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Exploring Opportunities and Barriers of Digital Technologies in Circular Manufacturing Systems: An overview and a research roadmap

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Abstract

The Circular Economy (CE) is being promoted by various economic and political actors as a response to current environmental challenges (climate, biodiversity among others.). However, the CE is struggling to establish its position in manufacturing systems. At the same time, researchers are predicting, particularly at the present time, that emerging digital technologies (DTs) from Industry 4.0 could facilitate the implementation of the CE within a production environment. Research on this subject is in its early stages, and few publications deal with the possible synergy between DTs and the CE. Thus, there are still many gaps in the field where, firstly, the environmental and social aspects are generally disregarded in favour of economic and technical ones and, secondly that few studies provide empirical proof of technological contributions to the setting up of circularity. Indeed, the majority of these studies are based on a collection of managers' points of view and offer perspectives based on questionnaires, interviews or focus groups. The aim of this article is thus to propose a systematic literature review of the opportunities, barriers and enablers of emerging DTs along with the CE focusing on manufacturing systems. In this paper a multi-disciplinary approach has been adopted which takes particular account of the humanities and social sciences. A critical analysis of research gaps and proposed opportunities in the literature both allows the proposal of a tool to guide academics in further studies and provision of empirical evidence. Based on the results of the literature review, a correlation matrix has been drawn up to assist in the search for empirical evidence thus enabling researchers to identify synergies or divergences of emerging DTs and the CE in manufacturing. The purpose of this tool is to provide a basis for setting up experimental plans to provide empirical evidence and encourage practitioners to transform manufacturing systems towards a greater circularity with the help of digital technologies.

1 Introduction

The urgency of the environmental situation is constantly highlighted by scientists from the Intergovernmental Panel on Climate Change (IPCC) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). The current increase in the concentration of greenhouse gases due to human activities - including industry - is leading to a significant rise in temperatures, which is having a major impact on the environment (rising sea levels, melting glaciers, intensification of extreme weather events, loss of biodiversity among others) (IPBES, 2019; Mukherji et al., 2023). This urgency is also brought by the fact that six of the nine planetary boundaries have been exceeded in 2022, while the crossing of these natural limits endangers humanity (Persson et al., 2022; Rockström et al., 2009). Scholars and the diverse economic and political actors view the circular economy as one of the alternative solutions. As opposed to the linear economy (take-make-use-dispose), the CE promotes the efficient use of resources at every step of a product's lifecycle, while reducing environmental impact (OECD, 2022).

The adaptation of production systems to the CE is, nevertheless, difficult. Many of the specific processes involved in circular production systems which restore discarded products to operational use, create operational difficulties and uncertainties. Additional complexities can also be observed in the management of workshop flows, for instance, the high variability of used products implies that personalised process flows are needed for each product (Klein et al., 2021). With this in mind, many researchers have postulated that emerging digital technologies - also known as Industry 4.0 technologies - have the potential to remove some of the implementation barriers (Bressanelli et al., 2022; Chauhan et al., 2022; Jabbour et al., 2018b; Rajput and Singh, 2019; Rosa et al., 2020). However, most of the resulting works have been conceptual or explanatory (Jabbour et al., 2022), and few have investigated the barriers to implementing emerging DTs in circular manufacturing systems (CMS). Those that have, have generally deduced the existence of barriers by supposition, or by methods based on

practitioners' opinions (surveys, interviews or working groups). This article, therefore, proposes to study such opportunities and barriers for the use of DTs in CE with a particular focus on manufacturing, based on a systematic literature review. As the number of publications in this field is constantly increasing, the first research objective (RO1) of this paper is to update current literature reviews based on the combination of both CE and DTs.

As the literature combining the two concepts is still in its infancy, it may be interesting to isolate the findings from the literature specific to CE or DTs and then identify potential synergies between the two concepts from this compendium of literature. The advantages of this approach are twofold. Firstly, a larger number of papers have focused on either CE or DTs, resulting in a larger body of literature to examine. Secondly, more researchers in the humanities and social sciences have focused on one of these two concepts separately, with different approaches as detailed in this article, allowing to bridge the existing gap of the absence of humanities and social sciences publication combining the two approaches. A similar observation can be made for the environmental sciences, which have not yet had time to fully investigate the impact of the use of DTs in manufacturing systems.

Thus, based on these works, which have attracted more attention in university realms and come from a wider range of fields than those which combine the two approaches, it is valuable to bring together all the opportunities and barriers to CE and DTs separately in the first instance. This compendium of literature permits, secondly, a grouping of those findings and additional assumptions to be made to those made in the literature combining DTs and CE. Moreover, to highlight this multi-disciplinary approach and show the divergences that may exist between different research communities more easily, this paper has separated the opportunities, barriers and enablers already identified by researcher for DTs or CE of each of the 'economic and technical', 'social', and 'environmental' pillars. All in all, this approach allows the synergies and contradictions that may exist between the CE and DTs to be highlighted, by going further than the update of existing literature on CE and DTs according to RO1. Particular attention being paid to the social dimension related to CE and DTs under study, as this pillar has been little studied in the concepts under review (Trevisan et al., 2021).

Ethics are also briefly discussed, to emphasise their importance in setting up manufacturing systems on these three pillars of sustainable development. Indeed, the advent of intelligent systems questions the uncertainties that may appear, and brings ethical risks regarding the autonomy of these systems which can make decisions that are not necessarily beneficial, interact with humans while generating stress and demotivation, or use data inappropriately for example (Berrah et al., 2021).

Thus, the second research objective (RO2) of this paper is to draw up an exhaustive list of the expected opportunities and barriers for the CE and emerging DTs, as far as this is possible, by using a multi-disciplinary approach and bringing elements of the humanities and social sciences. This approach aims to give a broader view of the opportunities and barriers that manufacturers may face in implementing CE, and can therefore help them to anticipate them.

Based on the results of RO1 and RO2, the third research objective (RO3) aims to support researchers to prioritise their work on the study of the cross-implementation of DTs and CE, and provide industrialists with concrete evidence on the benefits of the use of DTs to encourage them to enter or develop CE in their companies. Two elements are provided in response to RO3. The first tool proposed is a matrix that visually summarises the results of RO1 and RO2, and enables links to be made between the various elements found in the literature. This tool thus permits to identify potential synergies or cumulative effects (positive or negative) that could arise from the use of DTs in CE. This matrix also highlights the topics addressed in the research in line with the subject of this literature review, and highlights a list of promising synergies, whether already identified in the literature or not. This matrix thus highlights cases where the arguments in favour of synergy are missing or insufficient with a lack empirical proof, and by extension points to research opportunities on interesting synergies between DTs and CE.

The second proposed tool is a roadmap for prioritizing the empirical study of potential opportunities provided by new DTs in circular production systems. It aims to highlight potential synergies between the DTs and CE to furnish concrete evidence which will encourage manufacturers to enter a manufacturing mode integrating more circularity. The roadmap includes the use of the matrix introduced before.

The structure of the document is detailed hereafter. Section 2 introduces the main concepts studied in this paper. Section 3 presents the method used, and in particular, the methodology employed to conduct the literature review. Section 4 presents the results of the literature review consistent with RO1 and RO2. In section 5, gaps identified in the literature are highlighted and the tool and roadmap associated with RO3 are presented.

2 Theoretical Background

This section defines the main terms of this article, namely emerging digital technologies, circular economy and circular production systems. In the following parts, the focus is mainly on the opportunities, barriers and enablers for DTs or CE. An opportunity is defined as a possibility for improvement within the company (internally or in its business). A barrier is defined as an element that hinders or limits the success of a business or the achievement of sustainable development goals. An enabler is an element that encourages or promotes the implementation of practices related to circularity, digitalization or both.

2.1 Emerging Digital Technologies

The term ‘Emerging Digital technologies’ for the industry is used to describe DTs that could refer to ‘industry 4.0’, ‘4th industrial revolution’ or ‘smart manufacturing’ concepts. The term Industry 4.0 was introduced at the Hannover Messe in Germany in 2011 and mainly refers to the introduction of Internet-related technologies in Industry (Drath and Horch, 2014; Kagermann et al., 2011). Ten years after the introduction of Industry 4.0, Industry 5.0 have been introduced by European Commission as the capture of the value of new DTs, while respecting planetary boundaries and enhancing workers' well-being (European Commission., 2021). Many developments have been made on the subject in Industry 5.0, as shown by the literature review of Akundi et al. (2022) which advances research topics related to smart and sustainable manufacturing, or connectivity between humans and machines.

Oztemel and Gursev (2020) define Industry 4.0 as a method for transforming manufacturing through digitalisation to achieve automated digital manufacturing processes, through data exchange in particular. Ghobakhloo (2020) highlight twelve design principles of Industry 4.0, that are: Service Orientation, Smart Product, Smart Factory, Interoperability, Modularity, Decentralization, Virtualization, Real-Time Capability, Vertical Integration (i.e. at different hierarchical level), Horizontal Integration Product (i.e. in different stages of company processes), Personalization, and Corporate Social Responsibility. The goal of this concept is thus to make optimal decisions to optimize systems by integrating DTs (Chien et al., 2017).

Even if there is no consensus on the classification of DTs to include in Industry 4.0 (Laskurain-Iturbe et al., 2021), some technological innovation seems to be accepted by an important part of academics. As no single classification is accepted by the scientific community, a list of DTs is drawn up based on several classifications. Articles from Chiarello et al. (2018), Ghobakhloo (2018), Laskurain-Iturbe et al. (2021), Oztemel and Gursev (2020), Rübmann et al. (2015) and Tjahjono et al. (2017) are used to draw up the following list that is used in the literature review: automation and industrial robot (particularly Cobots that are robots working in collaboration with human in a same space), simulation and modelling, Internet Of Things (or IoT, constituting a network of connected devices that collect and transmit data on the process), Cloud Computing, Additive Manufacturing (or 3D-printing), Virtual and Augmented Reality, Cyber-physical systems (constituted of a network of objects connected to a computer simulation to monitor and predict the behaviour of a real system (Yin et al., 2019)), Identification technologies (to retrieve information about individual objects), and Machine-to-Machine communication (allowing machines to communicate with each other without human intervention). The acronym DTs is used in the following to refer to the technologies presented in this section and is mainly associated with the concept of Industry 4.0. The terms “Industry 4.0” is used when referring to the eponymous concept without restricting itself to the technologies associated with it.

Moreover, the Industry 4.0 concept remains unclear for some practitioners. Halse and Jæger (2019) assume that most companies had heard of Industry 4.0, but this concept could be interpreted in multiple ways and not all possibilities of the concept are perceived.

2.2 Circular Economy within the context of sustainability

The concept of CE takes its roots in a paper by Boulding (1966), where he has promoted a “closed economy” where the material remains in the system to be reused, and the term “Circular Economy” was first introduced by Pearce and Turner (1990).

According to Ellen MacArthur Foundation (2013), CE’s goal is to be “restorative or regenerative by intention and design”, and several objectives are derived from this statement: the elimination of waste and pollution, the circulation of products and materials at their maximum value, and the regeneration of nature. Since the publication of this report, researchers from different disciplines around the world have shown a growing interest in this topic (Kirchherr and van Santen, 2019). This diversity in research areas has led to a multitude of definitions. By synthesising of 114 definitions from the scientific literature, Kirchherr et al. (2017) define CE as: “an economic system that replaces the ‘end-of-life’ concept with reducing, alternatively reusing, recycling, and recovering materials in production/distribution and consumption processes. It operates at the micro level

(products, companies, consumers), meso-level (eco-industrial parks) and macro level (city, region, nation and beyond), intending to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity, and social equity, to the benefit of current and future generations. [...]”. This definition also highlights the importance of the three pillars of sustainable development – economic, social and environmental – introduced in Brundtland (1987).

2.3 Circular manufacturing strategies performed in Circular Manufacturing Systems

As part of a more sustainable production process based on CE, several strategies have been proposed for reducing the consumption of natural resources and materials while reducing waste production. These strategies are often defined by a series of concepts in Rs, such as the 9Rs strategies of Potting et al. (2017). Ordered by circularity impact, the prior strategies propose to rethink product use and design to keep the core functions and to increase the efficiency of the manufacturing processes to reduce environmental impact. Then, the extension of the lifespan has to be prioritized with strategies defined in the next paragraph. The least circular strategies are recycling by reprocessing matter or by incineration to create energy (Potting et al., 2017).

In the context of the manufacturing system, a focus is made on strategies ‘reuse’, ‘repair’, ‘refurbish’, remanufacture’ and ‘repurpose’ of Potting et al. (2017), as represented in Figure 1. ‘Reuse’ implies directly selling second-hand products that are in good condition, and ‘repair’ implies small work or part replacement on the product. ‘Refurbishment’ encompasses processes to put a product back into use after the upgrade and preventive replacement of some components for the same use (Potting et al., 2017). Remanufacturing takes place when the main components of a product are used to create a product ‘as-new’, within a process that typically includes inspection of the parts, cleaning, storage, disassembling, reprocessing, reassembling and testing (Sundin, 2004; Thierry et al., 1995). ‘Repurposing’ refers to the use of all or part of a product to give it a new use and different functions (Potting et al., 2017; Reike et al., 2018). Some other terms could be found in the literature, such as upcycling -consisting in giving a discarded product more value or quality- or downcycling – consisting in a reduction in terms of quality - (Helbig et al., 2022). Terms VRP (Value Retention Processes) is also used in the literature, and regroup strategies ‘reuse’, ‘repair’, ‘refurbish’ and ‘remanufacture’ (Thierry et al., 1995). This plurality of terms is accompanied by some confusion in the literature: remanufacturing and refurbishing are sometimes used as synonyms for example (Reike et al., 2018). It is therefore important to pay close attention to the terms and definitions used in publications.

The strategy “Reduce”, which has for objectives to optimize processes to decrease the use of natural resources and energy in the manufacturing (Potting et al., 2017), should also be used in addition to the above mentioned strategies , as represented by green arrows in Figure 1.

Depending on the manufacturing strategies chosen, the quality and performance expected differ between strategies (allowing a fully new life or only a partial service life (Russell and Nasr, 2022).

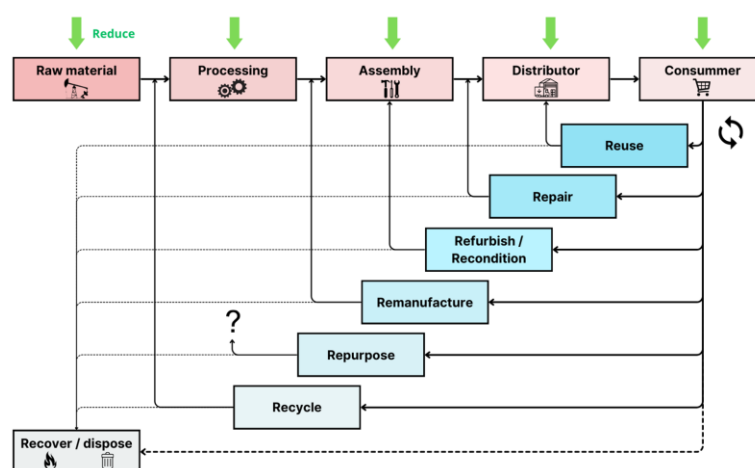


Figure 1 – Circularity strategy for manufacturing systems

Asif and Farazee (2017) have proposed a definition of a circular manufacturing system, as “a system that is designed intentionally for closing the loop of products/components preferably in their original form, through multiple lifecycles”. Within the scope of this article and following the presented concept below, Circular Manufacturing System (CMS) is used to refer to industrial production systems which aim to preserve or restore the value of a second-hand product through reusing, repairing, refurbishing / reconditioning, remanufacturing or repurposing. This article focuses on CMS that produce manufactured goods; thus, the construction or agro-food industry is excluded from the scope of this article.

3 Methodology

The next section presents the methods used in this article. To obtain an exhaustive list of the barriers, opportunities and enablers linked to DTs and CEs, a systematic literature review (SLR) respecting the principles prescribed by the PRISMA method (Moher et al., 2009) was carried out, in line with our first two research objectives. This initial methodology, containing three steps, is represented in Figure 4.

3.1 Methods for the systematic review of literature

To limit bias and provide a neutral analysis of the literature studied, the first step in the proposed methodology is to realise a SLR following the Preferred Reporting Items for a Systematic review and Meta-Analysis (PRISMA) Statement of 2020 (Page et al., 2021). This method provides a clear and structured framework that guided the identification, screening and selection of the most relevant articles concerning the research questions and the criteria developed through an iterative process. It aims to meet the first two objectives: to update existing literature reviews and to draw up a list of opportunities and barriers to the use of DTs in CMS. As the main objective of this literature review is to adopt a multidisciplinary vision integrating an important part of human sciences, other documents in ergonomics and occupational psychology are selected in parallel with the help of an experienced researcher, part of the co-authors of this paper, specialized in these subjects as detailed in the next sub-section. Added documents are indicated in the "Identification of new studies via other methods" part of the PRISMA flowchart in Figure 2.

3.1.1 Paper identification

Web of Sciences (WoS) and SCOPUS databases are used to extract the article information. The data retrieval was performed in February 2023 and updated in May 2023. Several preliminary tests were carried out to obtain the relevant keywords for this literature review. Keywords on CE, DTs (mainly referred to Industry 4.0 in the literature) and adoption conditions were selected and a search on the above-mentioned databases was carried out. Several abstracts and keywords in the extractions were studied in order to enrich the initial list of keywords, and were iteratively added to the database search until obtaining the most complete list possible of keywords relevant to our literature review.

The search string contained two main components. The first component focused on the circular economy, emerging technologies and derivative terms. Preliminary research allowed the selection of the following keywords, separated by "OR" operators: "Circular economy", "Remanufacturing", "Circular manufacturing", "Sustainable manufacturing" and "Industry 4.0". The second component focuses on benefits and obstacles. Through the same process of preliminary search of keywords, the following are selected: "Challenges", "Opportunities", "Gains", "Antecedents", "Barriers" and Ethic*. Those two strings are linked by an "AND" operator to obtain relevant articles in the expected prism to answer the research question. The research formula used is therefore: "(Circular economy" OR "Remanufacturing" OR "Circular manufacturing" OR "sustainable manufacturing" OR "Industry 4.0") AND ("Challenges" OR "Opportunities" OR "Gains" OR "Antecedents" OR "Barriers" OR Ethic*). Only peer-review articles, literature reviews and conference proceedings were selected. The following filters were also applied to the search in WoS and Scopus: documents in English published between 2011 and 2023. Indeed, Industry 4.0 concepts appeared in 2011 and there was a rise in publications around 2014. The buzz around the circular economy has also risen sharply after the publication of the first Mac Arthur Foundation reports in 2013 (Kirchherr and van Santen, 2019). Thus, the documents selected provide a literature review of all the work published since the advent of Industry 4.0. Furthermore, given that several literature reviews were also included in this article, any previous work had to be taken into account in these literature reviews both on DTs or CE, such as Lieder and Rashid (2016), Stock and Seliger (2016), Zhong et al. (2017). It should also be noted that some reports could not be retrieved, mainly due to a lack of information about the article in the export (DOI, link to the article, author contact).

Concerning, humanities and social sciences publications, it is important to take into account the particularities inherent in this field of research. Indeed, it should be noted that publications are to be retrieved from a very wide variety of information sources and that there is no common language used, hence the presence of a large number of non-English papers and the need to consider several databases and document types for investigations (Mangas-Vega et al., 2018).

As this paper is particularly concerned with emphasising the multidisciplinary aspect, in line with our second objective, and as the usual methodologies are limited to the social sciences, a specialist in the social sciences and humanities was involved in the selection of relevant complementary documents to add to this literature review. The filters applied above were therefore extended to documents containing books and publications in French. These complementary documents were added from Google Scholar for English language

publications and from the Cairn database for French language publications.

Some documents cited by reviewed articles are also added to enrich the analysis.

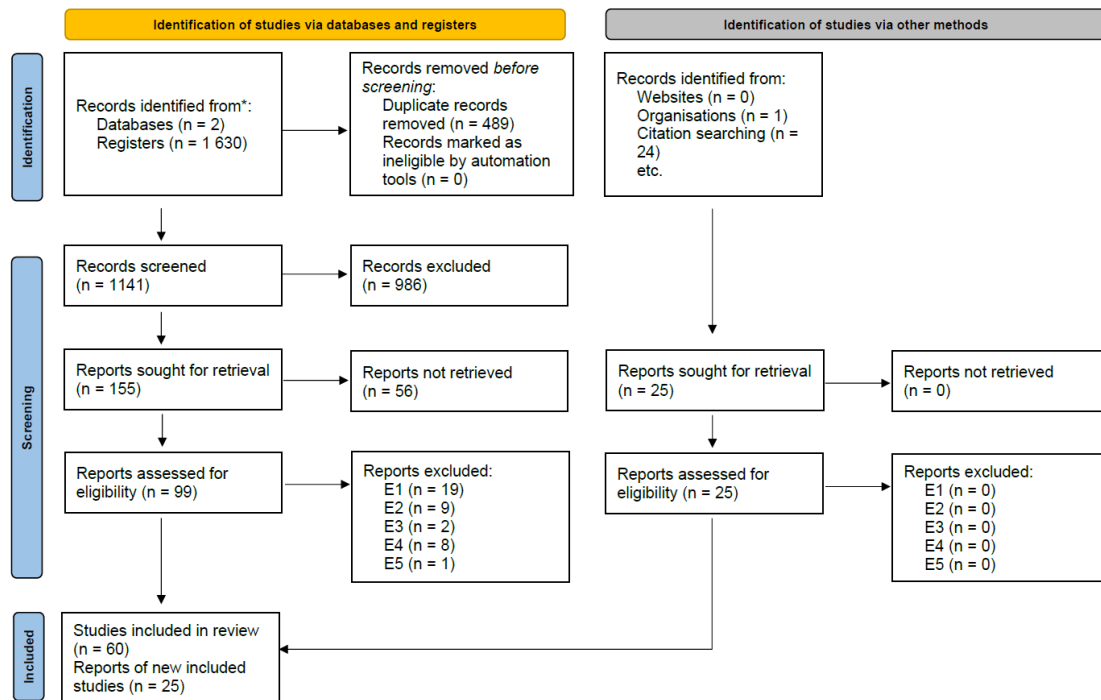


Figure 2 - PRISMA Flowchart [following the template of (Page et al., 2021)]

3.1.2 Paper screening

During the screening phase, the selection of papers was made by using criteria E1 to E5 which are reported in Table 1. Only papers that focused on both manufacturing and the study of opportunities, levers and barriers were retained in the study.

This article focuses on CMS that produce manufactured goods, that are defined as goods produced by “the application of labour and capital to raw materials and other intermediate inputs” by (Eurostat, 2023a). Primary goods (mainly raw materials and food) are therefore excluded from this study since they are not composed of elements found in nature (Eurostat, 2023b), so the main presented strategies are not applicable outside of recycling.

Table 1 – Exclusion Criteria for systematic literature review

Exclusion Criteria	Description
E0 – Search criteria or missing data	The paper is not an article or conference paper in English, published between 2014 and 2023; or certain key data to evaluate the article were missing.
E1 – Not focused manufacturing	The paper does not sufficiently address the implications of manufacturing.
E2 – Not focused on levers and barriers studies	The paper does not sufficiently address the study of levers and barriers.
E3 – Not focus on Circularity and Digital Technologies	Circularity or Digital Technologies are not the focus of the article (used as an example, supportive concept or keyword).
E4 - Too specific	The article focuses on a very specific point related to Digital Technologies or the Circular Economy, which is not replicable to other contexts or not relevant in the case of the study.
E5 – Other	An updated version of the paper or an extensive version of a proceeding was published by the same authors.

This literature review leads to the second step of the methodology, which aims to propose a first sorting of papers on the concepts that are studied (DTs, CE or a combination of DTs and CE), and possibly see if one or more pillars of sustainable development are identified.

3.1.3 Data study of the sample publications collected

To give an overview of current research, the sample of articles collected on Scopus and WoS is analysed, after removing duplicates. The distribution of publications is studied according to type, date and source. This overview permits the visualisation of the trends and dynamics of research in this field. Figure 3 shows the temporal distribution of publications from 2011 to 2023. The literature has been growing steadily on the subject since 2015, and this has particularly increased since 2021. Moreover, the articles from the original extraction are mainly journal articles (70.4%), followed by literature reviews and conferences (15.2% and 14.4% respectively).

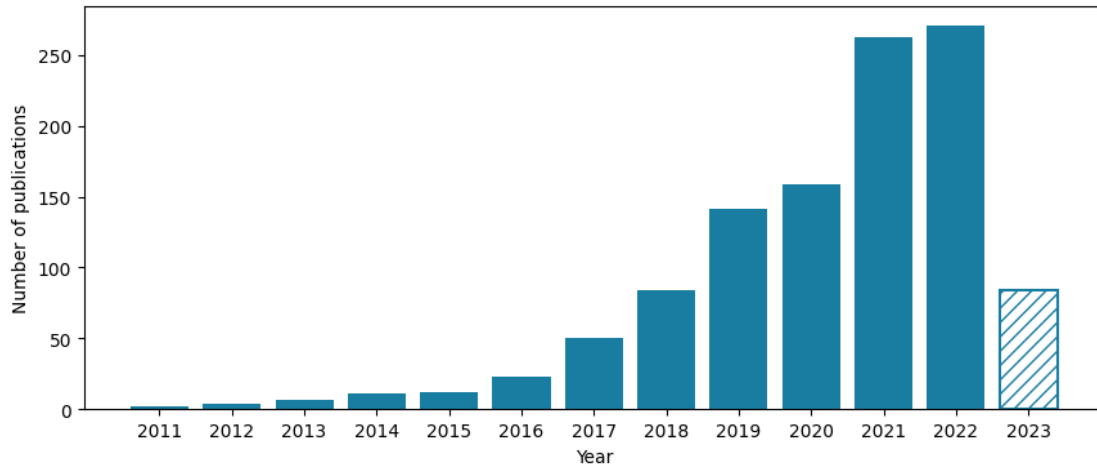


Figure 3 – Number of publications by year between 2011 and 2023

More than 600 different sources for publications are identified. Two journals whose main theme is sustainability seem to stand out in the publication panel, namely 'Journal of Cleaner Production' and 'Sustainability'. It should also be noted that publications can be found in a significant number of journals in several fields, testifying to the multi-disciplinary aspect of the research and the growing number of researchers from different fields interested in it, whether in engineering, managerial or environmental sciences.

3.2 Methods for classifying and analyzing results

From the collection and initial classification of the articles retrieved in the first two steps, as presented in section 3.1, the use of these publications is presented in this section.

First, the research profile (i.e. the topics studied and the methods used for research) of DTs and CE is presented. This is followed by the levers, barriers and opportunities for CE and DTs, which are detailed separately and classified according to the three pillars of sustainable development: economic/technical, environmental and social.

Each subsection is finalized with a table that summarizes the different opportunities, barriers and enablers that are to be retained for each concept and each pillar. An additional level of classification is proposed in these summary tables to indicate the level of management (strategic, tactic or operational) concerned by the item in question. These levels express in particular the time horizon and impact of the decisions: strategic decisions have a long-term impact (in the order of years), tactical decisions have a medium-term impact (in the order of weeks) and operational decisions have a short-term impact (in the order of hours or days). Moreover, the stakeholders are generally not the same either. Strategic decisions are generally taken by the highest level of management, such as choosing the level of automation. Tactical decisions may deal with issues such as the design of a workshop, the number of operators or production planning issues. Operational decisions generally deal with day-to-day operations, such as decisions about product variability or demand (Dolgui et al., 2022).

The various items in the table have been classified as barriers, opportunities and enablers when these classes were mentioned in the articles from which they were taken, or in accordance with the definitions presented in the introduction of Section 2. The different strategic levels have mainly been established on the basis of Dolgui et al. (2022) definitions, as these levels are not frequently cited in the articles of this review.

This first classification aims to link the two concepts on each of the pillars, to enable the reader to identify the synergies or cumulative effects (positive or negative) that may arise from the use of DTs in CMS. This pillar-by-pillar approach also enables the highlight of any divergences that may exist between different scientific communities.

Finally, each section is concluded by analysing the current literature on the use of DTs to achieve circularity in a manufacturing context, thus highlighting any synergies or cumulative effects already identified in the existing literature. The writing of these sections represents the third step in the process presented in Figure 4.

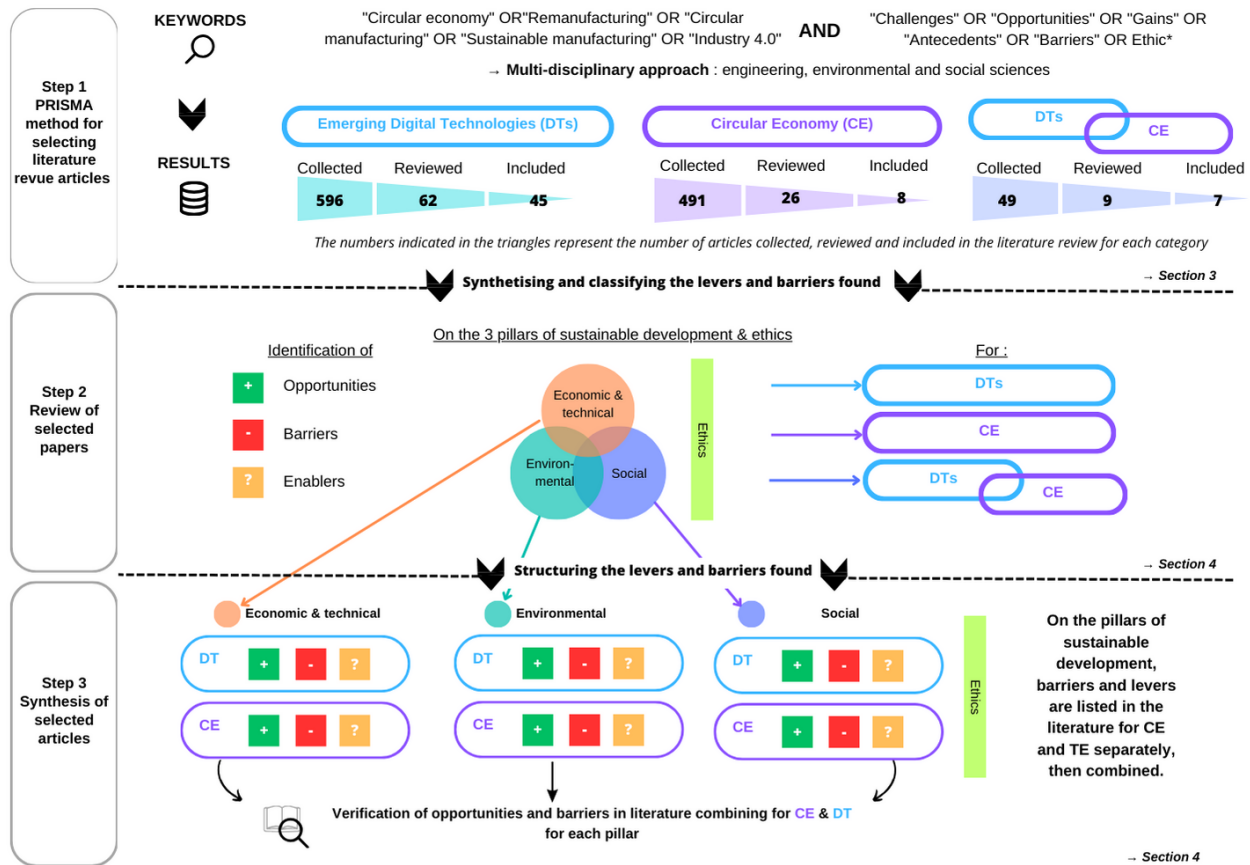


Figure 4 – Outline of the used methodology

4 Results

The following section presents the literature review on the opportunities, barriers and enablers of DTs and the CE, based on the selected paper in section 3.1 and according to the classification detailed in section 3.2. A short section will also highlight the importance of an ethical approach to the whole process.

4.1 Research profile

Firstly, observations are formulated based on data collected in the review literature and highlight the type of methodology used to provide evidence on the subject in question. As shown in Figure 4, the reviewed sample contains a majority of articles dealing with DTs, while the CE remains less covered. This could be explained by the small number of articles on manufacturing topics, and that the search string includes manufacturing aspects. Similarly, the number of articles combining DTs and the CE is also limited, as only 49 articles were collected in the database and 7 were kept in the SLR as shown in Figure 4.

4.1.1 Focus on digital technologies

A large number of studies have been carried out on the barriers and levers to the implementation of DTs (in particular as part of the industry 4.0 concept). Many literature reviews could be found on DTs with a focus on levers and barriers (Caiado et al., 2022; Chauhan et al., 2021; Habib et al., 2022; Ing et al., 2019; Orzes et al., 2018; Rehman et al., 2021). These reviews have often included opinions of managers (through surveys, interviews, workshops and/or focus groups) to add new elements or propose a critical analysis of existing literature reviews.

Some studies have attempted to specify the barriers by taking a different scope, especially regarding a given country or region, or the use of a particular technology. For example, there were studies on barriers to Industry 4.0 in Poland (Jankowska et al., 2023), in the UK for Small and Medium Enterprises (SMEs) (Masood and Sonntag, 2020), in Germany (Müller et al., 2018), in India (Kumar et al., 2022; Nimawat and Gidwani, 2021), in Denmark for SMEs (Stentoft et al., 2021), in Serbia (Vuksanović Herceg et al., 2020), in Mexico (Cuevas-Vargas and Fernández-Escobedo, 2022) and in Kazakhstan SMEs (Turkylmaz et al., 2021). These specialized country studies show differences in the type and importance of levers and barriers related to new technologies. Although

the barriers seem to be higher in developing countries according to Elhousseiny and Crispim (2022), even if they also seem to have greater opportunities associated with the implementation of DTs.

Other studies have tried to go further in the analysis of these barriers. Several authors have also sought to find the relationships and interactions between barriers, intending to prioritize the elements constraining the implementation of Industry 4.0 technologies, through the Interpretive Structural Modelling (ISM) -or derivative- and MICMAC approach (Alsaadi, 2022; Bakhtari et al., 2020, 2021; Goel et al., 2022; Karadayi-Usta, 2020; P. Kumar et al., 2021; Vimal et al., 2023). Bisht et al. (2023) used a DEMATEL approach to find the relationship between barriers of Industry 4.0, and Kumar et al. (2022) used the same approach with a focus on sustainability and SMEs. Kumar et al. (2021) tried to quantify the impact of a barrier of Industry 4.0 in a quantitative way through a graph-theoretic approach, and Kumar et al. (2020) used a Best-Worst Method for the same purpose. Nimawat and Gidwani (2021) used Analytic Hierarchy Process (AHP) and Analytic Network Process (ANP) analysis to rank barriers related to Industry 4.0. AHP method was also used for the same purpose by Sachdeva et al. (2022) with a focus on Indian SMEs, and Aygün and Ecevit Sati (2022) with a focus on Turkish SMEs.

The levers and barriers may also depend on the DTs involved. By interviewing 271 managers of SMEs in the UK, Masood and Sonntag (2020) tried to quantify the benefits and difficulties of implementing several specific DTs. They found that the majority of DTs were seen as beneficial, while the difficulty of implementing a technology varied significantly depending on the type of technology studied. Rikalovic et al. (2022) took a complementary approach to analyse barriers by focusing on certain technologies and concentrating only on the implementation phase. Machado et al. (2019) took a broader view by looking at the barriers that arise at different stages of implementation.

4.1.2 Focus on the Circular Economy and Remanufacturing

The number of publications on the CE is increasing, however, there are fewer documents specializing in the subject of manufacturing systems opportunities and barriers. Some literature reviews do exist, such as the one by Govindan et al. (2022) or Mishra et al. (2022). Manoharan et al. (2022) also proposed a ranking for enablers and barriers using Interpretive Structural Modelling (ISM) and DEMATEL approach. Similar papers do exist for remanufacturing, such as the one by Chakraborty et al. (2019) or Eguren et al. (2018).

4.1.3 Focus on papers combining the Circular Economy and Digital Technologies

Numerous scholars predict that emerging DTs will be a key element to unlock the potential of the CE (Bressanelli et al., 2022; Chauhan et al., 2022; Jabbour et al., 2018b; Rajput and Singh, 2019; Rosa et al., 2020). Jabbour et al. (2022) surveyed 132 companies in Brazil and found that the combination of the CE and TI4.0 could have benefice on economic, social, environmental and operational performance. It thus assumes a synergistic effect of DTs and CE. Prieto-Sandoval et al. (2019) pointed out that modernisation appears as one of the major enablers to achieve circularity, especially for SMEs. Thanks to a study of 161 companies in India, Rajput and Singh (2019) indicated that Industry 4.0 offer opportunities to enhance circular business models like remanufacturing, recycling, maintainability, extending product life cycles, and increasing product value. Hennemann Hilario da Silva and Sehnem (2022) also conducted work to list potential uses of technologies that could be useful in CE practices

Some related concepts also emerged, such as “Smart Circular Economy”, which is defined as an industrial system that “uses digital technologies during the product life-cycle phases to implement CE strategies and practices, aiming at value creation through increased environmental, social, and economic performance” by Bressanelli et al. (2022). In other words, the goal of this paradigm is to properly use information work, by providing appropriate data to the right person at the right moment to optimally use resources.

Nevertheless, the number of papers studying the CE and DTs remains low. In the scope of the study of levers and barriers in manufacturing, only six relevant publications were identified. Indeed, researchers generally approach environmental aspects through the broad prism of sustainability and include the CE as a concept that forms part of sustainable practices without a strong focus on CE. For example, Cochran and Rauch (2020) have proposed a framework to (re)design the company globally in a sustainable way by integrating simultaneously Industry 4.0 technologies and highlighting the CE as a sustainable practice. Several articles focusing on sustainability have also included aspects dealing specifically with the CE (Enyoghasi and Badurdeen, 2021; Furstenuau et al., 2020).

Moreover, existing papers dealing with the levers and barriers to implementing DTs for circularity generally do not focus on manufacturing. For example, Cui et al. (2021), Demestichas and Daskalakis (2020) and Vimal et al. (2023) focused on the use of technologies for circularity, mainly identifies barriers inherent to the

implementation of new technologies and do not take into account the particularities inherent to the CE in production. The most comprehensive work is proposed by Kayikci et al. (2021), who listed through a literature review and academic discussions 34 barriers to the adoption of smart and sustainable CE by exploring technological, producers, consumers, and policy challenges. Yang et al. (2018) also proposed an opportunity study concluding that DTs can address several challenges in remanufacturing.

However, those studies are often based on surveys of manager points of view, which could be biased, and no case study to quantitatively assess impact with a cross-disciplinary point of view is presented. In fact, in this section, half of the papers were based on collecting the views of industrialists using various methods (focus group, interview, survey, questionnaire), and the second half were based on literature reviews. Only one research paper presents a real case study, and it does not adopt a multidisciplinary approach.

Finally, publications also offer more detailed studies of the opportunities and barriers for particular DTs, such as the use of additive manufacturing (Tavares et al., 2023).

4.2 Levers, barriers and enablers in relation to performance and the economic pillar

The literature review first focuses on the technical and economic pillar, which aims to address the levers and barriers associated with setting up or modifying manufacturing systems from an engineering point of view along with cost and profitability aspects.

4.2.1 Focus on Digital Technologies in relation to performance and economic pillar

Büchi et al. (2020) have empirically demonstrated that local production units obtain greater opportunities depending on their degree of openness to Industry 4.0, i.e. the number of technologies implemented and the different stages of the supply chain where the concept is applied. These opportunities translate into increased flexibility and speed, greater production capacity, reduced costs and errors, better product quality and an improved ability to meet customer needs. These results seem particularly well suited to small, local units. Cuevas-Vargas and Fernández-Escobedo (2022) add other opportunities to those mentioned: greater product traceability, reduced stock, reduced documentation and non-value-added tasks. Zhong et al. (2017) also underline benefits in terms of integration with other stakeholders thanks to the use of product data.

Through a literature review and interviews, Raj et al. (2020) concluded that the absence of digital strategies and constraints in terms of resources could be seen as a major barrier. Indeed, the absence of digital culture and a minimal training of employees can prevent the implementation of Industry 4.0.

Halse and Jæger (2019) and Kamble et al. (2018) have also emphasized implementation costs as a major barrier. Raj et al. (2020) assumed that there was no certainty regarding the economical and productivity dimensions, which results in slowing down of capital investment. Legal and contractual uncertainties also appear to be barriers (Kamble et al., 2018). Moreover, the integration of technologies along the value chain often requires the participation of multiple stakeholders where the absence of standards may be accompanied by reduced commitment of those same multiple participants (Raj et al., 2020).

Yet another aspect is that there is no consensus about the profitability of emerging technologies for SMEs. Some researchers have noted that the risks of implementation increase as the size of the company decreases. Thus, SMEs could suffer more negative effects than benefits in the implementation of emerging technologies in their systems if these are not well prepared (Sommer, 2015). The benefits, as already mentioned, appear to be greater as the size of the company increases and depending on the business sectors (Müller et al., 2018). Indeed, it is not always easy for SMEs to acquire an appropriate level of maturity to implement new technologies (Stentoft et al., 2021). Through 14 interviews conducted with managers, Birkel et al. (2019) highlighted other risks associated with the dependencies that arise with the implementation of DTs. SMEs rely on external companies to manage the complexity of the technological aspects of their businesses due to a lack of in-house expertise, and therefore depend on their service providers for repairs and software upgrades in case of system failure.

The installation of DTs carries with it the risk of failure of low-mature technologies or the fact that some products are unadapted to technological processes (very low quantities of products for example) (Halse and Jæger, 2019; Raj et al., 2020). In addition, there are a lack of standards and reference architecture for digital systems, incompatibilities with existing machines that prevent retrofitting, and interoperability problems between technologies (Kamble et al., 2018).

Therefore, despite its advantages, data compilation is also accompanied by obstacles to its implementation such as the complexity of storing, gathering and extracting useful information from a large amount of different quality data (Birkel et al., 2019; Gaspar and Juliao, 2021; Khan and Turowski, 2016; Raj et al., 2020). Other

important related aspects are the protection of data from competition and cyberattacks, as well as questions about data ownership, (Birkel et al., 2019), and implementation of DTs requires an adequate technological infrastructure guaranteeing good connectivity (Raj et al., 2020).

Moving now to the level of adoption of a specific technology, such as the IoT in the article published by Cui et al. (2021), additional barriers concerning the technical aspects of the interface, compatibility and interoperability, upgrading, data integration and use, and security may also prevent implementation of these technologies. These barriers may lead some companies to never succeed in using these technologies because their application remains unmanageable by the staff (Abdulaziz et al., 2023). Other technologies have been explored in more detail in other publications, such as blockchain (Rejeb et al., 2022), additive manufacturing (Tavares et al., 2023) or intelligent robotics (Suha and Sanam, 2022).

A poor understanding of the concept of Industry 4.0, as well as doubts about its capacity to increase profitability, constitute a further barrier in managers deciding to put these technologies in place (Alsaadi, 2022; Kamble et al., 2018). Managerial decisions may be influenced by a preference to remain with more dated business models, and a lack of vision for the future (Bakhtari et al., 2021, 2020). Cugno et al. (2021) indicate that a company's openness to Industry 4.0 enables it to have a better knowledge to better understand the related obstacles, and apply incentives more easily, leading to improved company performance.

Lean production techniques seem to be an enabler, and even a prerequisite, in the adoption of Industry 4.0 concept at high levels. Although lean is a broader concept than just a set of practices, those techniques include Just In Time, pull production, Kanban, Total Quality Management and employee involvement (Shah and Ward, 2007). Because lean techniques have been implemented since the 1990s while Industry 4.0 is still emerging, lean production seems to have a systematically greater impact on improving operational performance than Industry 4.0 in the European context of the study of Rossini et al. (2019). Tortorella et al. (2019) have highlighted that only the adoption of technologies does not lead to improved performance in industry. However, the practices, behaviours, mindsets and organizational changes acquired through the prior implementation of lean are useful when combined with emerging technologies in companies aiming to enhance their operations in the context of Industry 4.0. Yilmaz et al. (2022) have emphasized the various beneficial effects of lean techniques and how to create a suitable environment for Industry 4.0, along with the social and environmental dimensions that can arise from the cross-implementation of lean and technology. Thus, lean seems to be an enabler in the implementation of Industry 4.0, and thus for DTs.

A synthesis of the main findings of this section is proposed in Table 2.

Table 2 - Opportunities, barriers and enablers for economic and technical aspects of digital technologies on strategic (S), Tactical (T) or Operational (O) levels (\emptyset is used when no information belongs to this category)

Performance and economic pillar for Digital Technologies		Sources	
Opportunities	S \emptyset		
	T Integration with other stakeholders	Zhong et al. (2017)	
	O	Increased flexibility, production capacity, quality, personalisation	Büchi et al. (2020)
		Increased product traceability	Cuevas-Vargas and Fernández-Escobedo (2022)
Reduced costs and errors			
	Reduced stock, documentation and non-value-added tasks.		
Barriers	S	Absence of digital strategies/culture	Raj et al. (2020)
		Lack of certainty about economic and productivity, implementation costs	Birkel et al. (2019)
		Lack of understanding about the benefits of some technologies	Alsaadi (2022)
	T	Constraints in terms of resources, absence of standards and lack of legislation	Raj et al. (2020)
		Lack of technological infrastructures, engagement of multiple stakeholders, dependencies with technologies and external companies, data processing	Birkel et al. (2019)
	O	Technical issues (cyberattacks, data privacy, failure of technologies, data protection	Raj et al. (2020)
inappropriate products for technological processes)		Halse and Jæger (2019)	
	Incompatibility with existing machines / Interoperability between technologies	Kamble et al. (2018)	
Enablers	Company's openness to Industry 4.0	Cugno et al. (2021)	
	Lean Production Systems	Yilmaz et al. (2022)	

4.2.2 Focus on the Circular Economy in relation to performance and the economic pillar

One of the major opportunities pointed out by Liu et al. (2023) is that CE seems to be beneficial in the longer term for revenue, return on sales, growth, profit and ROI. It is emphasised that a remanufacturer that gives its products a second life could potentially reach a broader market while bettering its reputation and acquiring knowledge which will help improve its product design (Lund, 1984).

However, the economic impact in the short term is more complicated to determine. Start-up costs are generally high which is one factor that deters companies from entering a circular business (Halse and Jæger, 2019). Some put to the fore the massive investment needed, entailing a negative economic impact (implementation costs, return on investment and implementation planning) in the short term (Jabbour et al., 2018b; Liu et al., 2023), while others have recognized that there are low entry barriers in terms of capital and know-how (less investment in machinery and inexpensive raw materials) (Lund, 1984). Moreover, most tasks in circular manufacturing systems involve manual work, thus creating high labour costs (Kurilova-Palisaitiene et al., 2018).

Many studies have focused on the operational impact of value retention processes. One of the major barriers is the lack of technical knowledge on how to put in place cleaner production technologies (Geng and Doberstein, 2008). Companies embarking on this path require acquire new skills to disassemble or repair used parts, and learn to live with uncertainty (Thierry et al., 1995; Kurilova-Palisaitiene and Sundin, 2014). Where uncertainty is concerned, core availability and quantity, timing, and variabilities of the initial products quality should be mentioned (Chakraborty et al., 2019; Kurilova-Palisaitiene et al., 2018; Wei et al., 2015). There are therefore an unpredictable number of operations in the process, which creates difficulties in production scheduling (Kurilova-Palisaitiene et al., 2018).

The difficulties of disassembly appear as a barrier due to irreversible joints or degradation during use (Halse and Jæger, 2019). Indeed, the impossibility to make adjustments, due to very low tolerance margins, can damage a part and make operations too costly to recover it (Ijomah, 2009). Compatibility problems between parts may also occur (Chakraborty et al., 2019), implying quality issues, especially in remanufacturing where the product is intended to be 'as-new' and to fit OEM specifications (Gunasekara et al., 2020; Thierry et al., 1995). Problems in quality management could be brought about by a lack of qualification among operators or insufficient standards application (Kurilova-Palisaitiene et al., 2018).

The number of references could also grow resulting in a more complex process, where multiple companies have to coordinate with each other (Halse and Jæger, 2019). Delivery and availability problems may also occur for non-standard or rare spare parts where suppliers have little demand (Kurilova-Palisaitiene et al., 2018).

These difficulties can potentially spread throughout the whole manufacturing process. Indeed, a high level of inventory is required to compensate lack or poor core quality, or the unpredictability of delivery of cores or parts needed for reprocessing. This entails a need for extensive storage space. The wait for spare parts is likely to be longer when there is a lack of communication with external suppliers. The absence of material flow control through MRP (Material Requirement Planning) or an outdated system lacking flexibility thwarts the coherence of information required for production. A further difficulty is in finding the right balance between supplied core and ordered parts (Kurilova-Palisaitiene et al., 2018).

Useful information about used parts is often missing. This information may be precious where the choice of an optimal scenario to recover a part is concerned. The types of information include the type, age, model, the quality or information about former users for example. Indeed, Thierry et al. (1995) noted that data are often scattered throughout the company and so exchanges of information imply the need for more and better collaboration between suppliers for Product Recovery Management to be successful. Difficulties in acquiring knowledge about a product could be due to the reluctance of OEMs to share product information so as to protect their intellectual property (Ijomah, 2009). Since optimal product recovery is often attained through the redesign of products and processes (Thierry et al., 1995), or the use of used data, a lack of accurate information on a product complexifies the choice of an optimal scenario for implementing circular practices (Geng and Doberstein, 2008; Su et al., 2013; Kurilova-Palisaitiene et al., 2015). The different recovery options for a product can also be interrelated, hence the need for adequate information. Finally, a lack of technical knowledge also constitutes a barrier, and current technologies are frequently too rigid for the tasks required in the recovery process (Mishra et al., 2022). The most challenging technological barriers appear in processes such as inspection, verification, testing and the recovery of some parts (Eguren et al., 2018).

It is also worthwhile noting/ that several external barriers depending on several factors (location, sector of activity, etc.) exist, although there is no consensus on these. Seitz (2007) identifies legislation, brand protection and customer orientation as motivations, while the lack of policies to promote sustainable actions or consumer involvement are seen as barriers by other researchers (Geng and Doberstein, 2008; Peng et al., 2021; Su et al., 2013).

Some of the challenges associated with remanufacturing, such as product quality, process lead time and inventory level challenges, could be improved by the implementation of lean in remanufacturing processes (Kurilova-Palisaitiene et al., 2018; Kurilova-Palisaitiene and Sundin, 2014).

A synthesis of the main findings of this section is proposed in Table 3.

Table 3 - Opportunities, barriers and enablers for economics and technical aspects for the Circular Economy on strategic (S), Tactical (T) or Operational (O) level (∅ is used when no information belongs to this category)

Performance and economic pillar for Circular Economy		Sources	
Opportunities	S	Improved revenue, return on sales, growth, profit and ROI on longer terms Broader market, company reputation, new knowledge for product design, low entry barriers in terms of capital and know-how	Liu et al. (2023) Lund (1984)
	T	∅	
	O	∅	
Barriers	S	Economic impact on the short terms / uncertain start-up costs	Halse and Jæger (2019), Jabbour et al. (2018b) Liu et al. (2023)
	T	Lack of technical knowledge High labour cost	Geng and Doberstein (2008); Kurilova-Palisaitiene et al. (2018)
	O	Uncertainties in timing, quantity, initial quality of products, number of operations Parts repairing: adjustment problems, risk of breakage, compatibility Quality management	Thierry et al. (1995) ; Kurilova-Palisaitiene and Sundin (2014).
		Inventory: high level of inventory, references management, waiting of spare parts Lack of information about products to restore Difficulty in choosing of optimal recovery scenario Rigidity of technologies for recovery processes	Chakraborty et al. (2019) Ijomah (2009) Mishra et al. (2022)
		Lean Production Systems	Kurilova-Palisaitiene et al. (2018); Kurilova-Palisaitiene and Sundin, (2014)

4.2.3 Focus on cross-implementation of the Circular Economy and Digital Technologies for performance and the economic pillar

On the technical opportunities point, studies highlight the benefits of new DTs in the remanufacturing processes, such as increased flexibility, the ability to produce small batches with high completeness, improved traceability and information sharing along the chain (Yang et al., 2018). For example, Fang et al. (2013) proposed a literature review on the use of smart embedded sensors in products at different stages of the product lifecycle, confirming in particular the potential contribution of data, but underlining the potential complexity linked to the analysis of these data.

In terms of financial opportunities, a survey and a case study by Liu et al. (2023) concluded that DTs could have a direct and positive impact on financial performance, but that these DTs have little impact on the relationship between circular manufacturing and business performance if they are implemented alone, based on the hypothesis that firm performance is mainly driven by practices rather than technologies. Adopting DTs alone (without changing practices) has no an impact on firm performance of companies in the case of CMS.

Regarding technological barriers, Kayikci et al. (2021) mainly identified the same as those mentioned in the section on barriers to DTs. On the producer aspects, the article stated that there are few business processes (which include standardisation of workflows, simplification of operations, and optimization of processes, ...) and unsuccessful frameworks to help companies in the implementation of CE. The complexity on a product level of CE implementation also increases the complexity and the operational risk (maintenance, outsourcing, difficulties in collecting products...). The vagueness of the definition of the CE for certain manufacturers slows down this transition towards more circularity.

Regarding financial barriers, Halse and Jæger (2019) found that the implementation cost is the only common barrier between the CE and DTs, and recommended using another methodological technique to look for other potential links through interviews and case studies. Kayikci et al. (2021) added that there is a divergence between costs and profits, and financial resources that are often insufficient for funding.

4.3 Levers, barriers and enablers for the environmental pillar

This second part aims to examine the environmental impact of the two concepts, taking into account not only the operating period but also the upstream and downstream stages, in order to consider the entire life cycle of products and DTs.

4.3.1 Focus on digital technologies for the environmental pillar

Several authors in the literature, such as Stock and Seliger (2016) or Jabbour et al. (2018b), predicted that DTs have the potential to fully realise environmentally-sustainable manufacturing at several levels: product, manufacturing, supply chain, etc. Cochran and Rauch (2020) assumed that environmental sustainability and protection is one of the goals of Industry 4.0, highlighting the ability of certain technologies to make users aware of the impact of production and energy consumption through continuous monitoring of connected objects. It also allows an increase in the reuse of materials and avoid waste, to reduce the use of paper thanks to the digitalisation of processes and to support the design of products and processes.

Indeed, new industrial DTs can ensure a more efficient use of resources and energy needed for production. The new technologies make it possible to reduce waste, limit overproduction and reduce energy consumption by efficiently producing with a stable level of product quality. For example, a system of automatic control of the products interconnected to the needs of the production line allows a reduction in raw materials requirements when production is low. Furthermore, the use of sensors for energy measurement and intelligent machines could reduce the consumption of the factory by controlling the various parameters of production (Waibel et al., 2017; Wang et al., 2016). The improvement of quality thanks to the better precision of the technologies can make it possible to drastically reduce the number of products with quality defects along the production line, thus reducing the use of production inputs (Braccini and Margherita, 2018).

However, these new technologies require large amounts of resources and energy for their production and use, and generate waste at the end of their life. Bonilla et al. (2018) proposed a literature-based analysis of the environmental impacts on the whole lifecycle of DTs with the aim of studying the impacts and challenges at the various stages of implementing and using the technologies over the short and long term. During the deployment phase (i.e. upgrading current tools/infrastructure and discarding old ones), there is an increase in the use of energy, raw materials (including rare earths) and fuel, as well as a large amount of waste (especially electrical and electronic waste). Indeed, there are difficulties in retrofitting existing tools to make them suitable for Industry 4.0, thus resulting in a large amount of waste that ends up in landfills (Birkel et al., 2019). During the operational phase (i.e. the phase during which companies transform materials into products), emerging technologies seem to contribute positively to many environmental sustainability goals, such as reducing the amount of materials used and waste, extending product lifetimes, and obtaining reliable data on production systems. Nevertheless, energy consumption must remain a target and has to be monitored: the use of technologies and necessary infrastructures (data centres, ...) leads on the one hand to an increase in energy consumption and allows on the other hand a reduction of these consumptions thanks to smart algorithms. However, there are very few quantitative analyses to demonstrate these hypotheses (Bonilla et al., 2018). The real impact of the implementation of DTs can therefore only be assessed in terms of the activities that are carried out, the way in which the use of the technologies is planned and the quantities of production (i.e. an increase in production implies an increase in the flow of energy and materials, thus cancelling the positive effect of new technologies). In the long term, however, the environmental benefits appear to outweigh the costs, if they are integrated with the objectives of sustainable development. Furthermore, Birkel et al. (2019) added another risk associated with Industry 4.0, which is that mass customisation creates highly individualised products, that are difficult for another consumer to reuse or resell them, thus becoming an additional source of waste.

It should also be noted that quantitative impact assessment was not part of the scope of the article by Bonilla et al. (2018) and that other methodologies should be employed, such as life cycle assessment, material intensity or energy accounting. This assessment is particularly important for some technologies that consume a lot of energy, especially those that require a lot of computational capacity such as blockchain or big data (Rejeb et al., 2022; Waibel et al., 2017). Designing systems with reduced energy consumption is a real challenge in implementing of technologies in production systems (Wankhede and Vinodh, 2021; Yadav et al., 2020).

A lack of motivation on the part of management to adopt sustainable practices or an inappropriate way of implementing sustainable practices (possibly inspired by other companies) appear to be two major obstacles in the decision-making process regarding DTs (Wankhede and Vinodh, 2021; Yadav et al., 2020).

A synthesis of the main findings of this section is proposed in Table 4.

Table 4 - Opportunities, barriers and enablers for environmental aspects for Digital Technologies on strategic (S), Tactical (T) or Operational (O) levels (\emptyset is used when no information belongs to this category)

		Environmental pillar for Digital Technologies	Sources
Opportunities	S	\emptyset	
	T	Make users aware of the impacts of production	Cochran and Rauch (2020)
	O	More efficient use of materials and energy Reduce waste, defects and use of papers	Cochran and Rauch (2020), Waibel et al. (2017), Wang et al. (2016), Braccini and Margherita (2018)
Barriers	S	Reluctance to management to implement sustainable practices Inappropriate way to implement sustainable practices	Wankhede and Vinodh (2021) Yadav et al. (2020)
	T	\emptyset	
	O	Resources and energy required for technologies production	Bonilla et al. (2018)
		Energy required for technology use Electrical and electronic waste	Birkel et al. (2019)
Enablers		\emptyset	

4.3.2 Focus on the Circular Economy for the environmental pillar

The energy savings for a remanufactured product are in the order of 75-80% compared to a new product, mainly due to energy savings at the raw material extraction and component manufacturing stages. In terms of material consumption, a remanufactured product would contain between 85 and 88% of used components, with the remainder made up of new materials (Lund, 1984).

Kerr and Ryan (2001) assessed the environmental benefits of remanufacturing – one of the most intensive recovery processes – throughout the product and system life cycle (i.e. including, for example, additional packaging and transport) of two photocopiers. They showed that remanufacturing results in savings of raw material consumption, energy consumption, greenhouse gas emissions, water consumption and waste sent to landfill. Modular photocopiers (designed for remanufacturing) provide greater environmental benefits than non-modular photocopiers in their case studies. In addition, Amaya et al. (2010) showed that the different recovery processes used during the life cycle influence the environmental impact. Applied to a case study of truck injectors for multiple life cycles and different percentages of recovered products, remanufacturing provides environmental benefits for each scenario compared to single use or recycling of injectors. A methodology has been developed to help designers and remanufacturers assess optimal scenarios for environmental concerns.

Nevertheless, the CE is often seen as environmentally friendly by default compared to the linear economy, and the environmental aspect is not necessarily evaluated, which can lead to poor decisions. According to the value retention strategy (VRP), the most environmental benefits are not necessarily to be attributed to the most circular conservation process (Haupt and Hellweg, 2019).

Furthermore, remanufactured machines often consume energy (motor, equipment, ...). It is therefore necessary to ensure that the energy gain is not negated during the operation phase if the new technologies allow a drastic reduction in energy consumption compared to the remanufactured machine (Lund, 1984). Circular activities can also lead to rebound effects (i.e. improved efficiency leads to lower prices, thus allowing more consumption of goods), thus reducing its environmental benefits (Zink and Geyer, 2017).

A synthesis of the main findings of this section is proposed in Table 5.

Table 5 – Opportunities, barriers and enablers for environmental aspects for the Circular Economy on strategic (S), Tactical (T) or Operational (O) levels (\emptyset is used when no information belongs to this category)

		Environmental pillar for Circular Economy	Sources
Opportunities	S	\emptyset	
	T	\emptyset	
	O	Reduction of raw materials consumption, energy consumption, greenhouse gas emissions, water consumption and waste going to landfill	Lund (1984), Kerr and Ryan (2001)
Barriers	S	Rebound effect	Haupt and Hellweg (2019)
	T	Difficulties to assess optimal recovery scenario	Zink and Geyer (2017)
	O	\emptyset	
	Enablers		\emptyset

4.3.3 Focus on cross-implementation of the Circular Economy and Digital Technologies for the environmental pillar

No specific article was found addressing the environmental issues of the cross-implementation of the two concepts in manufacturing, apart from a brief reference to the existence of potential rebound effects and another reference to the optimisation of energy consumption in the case of remanufacturing (Yang et al., 2018).

This highlights a serious research gap.

4.4 Opportunities, barriers and enablers for the social pillar

As mentioned earlier, the social aspect has been little studied in research. Thus, a multidisciplinary team comprising researchers in engineering and social sciences (particularly ergonomics and occupational psychology) has been assembled to enrich this section with recent elements from ongoing research on the subject and respond to the second research objectives of this paper as detailed in Section 3.

4.4.1 Focus on Digital Technologies for the social pillar

This section first considers the positive effects of DTs, generally assumed in the engineering literature, and then proposes a more contrasting view, generally proposed in the humanities and social sciences literature.

4.4.1.1 Assumed social benefits of emerging Digital Technologies for the social pillar

In a literature review, Caiado et al. (2022) noted that many authors perceive the use of DTs as socially beneficial. Among the supposed opportunities, the reduction of physical disorders, but also psychological (stress, mental workload, ...) are often mentioned (Cochran and Rauch, 2020; Romero et al., 2016). Tasks with the highest health risks for operators can be delegated to machines, thus reducing the number of accidents (Braccini and Margherita, 2018; Romero et al., 2016); and technologies could be used for risky tasks or by setting up hazard alerts based on the measurement of operator health and movements in the plant (Leso et al., 2018). The workstation can also be more personalised, human adapted and inclusive (age, gender, cultural background) (Leso et al., 2018; Romero et al., 2016).

DTs can therefore be a source of motivation by providing more creative and value-added activities with more autonomy and self-development while decreasing routine tasks (Leso et al., 2018). Better qualification of employees through an increase in the share of training could also be put forward (Braccini and Margherita, 2018). The use of automated systems that support the development of creativity, learning, invention, and improvisation skills at work while ensuring production targets and operational excellence allows operators to excel in their profession (Romero et al., 2016). Some DTs, such as virtual reality could be used to support the training of workers (Leso et al., 2018). Furthermore, a reduction of managerial pressure by virtualizing exchanges and making them more transparent are opportunities assumed by Leso et al. (2018). At a more global level, new DTs facilitate the possibility of respecting the balance between private life and work with more flexibility (Cochran and Rauch, 2020; Leso et al., 2018).

4.4.1.2 Assumed social barriers of emerging Digital Technologies

There are also many barriers to the adoption of these technologies regarding the social pillar, and one of the most frequently cited is the lack of digital skills among workers (Raj et al., 2020). Indeed, six out of ten adults lack basic ICT skills or have no prior experience with computers. Subsequently, the development of automation may result in the loss of 14% of current jobs during the next 15 to 20 years, while another 32% of jobs face the possibility of significant transformations (OECD, 2019). Moreover, soft skills also appear to be much more highly valued (Kergroach, 2017). Alhloul and Kiss (2022) identified twenty competencies divided into four categories that are necessary for the operator using DTs, including personal, social and interpersonal, technical and methodological skills. This confirms, according to the authors, that people are central to the success of DTs implementation. However, this need for new skills also entails the need for organisational and process change (Kamble et al., 2018).

Furthermore, many drawbacks for workers have been highlighted, particularly by researchers in the human sciences. Indeed, the complexity of tasks increases with emerging technologies, and the operators' knowledge becomes quickly obsolete. This digitisation and the information flow that results from it, therefore increases the mental load for the workers (Caroly et al., 2019). Thus, emerging technologies could create a greater work density and the impression of losing control, which thus entails an increase in physical danger (mental fatigue, psychological pressure and stress) (Leso et al., 2018). Even if digitisation could be seen as reducing arduous tasks (physical work, repetitive movements) or substituting simple tasks, it often entails more difficult mental operations that need more creativity (and that are seen as more engaging and motivating) (Caroly et al.,

2019). In addition, new technologies cannot reduce all risks, and new risks may emerge due to a lack of knowledge about the technologies involved (Leso et al., 2018).

The difficulty for operators to gain confidence in using these technologies is also a barrier to their implementation (James et al., 2022). Psychological barriers, such as the fear of data loss, may play an important role in the transition to DTs (Mahmood et al., 2021). Mental overload and associated stress may also increase when the employee is responsible for the operation of multiple machines, and gains in responsibility, which may lead to isolation and loss of social interaction due to the predominantly computerised tasks (Birkel et al., 2019).

Moreover, some technologies may pose more social risks than others. For example Birkel et al. (2019) present the risks associated with artificial intelligence in decision-making, which can give the impression of making wrong decisions and may not be accepted by humans. In the case of this technology, it is important to consider this aspect into account when implementing such technologies. A list of elements to be taken into account in the implementation of certain types of technologies is proposed for some technologies by Caroly et al. (2019).

All these barriers could explain resistance to change in digitalisation processes (Raj et al., 2020). Indeed, the introduction of new technologies is fundamentally changing the way industries operate and the labour market in the coming years, as technologies replace or accompany human operators. Companies need to pay particular attention to the social impact of implementation. If workers are not rewarded for their efforts in the transition to new technologies and the benefits to them are unclear, Müller (2019) argued that this lack of management support and a lack of a clear vision of the future could make it more difficult to adopt DTs. Increased resistance can be observed among operators and middle managers who are older and less comfortable with technology. As their experience is essential for the transformation of the company, the technological transition must provide them with training adapted to their specificities and ensure that they acquire an open-minded vision of these technologies. (Birkel et al., 2019).

This reluctance has also been studied through the Technology Acceptance Model, which highlights that DTs are more likely to be accepted if they are perceived as useful and easy to use. To determine usefulness, individuals look at the effort they have to put in, the social impact of knowing the tool, the applicability to their tasks, the quality that results from using the DTs, the way in which results are observable and communicable, and the opinions of colleagues about the importance of the tool (i.e. subjective norms). In order to determine the ease of use, individuals project themselves in the realisation of the task with the tool, they compare the effort required for the task in question and think about the technical resources they need, and they assess their degree of apprehension, cognitive spontaneity and perceived enjoyment with the DTs. (Venkatesh and Bala, 2008).

These technologies thus question the place and role of these tools within the activity and its conditions of realisation. Indeed, these technologies could provide new capacities for action and revalue the work of an individual (which could be described as enabling, empowering or even supplementing technologies), distort the activity by removing the meaning it had for the operator (which could be described as substitutive technologies) or require an urgent reconfiguration that destabilises the working conditions of individuals (Bobillier Chaumon, 2021, 2017). A prior risk assessment should therefore be carried out to identify health and safety issues. However, facilities should then be designed to minimise these identified risks according to the characteristics of the workers (skills, ...) and appropriate training should be provided to the workers. Cardoso et al. (2021) showed that the literature has demonstrated the importance of an ergonomic and human factors study during the design and implementation of operator-robot collaboration systems to reduce physical and cognitive stress. Ergonomic studies also need to study cognitive ergonomics in particular, and not just physical ergonomics (gestures, postures...) when assessing digitisation.

4.4.1.3 *Assumed barriers on a societal scope*

DTs also raise some societal concerns, such as the creation of inequalities (between young and old workers) or the disruption of jobs (Raj et al., 2020). With regard to inequalities that are likely to increase due to the already existing technological divide in the population, depending on age, socio-economic situation and gender (i.e. women are less represented in technological environments) (Kergroach, 2017; OECD, 2019). A study by Krzywdzinski (2017) has shown that the impact on jobs also depends on the country and the strategies of employee representatives and workers during the introduction of automation. Moreover, the creation of new jobs is likely to be polarised between the most qualified (especially in developed countries) and the least qualified workers (especially in developing countries).

To conclude, Margherita and Braccini (2021) indicated that the opportunities offered by DTs are often prioritised over the impact on operators of these technologies and that there is a lack of research on these

dimensions. However, they showed through a case study that a balance can be struck between the benefits of automation and the well-being of the workforce by adopting a worker-centred approach and achieving greater sustainability in manufacturing. Another study by Kadir and Broberg (2020) suggested through case studies that the well-being and performance of operators are negatively affected during the implementation of DTs, but that the impact becomes positive once the implementation has gone well. The article insists in particular on the place and commitment of the management in the transition, and in particular the role of communication to have to overcome the frustrations or fears associated with DTs (job loss, speed increase, security, ...) and support operators in the transition phase, when not all technologies are necessarily stable and reliable. Finally, Bonekamp and Sure (2015) insisted on the need to pay particular attention to continuous learning and training in order to have more skilled operators able to perform more complex tasks.

A synthesis of the main findings of this section is proposed in Table 6.

Table 6 - Opportunities, barriers and enablers for social aspects for Digital Technologies for on strategic (S), Tactical (T) or Operational (O) levels

	Social pillar for Digital Technologies	Sources
Opportunities	S Employment creation	Braccini and Margherita (2018)
	T Greater attractiveness of jobs Reduce monotonous tasks and more creative tasks	Braccini and Margherita (2018)
		Leso et al. (2018)
	O Reduce physical and psychological disorders (stress, mental workload, ...) Reduce accidents numbers Flexible working conditions Development of creativity, learning, invention, and improvisational skills More inclusive jobs Reduce hierarchical pressure	Cochran and Rauch (2020)
		Braccini and Margherita (2018)
		Romero et al. (2016)
		Leso et al. (2018)
Barriers	S Lack of digital skills among workers Increase of inequalities	Raj et al. (2020) Kergroach, 2017 Leso et al. (2018)
	T Resistance to change Ethical risks	Raj et al. (2020)
		Trentesaux and Caillaud (2020)
	O Increase in tasks complexity and mental loads Quick obsolescence and mismatch of skills Banalization of control and real-time monitoring Increase in stress Isolation and loss of social interaction Control loss and reduced confidence Threaten work-life balance New types of accidents Low usefulness or ease of use perceived by operators	Caroly et al. (2019)
		Birkel et al. (2019)
		Bobillier Chaumon (2021, 2017)
		James et al. (2022)
		Leso et al. (2018)
		Venkatesh and Bala (2008)
Enablers	Continuous learning and education	Bonekamp and Sure (2015)
	Management support and a clear vision of the future	Müller (2019)

4.4.2 Focus on the Circular Economy for the social pillar

Disposed products involve very long process times and therefore a lot of workforce as a result of the non-discrete nature of the processes and the impossibility to standardize operation (Marzano et al., 2018), leading to a strong need for manual work. Ijomah (2009) assumed that the second-hand market has societal benefits, thanks to the creation of jobs and local communities, the training of low-skilled workers and the creation of a market to make products accessible to the most disadvantaged. Lund (1984) found that 60% of workers in remanufacturing are low-skilled, and suggested that the most important skills for these workers are quality consciousness.

Remanufacturing offers less monotonous work. Workers need more training and skills to adapt to the variety of situations and thus gain long-term benefits and greater job satisfaction. This training could be provided by experienced workers to pass on their experience of dismantling and reassembling products. However, mass production leads to a decrease in the skills of the workforce and a shortage of qualified workers (Giutini and Gaudette, 2003; Ilgin and Gupta, 2012).

To adapt to the difficulties in the disassembly and reassembly phases (availability of parts, lack of technical information, delays related to the purchase of new parts or certain processes, the operators acquire unique skills to recreate unique product (Guelle et al., 2023). Moreover, the remanufacturing steps require precise sensory, material and cognitive skills from the operators to perform several steps of the related processes. The

use of visual, auditory or tactile senses is valuable in the diagnostic phase of the components to know the remanufacturing strategy applied to the latter (maintenance or diversion of its use). Collective activities seem to be required at several stages of the remanufacturing process, such as part diagnosis and reassembly (Guelle et al., 2022).

As the flow of materials and information is irregular, the activity of the operators is also irregular, and the activities may involve risks to the health of the operators (strained posture, etc.). As the products are very variable, the tools required for the activity are not adapted to the task. The skills required in remanufacturing (particularly in the disassembly/reassembly, inspection and testing phases) are therefore varied and extensive. It is necessary to familiarise employees with the technical criteria of highly variable products in order to guarantee them the autonomy required for such tasks, which require constant compromise. The highly variable nature of remanufacturing requires a high degree of agility and flexibility. Ergonomics and work psychology are therefore crucial factors to guarantee the development of skills, a good organisation of individual and collective work, and the maintenance of operators' health (Caroly et al., 2019).

Nevertheless, very little work has been done on this subject. A synthesis of the main findings of this section is proposed in Table 7.

Table 7 - Opportunities, barriers and enablers for social aspects for the Circular Economy on strategic (S), Tactical (T) or Operational (O) levels (\emptyset is used when no information belongs to this category)

		Social pillar for the Circular Economy	Sources
Opportunities	S	creation of jobs and local community training of low-skilled workers	Ijomah (2009)
	T	\emptyset	
	O	less monotonous tasks	Giutini and Gaudette (2003) Ilgin and Gupta, 2012)
Barriers	S	\emptyset	
	T	\emptyset	
	O	Irregular activity Health risks (posture, ...) Long training required	Caroly et al. (2019) Guelle et al. (2023) Giutini and Gaudette (2003) Ilgin and Gupta (2012)
Enablers		\emptyset	

4.4.3 Focus on cross-implementation of the Circular Economy and Digital Technologies for the social pillar

As with environmental issues, few studies have analysed the social implications of the subject under study (apart from managerial issues), with the exception of two barriers that have been suggested in the literature. Kayikci et al. (2021) suggest that there is a lack of skilled resources with the expertise associated with the transition to a CE. Moreover, the ability of machines to reproduce the sensory capabilities of the human operator in the diagnostic phase seems more complex. By analysing the tasks performed by the operators in remanufacturing, several DTs could be envisaged to support operators in their activities, through the delivery of relevant information for product diagnosis and monitoring along the production line (Guelle et al., 2022).

In conclusion, the opportunities, barriers and enablers of the three pillars of sustainable development for DTs and CE have been presented and summarised in Tables 2 to 8, responding to the second research objective. An analysis of the use of DTs for CE in production has also been proposed, responding to the first research objective. The special focus on the social aspect proposed in part 4.4 also responds to the second research objective.

4.5 Ethics

Concerning ethics, there are no definitions that are shared by the different scientific communities and are stable over time (Trentesaux et al., 2021). A frequently used definition for ethics comes from the philosopher Ricoeur (1990) who describes it as "aiming for real life with and for the other in just institutions".

Furthermore, emerging technologies and connected devices monitoring continuous data also raise issues of confidentiality, the banalization of control and real-time monitoring (Caroly et al., 2019; Leso et al., 2018). The incorporation of ethics is a pre-requisite to ensure the benefits of DTs. For Berrah et al. (2021), ethics should be included in the definition of performance. According to the authors, the current definition of performance includes the efficient use of tools, the efficient achievement of goals and creation of relevant goals. However, the

accumulation of data through DTs and the implementation of increasingly autonomous systems with uncertainties threatens the sustainability of activities if the ethical dimension is not taken into account. Ethical issues, such as the assignment of objectives, the method of measurement or results retention, or the use of data, must be addressed throughout a project to introduce emerging technologies to ensure the durability of a project. With the increasing complexity of autonomous and intelligent systems, it could, however, be difficult to fully assess the effectiveness of those technologies, and thus the emergence of ethical risks with the implementation of those technologies (Trentesaux and Caillaud, 2020).

These ethical issues are all the more important to anticipate, as regulations are currently being created. For example, the EU AI Act, which aims to guarantee security, transparency, non-discrimination, respect for the environment and other harmful outcomes of artificial intelligence (European Union, 2023).

5 Discussion

The following section is devoted to an examination of the criticisms of current research in relation to the themes explored in this paper. This is followed by a synthesis of research suggestions from the literature review, which is discussed and finalised. Finally, a tool is proposed to assist researchers in establishing a roadmap for their research into the implementation of DTs within CMS.

5.1 Questioning the current state of research: gaps and critics

5.1.1 Critics

Despite its growing research interest, the CE is struggling to be translated into concrete actions by practitioners. The Circular Gap Report (Fraser et al., 2023) reported a progressive decrease in circularity on a global scale: from 9.1% in 2018 to 8.6% in 2020; this indicator falls now to 7.2% in 2022. Based on several circularity indicator works (Haas et al., 2020, 2015; Mayer et al., 2019), a series of circularity and socio-economic indicators are calculated using statistics on resource extraction and use, waste flows, recycling and downcycling. The various indicators are tabulated at a global level and specialised by country to give a clearer picture of the situation (Circle Economy, 2023).

Several criticisms also taint the way research is conducted. Kirchherr and van Santen (2019) underlined that this domain lacks empirical proof (55% of empirical work and 45% of conceptual work) and large-scale real-world studies to help parties implement the CE. Moreover, the social pillar has been neglected and the literature provides little evidence for the environmental benefits of a CE (Corvellec et al., 2022; Trevisan et al., 2021). As mentioned earlier, the CMS system relies heavily on manual processes, with the operator playing a central role in workshop operation. Therefore, it is crucial to examine the social aspects that are closely tied to CMS performance. There is thus a need for practitioners to have concrete studies and solutions to operationalize the CE in their activity. Millar et al. (2019) pointed out that few studies clearly explain how the CE can be implemented and explicitly how CE can provide economic growth without harming the environment and promoting social benefits. They concluded that the CE may ultimately have the same negative effects as linear economy on the environment, due to the energy consumption required for recovery, waste generated, impossibility to have a real closed loop due to thermodynamic laws, the challenge of fully replacing linear activities with circular ones, the unknown effect on social equity and environment of product life extension and the risks of rebound effects. Nevertheless, they assumed that the negative effects appears more gradually with CE. Korhonen et al. (2018) underlined the complexity of research on CE, which takes into account several players and research fields, and which do not share the same definition of CE, as shown by the variety of definitions found by Kirchherr et al. (2017).

There are few articles on the controversial impact of DTs in the engineering literature. Among these, Bakshi and Paulson (2022) indicated that expectations for DTs use in terms of sustainability are very high. However, implementing these technologies in a 'business as usual' strategy and to maximize corporate profit as is often done today is unlikely to lead to sustainability and risks displacing negative environmental and social effects beyond engineering studies. Thus, decisions should be made using methods -such as Environmental and Social life cycle assessments- to design and assess sustainability impact and to have data from technology providers to assess the impact of their products. There is also an urgent need for researchers working on DTs to collaborate with environmental and social science, as well as sustainability experts. This lack of collaboration between fields of research and the different opinions of communities often leads to widely divergent views in the literature. This is particularly true for environmental impact (reduced impact during operations thanks to DTs versus increased impact from the manufacture and use of DTs, for example). The same applies to social impact

(reduction of physical arduousness and the creation of more interesting missions versus increase in cognitive load and misalignment with the workforce skills).

5.1.2 Research gaps

Concerning the studies that connect the CE and DTs, Jabbour et al. (2022) emphasized that they are mainly conceptual or exploratory, without empirical data. Enyoghasi and Badurdeen (2021) noted that many of the benefits of DTs in terms of sustainable practices (e.g. reduce, recover, reuse, redesign, remanufacture, recycle) have not been studied. Hennemann Hilario da Silva and Sehnem (2022), Prieto-Sandoval et al. (2019), Cui et al. (2021) and Liu et al. (2023) recommended concretely checking whether DTs can really support the CE in manufacturing industries with rigorous empirical research. Bressanelli et al. (2022) recommended that research should develop methodologies and use quantitative methods to confirm hypotheses made between DTs and CE, especially their impact in terms of resource depletion, energy use, and waste production. Future research should also combine several DTs to examine the interactions between these technologies in the context of CMS. Vimal et al. (2023) indicated that barriers of DTs and the CE have been separately studied, thus comes the need to study the combination of the two concepts. Chauhan et al. (2022) proposed about thirty research questions linking DTs and the CE.

Research gaps have also been identified in the three pillars of sustainable development. Trevisan et al. (2021) concluded that the social aspect is often neglected in favour of the economic and environmental aspects. Lieder and Rashid (2016) highlighted that research does not focus a lot on the economic benefits or competitive advantage of industrial actors, thus circular transitions are mostly seen as a constraint for industrial rather than an opportunity. Bressanelli et al. (2022) indicated that they are still no proof that the use of DTs for CE outcomes balances their inherent environmental costs, thus the need to better understand the environmental impact of technologies.

In conclusion, there is a serious lack of empirical evidence to encourage manufacturers to move towards more circular production. In order to determine what empirical evidence is needed, it seemed necessary to make a list as exhaustive as possible of the opportunities and barriers of DTs in a CMS context in order to find out what needs to be proven. This section proposes a tool for cross-referencing the opportunities and barriers associated with the use of DTs in CMS, highlighting the gaps and criticisms in the research on this topic, and finally providing a roadmap for researchers who wish to work on providing empirical evidence that answers the third research objective of this paper.

Several studies could be carried out to provide empirical evidence and fill the gap, such as numerical simulations and laboratory simulations based on real case studies in companies, or monitoring the implementation of DTs in real CMSs.

5.2 The proposition of a roadmap to study the possible divergences and symbioses of the Digital Technologies implementation in a Circular Manufacturing System

As seen in Section 4, the list of challenges and opportunities brought by DTs to create CMS is incomplete in the proposed literature review, especially on environmental and social aspects. Moreover, as seen in Section 5.1, there is also a lack of empirical evidence on those topics. The methodology proposed in Section 3 is therefore extended by two additional steps to address this research gap.

To make it easier to identify gaps in the research, the fourth step of the methodology is to provide a matrix summarizing the main findings to offer a visual tool to help in the detection of possible synergies on this subject. In a fifth step, a roadmap is proposed to help researchers to provide empirical evidence for the potential synergies in the use of DTs in CMS. The methodology is represented in Figure 6.

5.2.1 Step 4: a matrix to identify synergies and divergence in research about Digital Technologies and Circular Manufacturing Systems

After collecting barriers for DTs and the CE from cross-disciplinary knowledge in Step 3, the latter is synthesized keeping a pillar approach (technical and economic/environmental and social) as carried out upstream. These elements are then presented in matrix form, with DT-specific elements in the row, and these for the CE in columns. The opportunities are indicated at the beginning, classified by a pillar (red for the economic, blue for the social and green for the environmental), and the barriers are identically classified in the second part of the list. The full version of the matrix can be found in Figure A1 in Appendix. An extract of this correlation matrix of DTs possibilities for CMS is simplified and proposed in Figure 5, and the method used to create it is synthesized in Figure 6.

Then, the correlation matrix is completed with articles that deal with the use of DTs for CMS. Symbols representing the type of evidence proposed in the publication are used to complete the matrix. Empirical evidences are represented by the symbol "✓". Conceptual evidence and evidence obtained by collecting opinions from practitioners are represented by the symbol "?". This literature review has only highlighted conceptual elements, thus only the symbol "?" is used, and the symbol "✓" could be used to update the correlation matrix in the future.

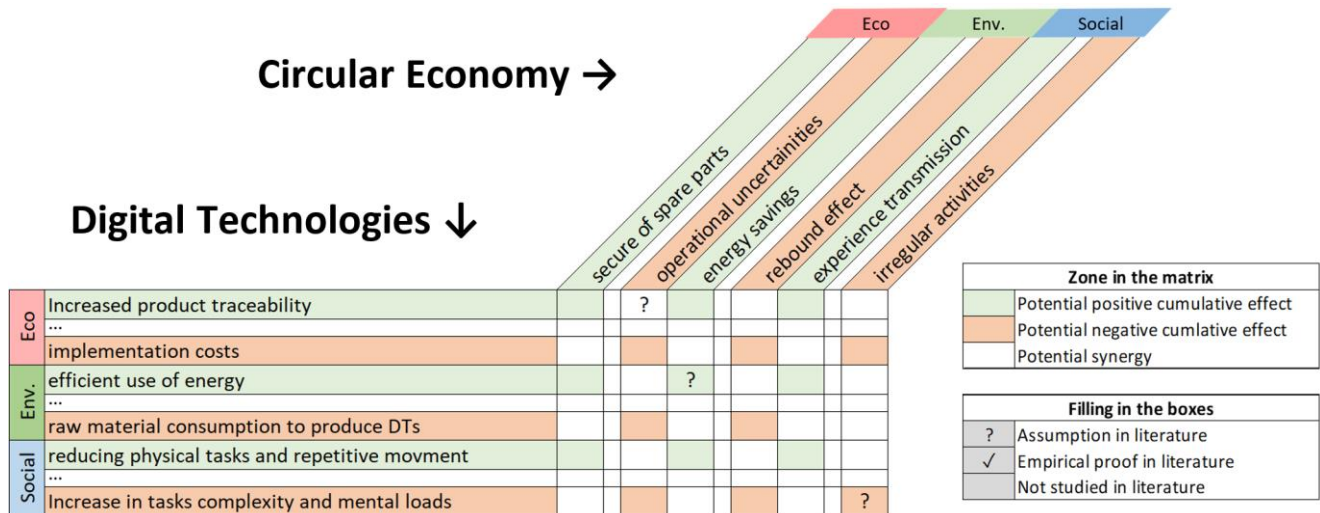


Figure 5 - Overview of the correlation matrix of Digital Technologies possibilities for Circular Manufacturing Systems

In the matrix, several zones are also delineated to highlight the effect induced when combining the two elements: areas with a green background represent zones where two opportunities reinforce each other positively, areas with an orange background represent zones where two barriers mutually aggravate a negative effect and zones with a white background represent an opportunity of one of the concepts acting as a lever to overcome the barrier of the second concept, in which case the terms synergies will be used. This synergistic effect can take place on two elements linked to the same pillar of sustainable development, but this is not necessarily the case.

The result allows the questioning of the possibilities to overcome the barriers of the CE by DTs, or vice versa. The matrix shows that 12 synergies, 2 cumulative positive effects and 6 cumulative negative effects have been assumed in the literature reviewed for this article. Thus, less than 2% of the relationships between the two concepts identified in the matrix have so far been assumed in the literature reviewed for this article. There are therefore many avenues of research to be explored on the topic of the implementation of emerging digital technologies for circular production systems. This matrix thus aims to be completed as the scientific community progresses on this subject. The following part provide a roadmap proposition to fill the gaps identified in the matrix.

5.2.2 Step 5: a proposition of a roadmap

A strategic plan to help research in synergies identification and empirical proof quest is presented in this part.

The proposed roadmap contains four key milestones, as represented in Figure 6:

1. Initialisation of the research project: After setting up a research team - preferably multidisciplinary - a general research objective should be identified to respond to one of the gaps identified in this article. To identify a research question, a matrix summarising the findings of this article is proposed in section 5.2.1. This tool allows the visual identification of current research gaps, with segmentation by pillars of sustainable development to help researchers select objectives according to the skills available in their research team.
2. Conceptual design of the research: Based on the general topic identified in the first step, a complementary literature review can be carried out to update the existing literature and to clarify the research objectives. One or more methods must then be chosen to provide conceptual evidence, such as numerical simulations, simulations on technological platforms or industrial case studies. Concepts surrounding the choice made must then be defined.
3. Technical design of experiments: At this level, technologies must be selected in an attempt to empirically analyse the opportunities and barriers associated with them. At this stage, an experimental plan and an

analysis grid are drawn up to define the objectives of the experiments, the experimental conditions and the indicators, taking into account several pillars of sustainable development. In an empirical experiment to study the impact of emerging technologies or CE, it is important to adopt a systemic and sustainable vision to analyse the interaction between several DTs. This systemic vision is particularly important to assess the environmental impact of the solution, with methodologies such as life cycle analysis, in order to really position the contribution of digital tools.

- Synthesis and conclusion: analysis of the results and summary of the case where synergies seem to work.

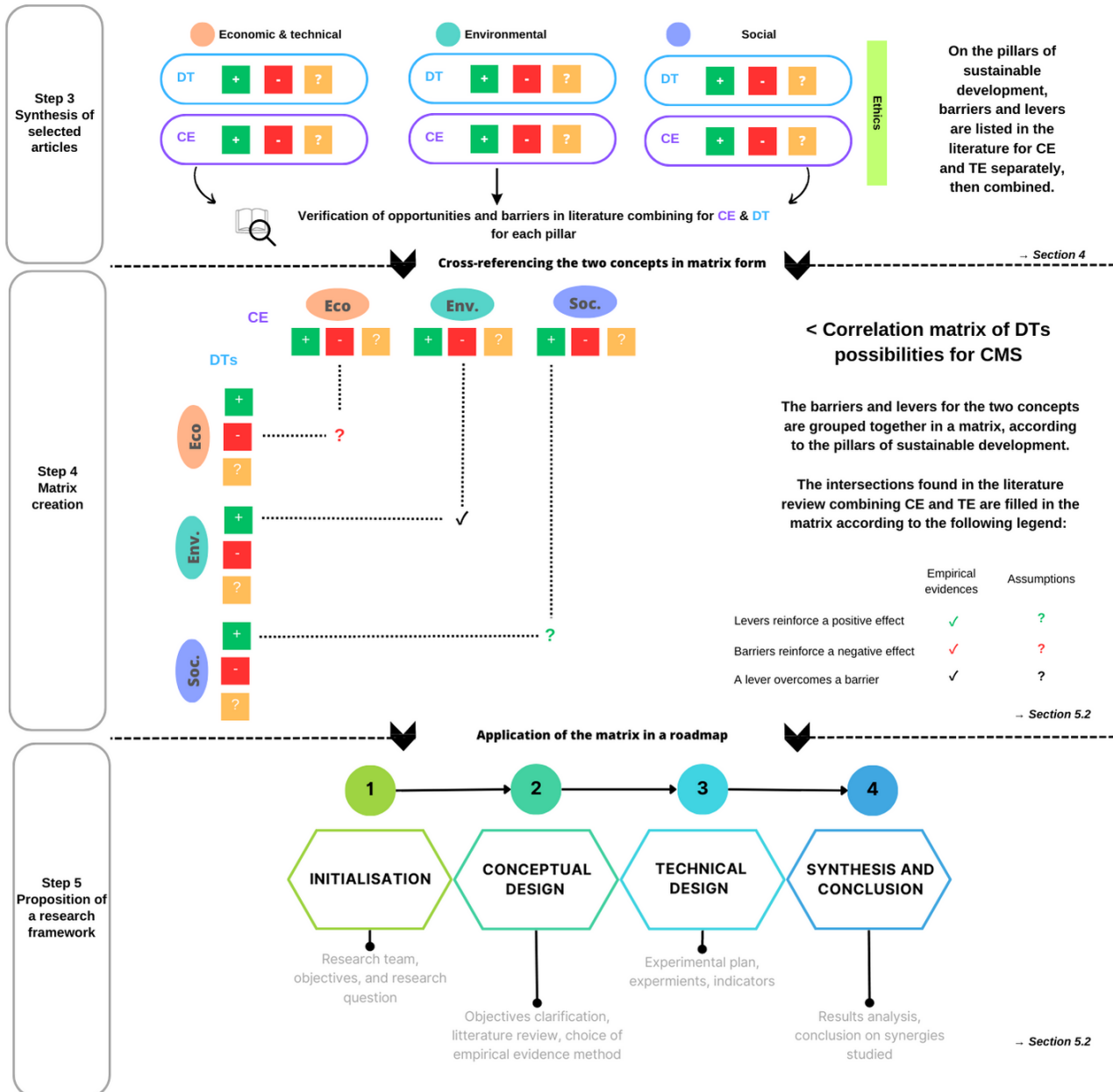


Figure 6 – Methodology for the roadmap and correlation matrix creation
(CE: Circular Economy; DTs: Digital Technologies, CMS: Circular Manufacturing Systems)

Similarities can also be highlighted between this roadmap and the methodology for the interdisciplinary research framework of Tobi and Kampen (2018), which has been validated through two examples in their article. Furthermore, applying this roadmap is one of the next steps to validate it through several research projects.

5.2.3 Use of the matrix to apply the roadmap

The matrix (and the empty parts in it representing gaps in the research) proposed in Figure A1 in Appendix can serve as a basis for future research. Indeed, many assumptions of synergies can be suggested, and have not necessarily been pointed out by the scientific community, especially on social and environmental parts. Supplementary hypotheses can thus be formulated from the matrix, and serve as a basis for the realisation of an

experimental design to validate them empirically with various techniques (by simulation or case studies) and cover the obvious lack of evidence.

From the previous matrix, it is for example possible to establish a list to explore the links between opportunities and barriers of the two concepts studied, such as:

- Can an opportunity offered by DTs answer a barrier related to the CE (or vice versa)? Several articles have already made assumptions on this point. As mentioned above and as an example, the aggregation of data from DTs sensors or artificial intelligence technologies could allow a better gauging of the condition of a product to choose an optimal recovery scenario. Nevertheless, very little evidence exists on these, hence the need to conduct experiments to determine this.
- Does the aggregation of several barriers related to the two concepts increase the overall difficulty of the project (or respectively, can the aggregation of several opportunities act as a lever to transition to circular models)? For example, a question could be if the physical and mental complexity of the tasks linked to remanufacturing coupled with the mental load linked to DTs worsens or not the well-being of the operators.

To give an example of how the framework could be used, consider a multidisciplinary research team with expertise in workshop management and equipped with Autonomous Mobile Robots (AMR). With the aim of exploring potential digital solutions for circularity available in their laboratory, this team could highlight some issues identified in the matrix in relation to their skills and equipment, such as operational uncertainties in CMS. Based on the results of this review article, additional elements detailing these difficulties could be selected from the literature in order to more precisely define the topic, the detailed objective of the project and the potential use of AMR to overcome the selected barrier. Based on these elements, an experimental protocol that includes digital technologies could be drawn up to carry out the necessary experiments. By following the steps in the framework, the research team could conclude on the ability of AMR to improve, for example, flexibility or traceability in the context studied.

The evidence to be brought must also take into account the elements that have been highlighted above on the three pillars of sustainable development. In addition, to determine whether emerging DTs could have potentially positive effects, these experiments could identify risks that must be anticipated when adopting these technologies to ensure social and environmental sustainability in particular.

5.3 Limitations of the study

Several limitations of the literature review should be highlighted to highlight the possible limitations of the matrix. The first concerns the choice of databases (Scopus and WoS), which potentially excluded several relevant articles that were not indexed in the journals belonging to these databases or that could not be accessed. It is thus possible that the results are incomplete in some aspects. Articles that were not in English or not accessible were excluded, giving rise to the same limitation. Due to the recent nature and dynamism of the targeted research fields, the knowledge in the field is constantly evolving and some very recent articles could not be included due to the delays in their finalization or publication. As mentioned in Section 3, the multiplicity of databases, formats and languages used in the humanities and social sciences makes it difficult to identify all the documents relevant to the research topic. The results in this area are therefore probably also incomplete.

Moreover, due to divergent opinions in the scientific community, some opportunities and barriers may be contradictory in the review and thus in the matrix. For the sake of completeness and to represent as accurately as possible the state of current research on these subjects, all the levers and barriers found in the literature were retained. These divergent elements may also be influenced by the context of implementation, and prove to be either a barrier or an enabler depending on the conditions of application of the DTs or the CE.

Thus, supplementary investigations to address the challenges in using digital technologies for circular economy could be conducted to validate the matrix, such as literature reviews, industry surveys, or on-site field studies.

6 Conclusion

The aim of this paper was twofold. Firstly, to address the gap related to the lack of comprehensiveness in identifying opportunities and barriers associated with the convergence of DTs and CE; secondly, to introduce tools that can assist researchers in gathering empirical evidence regarding how DTs contribute to practitioners of CE by collecting the barriers and opportunities within the article. In line with this topic, an exhaustive list of the opportunities, barriers and enablers associated with DTs and CE, focusing on manufacturing aspects and with the objective of updating existing literature reviews has been the first of two main objectives RO1 and RO2. This list

has been drawn up based on the literature combining CE and DTs, but also on the literature on each concept separately to fill the above-mentioned gap. Through a critical analysis of the current literature, it has been highlighted that the majority of research on the relationship between CE and DTs tended to be conceptual or exploratory, and that there is a glaring lack of empirical research on concrete industrial cases. A roadmap and a tool to fill these gaps has thus been proposed in this article, in line with RO3. To facilitate the identification of research gaps and based on the collection of barriers and opportunities from the literature, the tool consists of a matrix that highlight the possible synergies and divergences between emerging DTs and CE in manufacturing. These divergences or synergies can thus serve as a basis for studying the impact of the simultaneous implementation of emerging technologies and CE in manufacturing systems. This matrix could thus be used to determine concrete links worthy of further research through case studies or manufacturing simulations.

An original feature of this article has been to include a multidisciplinary perspective by including articles from the humanities and social sciences in the compendium of reviewed articles. Firstly, it is essential to include social and environmental issues to be in line with the principles of sustainable development and deal with the current environmental situation. Secondly, the highly manual nature of operations in CE and the importance of the human aspect present in several decision-making processes in CE, leads to a strong link between human activity and production system performance. Thirdly, this article has also brought to light the differences of opinion between the various scientific communities and shows the relevance of adopting a systemic and sustainable perspective in the assessment of effects to decide on the manufacturing system. The implications of DTs sustainability should thus not be taken for granted either because these depend on the setting and circumstances under which businesses operate. Consequently, these elements should be included in an experiment so as to obtain more concrete data on the cross-implementation of circularity and emerging technologies.

To give industrialists more concrete proof and gain their support in the shift to these circular production systems, the next step of the project will be to disseminate empirical evidence, both technical and experimental, to ascertain the impact of DTs in circular production systems. Those evidences are intended to be acquired through the use of digital simulation and laboratory simulation alongside case studies in companies. Subsequent research on this subject will also lead to a number of recommendations for decision-makers on how to apply the right incentives and adapt regulations to accelerate and facilitate the transition of industry to circularity.

The application and validation of the proposed correlation matrix and roadmap, with a view to satisfying the previously proposed research perspectives, is the next stage in the Circular research project currently being carried out at the Université Grenoble Alpes.

Credit authorship contribution statement

Maxence Denu: writing, original draft ; Pierre David: writing, original draft ; Fabien Mangione: writing, original draft ; Aurélie Landry: writing, original draft

Declaration of competing interest

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

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Appendix

The full Correlation matrix of Digital Technologies possibilities for Circular Manufacturing Systems is proposed in Figure A1 in this appendix.

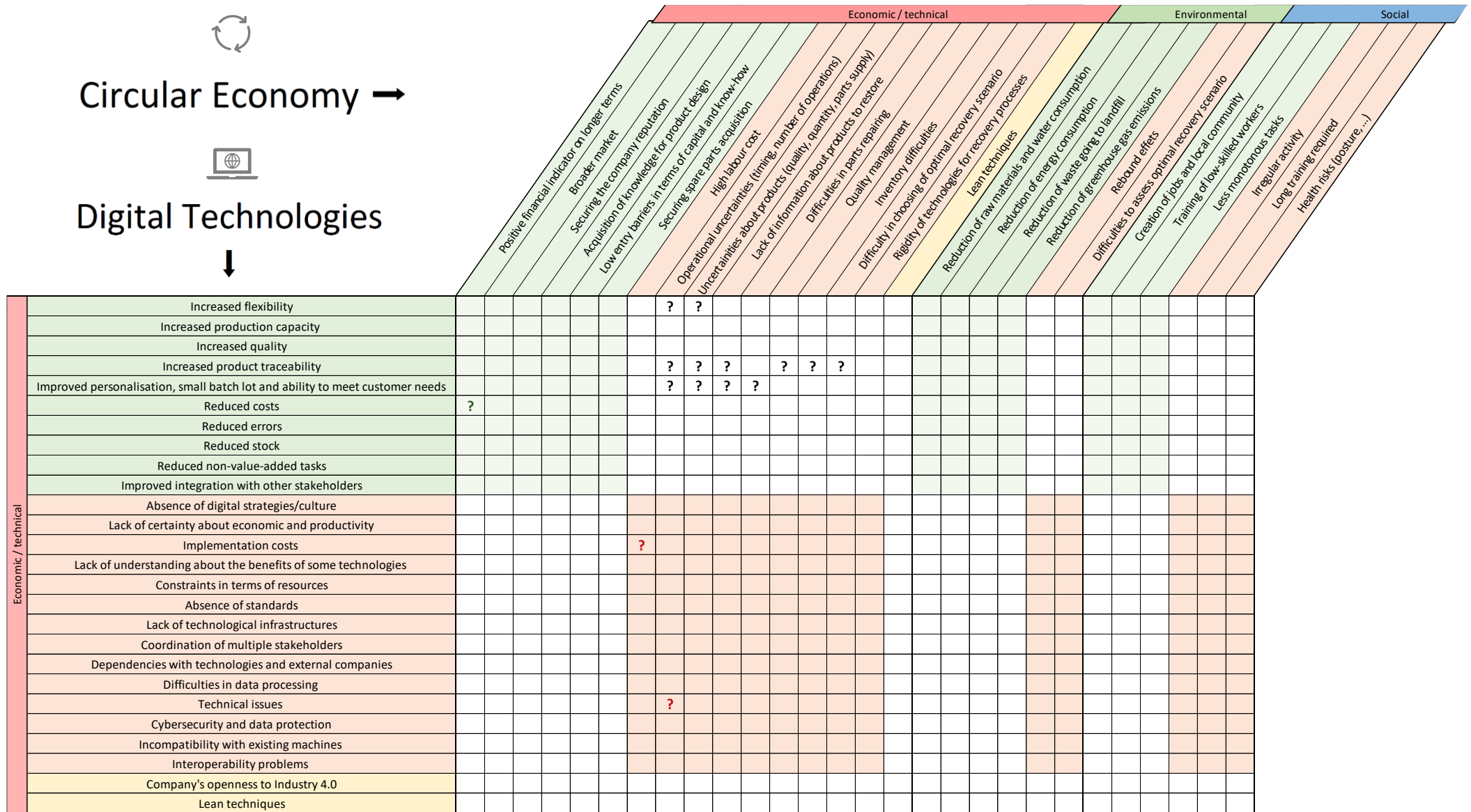


Figure A1 - Correlation matrix of Digital Technologies possibilities for Circular Manufacturing Systems

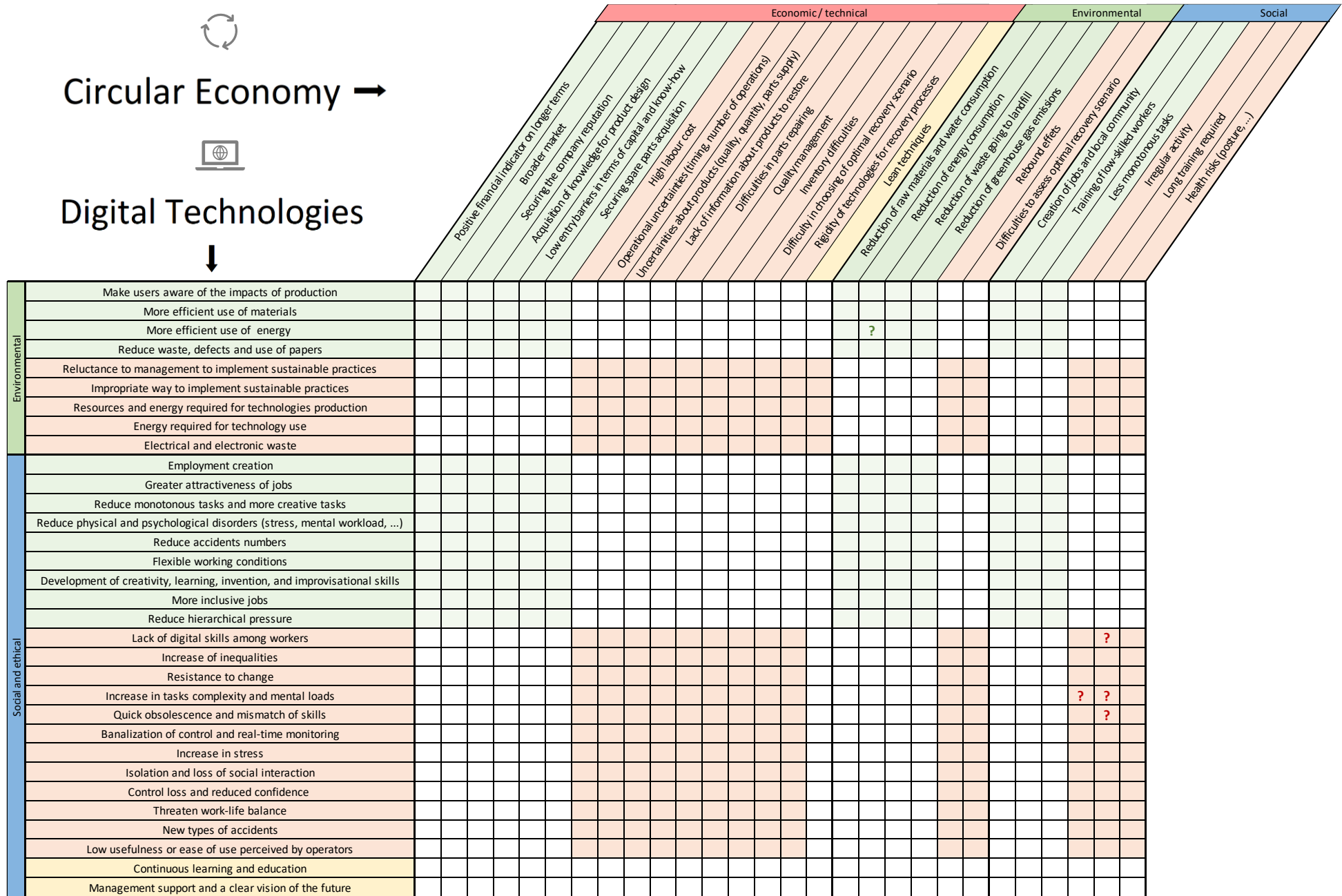


Figure A1 (continued) - Correlation matrix of Digital Technologies possibilities for Circular Manufacturing Systems

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