and/or customers; therefore, it might enable a more efficient development of PSSs. Similarly, IoT offers a seamless interface with customers to collect the data and information needed for the above-mentioned AI applications. It is worth mentioning that this result intensifies the relevance of these technologies for the area of intervention under investigation. Big Data Analytics and Machine Learning, although comprised in this area of intervention, appear to have a lower enabling impact; this can be explained by the substitution effect with AI, with which they share similar roles in the design of the interface with customers.

In general, the empirical analysis shows that some DTs can support the implementation of specific CE practices to extend product life cycle, while they are less relevant or negligible for other practices. Indeed, DTs enabling the CE practices belonging to the two areas of intervention have a significant difference in the distance between each other, as shown in Figure 1.

5. DISCUSSIONS

The results deriving from the empirical analysis provide important theoretical implications.

First, the research adds to the existing studies deepening the role of DTs in manufacturing industries. It shows the peculiarities of DTs to support manufacturing companies in achieving objectives of designing a circular product, such as the improvement of their environmental impacts related to production activity or an effective product life cycle management. This is the case, for example, of Simulation technologies enabling product LCA (Laskurain-Iturbe et al., 2021; Rönnlund et al., 2016; Rose, 2001), or the case of the Additive Manufacturing technology, enabling product lifecycle extension (Marconi et al., 2019; Abbasi & Kamal, 2020; Ertz et al., 2022; Hettiarachchi et al., 2022; Sauerwein et al., 2019).

Second, the results of the empirical analysis provide valuable insights into the role of digital technologies (DTs) in enabling circular economy (CE) practices for product life cycle extension in manufacturing companies. This study expands upon existing literature by demonstrating that DTs do not act as generic enablers of CE practices, but exhibit differentiated impacts depending on the specific intervention area—either redesigning products or redesigning the interface with customers.

These findings challenge the prevalent assumption in CE literature that DTs transversally support all CE practices (Cagno et al., 2021; Ranta et al., 2021). Instead, our results highlight that certain technologies are more effective for specific CE practices, reinforcing the need for a more nuanced understanding of their role.

The empirical analysis confirms that Simulation and Additive Manufacturing are particularly critical in enabling product redesign—a key area for extending product life. Prior research emphasizes that Simulation technologies facilitate LCA and material flow modeling (Rönnlund et al., 2016; Laskurain-Iturbe et al., 2021), ensuring that products are designed with circularity in mind. Our findings support this claim by demonstrating that companies leveraging Simulation are better positioned to optimize resource efficiency and extend product longevity.

Similarly, Additive Manufacturing emerges as a key enabler of Design for Disassembly and Remanufacturing, confirming its role in modular product design and resource-efficient reengineering (Ertz et al., 2022; Sauerwein et al., 2019). The ability to produce components in a customized and flexible manner enhances companies' ability to close material loops (Abbasi & Kamal, 2020). This evidence aligns with the broader perspective that Additive Manufacturing can support circular business models (Urbinati et al., 2023), particularly by enabling on-demand production and minimizing material waste.

While less pronounced, technologies such as Augmented Reality, Cybersecurity, Autonomous Robots, Cloud Computing, and RFID also contribute to product redesign, but with a lower enabling impact. Their role appears to be more supportive rather than foundational, assisting in process optimization, data security, and traceability of circular products (Chauhan et al., 2022; Bekrar et al., 2021). For example, Augmented Reality and Cloud Computing are used for supporting the design phase, enabling for example prototyping activities through digitalisation (Rocca et al., 2020), while RFID and Cybersecurity are technologies to be known to be efficiently embedded in the product during its design phase (see, for example, Condemi et al., 2019). Autonomous Robots represent a digital technology that allows designing better processes for manufacturing, even though this technology is still limitedly widespread in the market as of today (Ahmed et al., 2022). Finally, AI enables a more efficient development of customers' servitization purposes (Agrawal et al., 2022), while IoT, Big Data Analytics, and Machine Learning support AI applications through collecting, storing, and analysing customers' data and information (Alcayaga et al., 2019; Bahrin et al., 2016; Laskurain-Iturbe et al., 2021; Noman et al., 2022).

As far as the redesign of the interface with customers is concerned, the results further reveal that AI and IoT are crucial for redesigning the interface with customers, particularly in the development of Product Service Systems (PSS) and Take Back Systems (TBS). The strong association between AI and IoT in this area confirms prior research indicating that AI-driven customer insights enhance circular business models (Ghoreishi & Happonen, 2020; Agrawal et al., 2022). Specifically, AI's ability to predict customer behavior facilitates the design of personalized and data-driven service offerings (e.g., predictive maintenance, leasing models) that extend product life cycles. Similarly, IoT provides the necessary infrastructure to collect and transmit real-time product usage data, enabling optimized resource management and reverse logistics (Laskurain-Iturbe et al., 2021; Bressanelli et al., 2018). This finding aligns with previous studies emphasizing IoT's role in enabling closed-loop systems (Pagoropoulos et al., 2017). Our Correspondence Analysis, however, suggests that adoption decisions on these technologies should be sequenced or packaged, rather than treated as independent investments, a point rarely made in CE-DTs studies, which tend to look at technologies in isolation.

Although Big Data Analytics and Machine Learning also appear in this cluster, their role seems less prominent than AI. This evidence may be explained by a substitute effect, as AI inherently incorporates predictive and analytical functions that overlap with the capabilities of Big Data and Machine Learning (Alcayaga et al., 2019; Noman et al., 2022). However, their complementary role in data-driven decision-making for CE remains relevant.

In sum, the results of the empirical – yet exploratory – analysis strengthen the need for better understanding of the role of DTs in CE contexts by linking them to the specific goals to either redesign circular products or engage customers. Indeed, as emerging from our analysis, manufacturing companies exploit DTs that favour CE practices enabling product life cycle extension not generically but through two distinct technology constellations, each aligned with a different intervention area.

6. CONCLUSIONS

The paper contributes to the existing literature on CE by confirming the role played by DTs as enablers for the adoption of CE practices. This role addresses two different areas of intervention that manufacturing companies are called upon to consider while implementing CE practices for product life cycle extension, namely the redesign of products and the redesign of interface with customers. Second, the paper highlights the enabling role played by specific DTs in each area of intervention. In particular, the exploratory survey-based empirical analysis involving 41 Italian companies operating in different manufacturing sectors provides practical evidence of particular relationships between some DTs and specific CE practices for product life cycle extension (Centobelli et al., 2020; Franzò et al., 2021). While scientific literature suggests that digital technologies behave transversally across the adoption of CE practices, the results highlight how specific DTs are more effective than others for the adoption of specific practices.

The study provides managers with practical recommendations for properly approaching the transition process towards CE in their manufacturing companies by exploiting DTs. Companies that still operate with a linear business and struggle to begin the CE transition can now be more aware of which technologies support more than others specific CE practices, and start the transition with clearer objectives about their twin transition. In other words, based on the specific targets to be achieved in each area of intervention enabling product life cycle extension, managers are provided with a comprehensive picture of the most promising enabling DTs.

Furthermore, the study may inform policy makers in charge of designing new policy instruments that support manufacturing companies in the transition towards CE, especially by considering the need to foster the adoption of specific DTs as enablers of specific CE practices. For example, policymakers should focus on targeted incentives to foster the adoption of specific DTs based on their demonstrated impact on CE practices.

Beyond the traditional limitations characterising the nature of the study, such as the size of the sample and the qualitative, exploratory approach that limits the generalisability of the results obtained, interesting research avenues do emerge. First, the obtained results are driven by the diffusion level of DTs favouring the adoption of CE practices and it is thus possible that not all the available DTs identified within the literature may be used in our research. Second, the research has not analysed the enabling effect of the concurrent adoption of several DTs for the adoption of specific CE practices, such as the combined effect generated by Artificial Intelligence, Big Data Analytics and IoT if applied for Take Back Systems and/or PSSs. This evidence may be of particular interest for future studies, since the adoption of specific CE practices by companies may require the concurrent adoption of more DTs to be successfully implemented. This could be done via a time-series analysis to investigate the causality, such as a Granger-causality test in Bayesian frameworks (Chen & Lee, 2017). In addition, the current debate also focuses on possible mediators of the relationship between DTs and CE practices. Furthermore, the focus of the analysis is on a limited number of CE practices, which hints at the need for a further future investigation into exploring the variety of such practices. Finally, the sample is limited to Italian manufacturing companies – thus excluding other sectors and countries, posing limitations for the generalizability of the results in other contexts, as a specific region entails unique features. Future research is encouraged to replicate or expand the sample size, as well as perform empirical analyses in other geographical contexts.

AUTHOR CONTRIBUTIONS

Simone Franzò: Writing – review & editing, Writing – original draft, Validation, Supervision, Data curation
Andrea Urbinati: Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Conceptualization, Data curation
Davide Chiaroni: Writing – review & editing, Supervision, Conceptualization, Data curation
Fausto Pacicco: Methodology, Visualization, Validation, Data curation

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DECLARATIONS

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APPENDIX: SURVEY QUESTIONNAIRE

PART I: General Information

- Company name
- Company manufacturing sector (NACE code)
- Respondent's role

PART II: Circular Economy Practices

- Which circular economy practices have been implemented by your company for:
  (Available answers: A – Yes; B – No, but we intend to implement it in the future; C – No, and as of today there is no intention to implement it in the future)

  a. Redesign of products
     i. Design for Remanufacturing
     ii. Design for Refurbishing
     iii. Design for Repairing
     iv. Design for Reusing

  b. Redesign of interface with customers
     i. Product Service System
     ii. Take Back System

PART III: Digital Technologies Supporting the Adoption of Circular Economy Practices

- Which digital technologies have been exploited by your company to support the adoption of circular economy practices?
- (Available answers: A – Yes; B – No, but we intend to exploit it in the future; C – No, and as of today there is no intention to exploit it in the future)
  a. Cloud Computing
  b. IoT
  c. Big Data Analysis
  d. Autonomous Robots
  e. Simulation
  f. Additive Manufacturing
  g. Augmented Reality
  h. Cyber Security
  i. Artificial Intelligence
  j. RFID
- Which specific digital technology (or technologies) has (or have) been exploited by your company to support the adoption of a specific circular economy practice (and why)?
  (Available answers: for each circular economy practice for which you answered 'YES' to the previous question in Part II, please specify which specific technology (or technologies) has (or have) been exploited to support its adoption among those that you declared to adopt in the previous question)