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Exploring the influence of industry 4.0 technologies on the circular economy

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ABSTRACT

In the last decade, both Industry 4.0 technologies and the circular economy have expanded exponentially and they have received epistemological attention. However, there is a lack of studies about the influence that each of these technologies has on the main areas of action covered by the circular economy. This study responds to this gap by investigating the influence of the major technologies: Additive Manufacturing, Artificial Intelligence, Artificial Vision, Big Data and Advanced Analytics, Cybersecurity, Internet of Things, Robotics, and Virtual and Augmented Reality on the main areas of action covered by the circular economy. Namely, reduction of inputs consumption, reuse, recovery, recycling and reduction of waste and emissions. An initial study, based on a survey of 120 project managers, and a multiple case study of 27 projects, through 31 personal interviews and review of internal and external documentation have been conducted in order to investigate the real influence of each technology on the circular economy.

Overall, the results confirm the existence of a wide range of influences that Industry 4.0 technologies offer to companies for improved circularity. These improvements are mainly related to reduce material and energy consumption, and waste and emissions generation. However, there are important differences between the potential impacts of each technology. In particular, there is most evidence of the positive impact of additive manufacturing and robotics. Likewise, the results obtained suggest the need to continue exploring the new impacts generated by the continuous development and integration of technologies.

1. Introduction

In recent years, many countries and international organizations have been adopting principles of the Circular Economy (CE) paradigm as one of the main components of their agendas for sustainable growth. The key objective is to transcend from the current linear economic model, based on “extract, produce, use and throw away”, to a model where the use of all available resources is maximized (Geissdoerfer et al., 2018). Japan was the first country to introduce CE legislation. In 1991, Japan implemented a law for the effective utilization of recyclable materials. Subsequently in 2002, China, aware of the serious health, social and environmental problems caused by intense industrialization, hasty urbanization, changing consumption patterns and population growth, developed a program for the implementation of CE as a potential strategy for sustainable development (Ogunmakinde, 2019). Later, in 2008, China enacted the CE Promotion Act (PRC, 2008). Germany, with their CE Act (Versteyl et al., 2012), and South Korea, with its Resource Circulation Framework Act in 2016 (Fitch-Roy et al., 2021), are two other examples of industrialized countries that have taken firm steps towards CE.

These strategies require structural changes that should take advantage of the new opportunities that technological progress and innovation

Abbreviations: CE, Circular Economy; CERs, Rs covered by the Circular Economy; RIC, Reduce Input Consumption; RWE, Reduce Waste and Emissions; I40, Industry 4.0; I40T, Industry 4.0 Technology; AM, Additive Manufacturing; BDAA, Big Data and Advanced Analytics; AI, Artificial Intelligence; AV, Artificial Vision; CS, Cybersecurity; IoT, Internet of Things; RB, Robotics; VAR, Virtual and Augmented Reality; M, Manager; T, Technician; DM, Detection Method; I, Interviews; D, Documentation; V, Visits; SSE, Significance Sources of Evidence; TS, Theoretical Saturation; TP, Transferability of the Phenomenon; ILE, Impact Level of Evidence.

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offer. Sustainable development depends profoundly on its relationship with technological development (Bashtannyk et al., 2020). In this context, the so-called 4th Industrial Revolution (I40) seems to have the potential to bring about change (Frank et al., 2019). This new concept is the result of the combination of distinct technological pillars (Kagermann et al., 2013). These are the basis for the development of new interconnection technologies. I40 was defined as a new paradigm for improving process/business performance using digitization and integration (vertical, horizontal, and end-to-end) of cyber technologies (Ghobakhloo, 2018). However, I40Ts are not only potentially beneficial because of their manufacturing advantages, but also because they can be used to drive the transition to a CE by maximizing the use of available resources and minimizing waste and emission (De Sousa Jabbour et al., 2018). Therefore, I40 must be developed to produce within environmental constraints to orient economies towards sustainability (Bonilla et al., 2018).

However, Rosa et al. (2020) and Frank et al. (2019) point out that there is no unanimity on how I40Ts affect circularity nor on the potential change, they offer to companies. Those authors, however, stress that I40Ts offer countless opportunities to help improve circular performance. On this point, Dubey et al. (2019) state that there is not enough academic work linking I40Ts to sustainability, and even less research analyzing the relationship between different I40Ts and CE (Bag and Pretorius, 2020; Dalenogare et al., 2018; Fettermann et al., 2018; Tjahjono et al., 2017).

Taking into account the existence of this gap in the literature, this paper aims to clarify the influence that each I40T has on the main fields of action of industrial companies that encompass the CE, using the same research methodology to study each of them. To this end, the rest of this paper is organized as follows: after this introduction, a literature review on the influence of I40Ts in the CE is presented. Section 3 describes the methodology. Section 4 shows the results obtained from the empirical study. Section 5 presents the discussion. Finally, before the list of references, Section 6 provides the conclusions, limitations, implications and future lines of research.

2. Literature review

First section presents the CE paradigm and its main areas of action covered by the CE. Next, the I40Ts are presented and, finally, the state of the art on the impact exerted by the I40Ts on the different areas of action of the CE is reviewed.

2.1. Circular economy

The CE is a paradigm shift in the way natural resources are used. At the core of the CE is the closed flow of materials, reducing and minimizing through multiple phases, inputs (raw materials, water and energy) and unwanted outputs (waste and emissions) from the system (Haupt et al., 2017). To this end, Moriguchi (2007) noted the need for an integrated approach that links upstream resource efficiency with downstream waste and emissions issues. Moriguchi (2007) points out that the value of products, materials and services must be maintained for as long as possible through the Rs covered by the EC (CER) principles. This implies moving to a circular economic model where "reduce, reuse and recycle" are key to maximizing circularity.

In the academic literature, we find different approaches based on strategies known as R-strategies. These approaches are similar to each other and are based on the Van Lansink Ladder. They differ mainly in the number of circularity Rs they present (Potting et al., 2017), starting from the approach of Haas et al. (2015) that includes only the 3Rs principles (reduce, reuse and recycle). Other authors add the maximization of value recovery as a consequence of closed flow and the minimization of waste and emissions (Goyal et al., 2018; Singh and Ordoñez, 2016; Lieder and Rashid, 2016; Haupt et al., 2017; Merli et al., 2018; Goyal et al., 2020; Rosa et al., 2020). Taking these studies into account, the model in Fig. 1 is proposed, which is a combination of the R-lists developed by Vermeulen et al. (2014) and Rli (2015). The proposed model allows for the formulation of circularity strategies while maintaining the primary function of a product.

The CERs included in this model are (Vermeulen et al., 2014; Rli, 2015):

- Reduce Input Consumption (RIC) such as materials, energy and water: Focus on smarter product use and manufacturing. This R includes rejecting redundant products, rethinking their design (looking for multifunctional products), their manufacture (simplifying and minimizing resource use) and their use (more intensive, e.g. by sharing products).
- Reuse: The objective of this R is to directly extend the useful life of a product. It focuses on the reuse of products or components in the same type of product discarded by another consumer, when they fulfill their original functions.
- Recovery: This R includes actions to extend the useful life of products and their parts. These actions are repair (repairing or maintaining defective products), reconditioning (restoring old products and bringing them up to date), remanufacturing (using components in the same type of products) and components reuse (using components or discarded products in other types of products).
- Recycling: Aims at the useful application of the material. The process should focus on obtaining a high degree of quality of materials to replace the use of natural resources.
- Reduce waste and emissions (RWE): This is a consequence of the other Rs. It should be focus on resource recovery. At the end of the process, CE requires a waste and emissions management strategy that should seek to reinforce the recirculation of resources, minimizing environmental consequences.

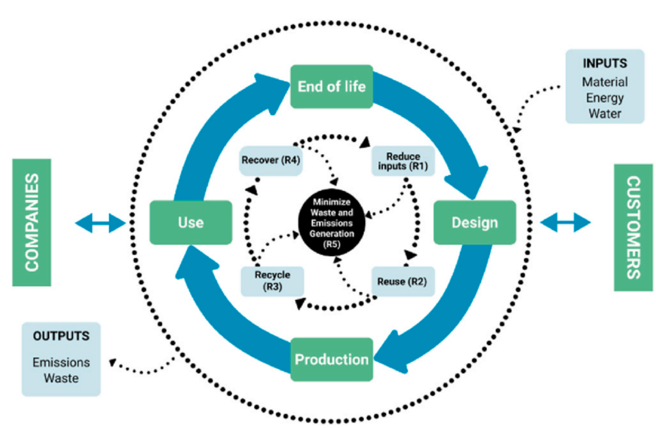

Fig. 1. CE model for industry.

2.2. Industry 4.0 technologies

I40 is mainly based on the integration of information and communication technologies and industrial technologies. Its main objective is to increase the efficiency of production and management systems for higher profits (Lichtblau et al., 2015). I40 seeks to create a cyber-physical system to develop a digital and smart factory, creating a highly flexible production model of personalized and digital products and services, with continuous interactions between people, products and devices during the production process (Kagermann et al., 2013). Indeed, with digital transformation, smart factories will make work (with increasingly complex processes) easier for the people staffing them, while ensuring that production can be simultaneously attractive, sustainable in an urban environment and profitable (Kagermann et al., 2013).

There are different classifications of I40Ts based on the development of each technology and its application (Oztemel and Gursev, 2020). In general, there is no clear consensus in the literature on how to group them (Tjahjono et al., 2017; Dalenogare et al., 2018; Fettermann et al., 2018; Ghobakhloo, 2018). However, most research hinges on the following eight groups of I40Ts (De Sousa Jabbour et al., 2018; SPRI, 2017):

- Additive manufacturing (AM): It refers to all manufacturing techniques by addition of material used to produce new, complex and durable components. It is a computer-controlled industrial process that involves 3D printing. AM creates three-dimensional objects by depositing materials, usually in layers (Oesterreich and Teuteberg, 2016).
- Artificial Intelligence (AI): It is a cognitive science for improving decisions with important research activities in many areas such as, image processing, natural language processing, robotics or machine learning (Lee et al., 2018).
- Artificial Vision (AV): It is based on capturing a digital image or video (usually through a camera) of industrial processes. Extracting a series of data and analyzing them and, once evaluated, making a decision accordingly (Alonso et al., 2019).
- Big Data and Advance Analysis (BDAA): The combination of the use of IoT and Cloud allows different equipment and production systems or management systems of companies and customers to be connected. Through BDAA, the data collected is constantly updated and analyzed and decision-making processes are improved. This helps to improve manufacturing flexibility, product quality, energy efficiency and equipment service (Rüßmann et al., 2015; Strange and Zucchella, 2017).
- Cybersecurity (CS): In a hyperconnected environment, it is necessary to ensure secure and reliable communications between systems that guarantee protection from possible theft or destruction of information or alterations in the manufacturing process and quality defects in products or a total shutdown due to cyber-attacks (Thames and Schaefer, 2017).
- Internet of Things (IoT): IoT aims to solve communication problems between all objects and systems in a factory (Frank et al., 2019). IoT combines intelligent and autonomous machines, advanced predictive analytics and machine-human collaboration to improve productivity, efficiency and reliability (Wong and Kim, 2017; Thramboulidis and Christoulakis, 2016).
- Robotics (RB). As manufacturing tasks become more individualized and more flexible, machines will need to perform variable tasks collaboratively without reprogramming. To this end, robots are becoming more autonomous, flexible, and cooperative, and will soon be able to interact with each other and work safely with humans, and even to learn from them (Kamble et al., 2018).
- Virtual and Augmented Reality (VAR): VAR allows simulating real situations to train workers, avoid dangerous situations, improve decision-making and/or work with procedures. In addition, VAR allows the creation of an enhanced version of reality in which live direct or indirect views of real-world physical environments are augmented with computer-generated overlay images (Oztemel and Gursev, 2020).

2.3. Influence of the industry 4.0 technologies on the circular economy

Niehoff and Beier (2018) highlight the ability of I40Ts to profoundly transform industry and they add that there is a need for this transformation to be monitored from a sustainability science perspective in order to provide solutions to environmental problems in industry. Gilchrist (2016) also argues that it is necessary to take this perspective into account as it allows companies to combine quality and general competitiveness with environmental solutions. However, Kamble et al. (2018) in a review of 85 papers on I40Ts, noted that only 18% took into account a sustainability-related perspective. In addition, the proportion of studies on I40Ts that refer to CE is lower. Moreover, most of the studies on the influence of I40Ts on CE have dealt with the subject in a general way; very few have compared the impact of each technology individually.

Among these studies, the research developed by De Sousa Jabbour et al. (2018) is noteworthy. Based on a literature review, they designed a pioneering roadmap, which shows that I40Ts have the potential to pave the way for CE principles. At the empirical level, more studies are needed. Prause and Atari (2017) developed a case study based on semi-structured interviews with experts and secondary data. The authors found that AM and BDAA influenced all CERs, but they did not detect impacts from other technologies such as IoT, RB and VAR. However, the study did not include technologies such as AI, AV and CS.

In this regard, the World Economic Forum (2019), in the 2019 White Paper, pointed out that the adoption of I40Ts is leading to tangible improvements that are driving business value. Many of these improvements are helping to reduce resource consumption. Some authors share this view and include the reduction of energy and material resource consumption among the potential capabilities of I40Ts (Berman, 2012; Wee et al., 2015; Chen et al., 2015; Hermann et al., 2016; Oesterreich and Teuteberg, 2016; Yuan et al., 2017; Müller et al., 2018). Among them, Wee et al. (2015) specified that I40Ts help companies to improve the efficiency of labor, capital, materials, energy, time and resource consumption. When analyzing the influence of specific technologies, several authors pointed out that AM technology has the potential to reduce the consumption of raw materials (Mellor et al., 2014; Oettmeier and Hofmann, 2017) and energy consumption (Campbell et al., 2011; Kellens et al., 2017; Rejeski et al., 2018). Other studies indicate that BDAA (Bahrin et al., 2016; Rüßmann et al., 2015), IoT (Shrouf et al., 2014; Lin et al., 2016; Tao et al., 2016; Wan et al., 2016) and VAR (Rodič, 2017) technologies also contribute to reduced energy consumption. Specifically, regarding to IoT, Lin et al. (2016) proposed a method for prolonging network lifetime, deploying energy-efficient systems and reducing the replacement frequency of faulty sensors to reduce consumption.

In the literature, papers linking I40Ts to reuse and/or recovery are less abundant. I40Ts in general (Chang et al., 2017), and BDAA and AM technologies in particular (Bloomfield and Borstrock, 2018; Marconi et al., 2019), have been considered a good support for dismantling or reusing materials. AM can be useful to assist product or component remanufacturing (Lahrour and Brissaud, 2018; Leino et al., 2016). Also Wittbrodt et al. (2013) found that AM technology allows the user to recover parts in poor condition by converting them into filament. However, Uriarte-Gallastegi et al. (2020) limits this recovery in some cases when using certain additives. BDAA can also help to evaluate cost reduction strategies through remanufacturing (Ge and Jackson, 2014) and IoT can help to develop innovative remanufactured products (French et al., 2018).

Regarding to recycling, AM seems to be the I40T that features most in studies which analyze impacting technologies. In numerous studies, AM technology is considered to positively influence recycling (Pavlo et al., 2018; Sauerwein and Doubrovski, 2018; Woern et al., 2018; Zhong and Pearce, 2018). However, Uriarte-Gallastegi et al. (2020) pointed out that this issue depends on the type of sub-technology. There are few studies on the remaining I40Ts. Specifically, Lin (2018) points out that BDAA can help with recycling issues during product design and Van Schaik and Reuter (2016) that VAR can help to calculate a set of recycling performance indicators.

Finally, in regards to RWE, the World Economic Forum (2019) quantified that 44 sites worldwide obtained an average waste reduction of more than 40% after the implementation of I40Ts. Without this level of quantification, Müller et al. (2018) and Peukert et al. (2015) share the fact that there is a positive contribution to waste reduction. Likewise, Peukert et al. (2015) point out that I40Ts also help to reduce greenhouse gas emissions. In the particular case of AM, they facilitate manufacturing closer to the final consumer, resulting in less pollution due to reduced transportation needs, greater decentralization of value chains and greater user orientation (Uriarte-Gallastegi et al., 2020). In addition, Mellor et al. (2014) points out that AM reduces the need for inventory and consequent product loss. Regarding RB technology, some authors

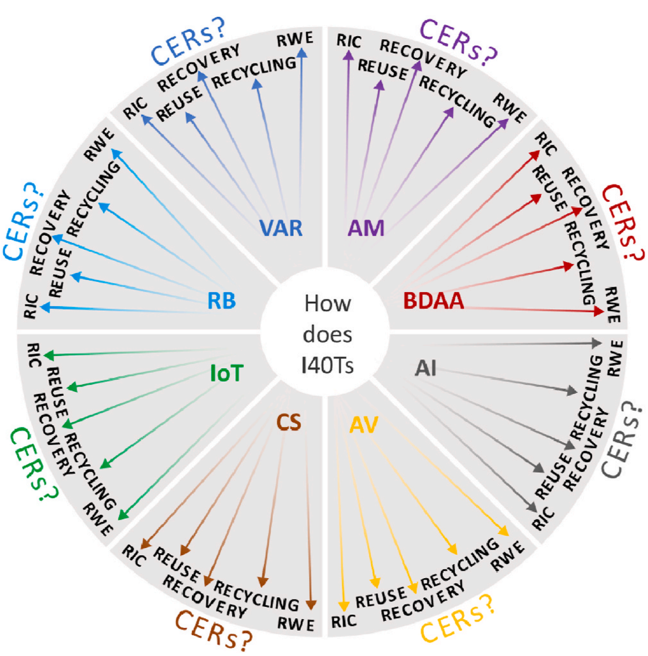

Fig. 2. Research questions.

consider that it improves product life cycle management, prolongs product life and decreases waste generation (Caggiano, 2018; Herterich et al., 2015). Waibel et al. (2017) predict that, in the future, manufacturing companies will use network technology to link production with suppliers and customers, decreasing the need for inventory and the manufacturing of products that become obsolete. Moktadir et al. (2018) are confident that the use of AV and VAR can help reduce waste generation by minimizing the rate/quantity of production failures.

With this background, the need for empirical studies which contrast the impact of I40Ts on CERs (De Sousa Jabbour et al., 2018; Rajput and Singh, 2019; Rosa et al., 2020) has been identified. Considering this aspect, this study aims to clarify the following RQ.

Main RQ → RQ 0: What is the influence of I40Ts on CE?

Taking into account that the planning of the study includes 8 I40Ts and 5 CE indicators, and that the literature has pointed out the need to analyze the influence that each I40T has on each CE indicator with a common methodology, forty RQs linked to the RQ 0 have been formulated. By analysing these influences (represented by the arrows in Fig. 2) the study aims to obtain a greater degree of research depth.

RQ 1–40: How does each I40T (AM, AI, AV, BDAA, CS, IoT, RB, VAR) influence each of the CERs (RIC, Reuse, Recovery, Recycling, RWE?

3. Methodology

The research process started with a review of the literature on the subject. The result of the review allowed us to define the propositions, objectives and RQs and the design of the research scheme (see Fig. 3).

A qualitative methodology based on case studies was chosen for several reasons. First, the phenomenon being studied is under-researched and complex. In addition, the I40Ts are in the early stages of their development and diffusion process (Rosa et al., 2020). For this reason, a holistic 27-project case study was carried out to analyze a heterogeneous, multidimensional phenomenon with a complex unit of analysis.

Thus, in a first phase, a preliminary study was carried out as an approach to the study phenomenon. Specifically, a questionnaire was conducted targeting a sample of I40Ts projects carried out in Europe, America, Asia and Africa, which participated in BIND 4.0, an international public-private acceleration initiative from the Basque Country, Spain (SPRI, 2017). Case-study research makes it possible to perform a quantitative study and analyze the results using qualitative methods that help to understand the reasons for relationships between groups of data (Eisenhardt, 1989; Gummesson, 2006).

The questionnaire included simple questions, all with the same structure to prevent the design of the questionnaire from influencing participants' responses. Questions were stated as follows: "Evaluate the influence (direct, indirect or potential) that your project may have on …". To answer, the same Likert scale was used (*-4*, has a very strong negative influence; *0*, no influence, +*4*, has a very strong positive influence) (Schumacher et al., 2016). In addition, participants had the opportunity to add information to clarify their answers in the open-ended questions. To define a final version that would avoid misinterpretations, pretests were conducted with five companies (Malhotra and Grover, 1998). In total, 130 responses were obtained from 168 I40T projects presented at the four meetings organized by the BIND 4.0 program. Ten of the responses obtained were discarded because they were incomplete. The final response rate was 71.4%. The responses were classified by I40Ts, according to the classification used by SPRI (the Basque public agency for business development, precursor of the BIND 4.0 program) (SPRI, 2017): AM (11), BDAA (24), AI (28), AV (8), CS (5), IoT (27), RB (6) and VAR (11).

Although the sample was insufficient to give a minimum level of confidence, when applying statistical techniques, it allowed us to obtain very useful information to refine the case protocol and the evidence collection plan at the preparatory stage of the case study. Likewise, the fieldwork of the first phase was completed in through follow-up meetings with participants in the case study. Interviews were held with organizers, speakers and participants in these meetings, and additional Internet-based research helped obtain relevant information on I40Ts adoption projects.

This first phase facilitated the selection of the case studies. They were intended to be informative, to answer the research questions and to have a minimum representation of all technologies (Stake, 1995; Patton, 2015). Twenty-seven cases of projects participating in different editions of the BIND 4.0 program were analyzed: AM (4), BDAA (3), AI (4), AV (2), CS (2), IoT (6), RB (2) and VAR (4), which are briefly described in Table 1.

Taking into account the feasible means for the development of the qualitative study, the authors established the following set of fundamental techniques to obtain sources of evidence:

- In-depth interviews with managers (M) and technicians (T). Interviews were carried out according to an interview script, a shortened version of which had been previously sent to each interviewee.
- Analysis of multiple sources of evidence (I40 project reports, technical documentation, test reports, internal communications …).
- On-site visits to companies to collect data through passive and active observation (methodological triangulation).

All case study analyses have followed a general analytical strategy, for which priorities have to be defined: what to analyze for and why. Yin (2017) proposes to base the strategy on the elaboration of theoretical propositions or RQs, the development of case descriptions (from quantitative and qualitative data) and the examination of rival explanations. To this end, he proposes the cross-case synthesis technique. For the application of this technique, the methodological indications of Miles et al. (2018) were followed, which are based on examining, categorizing, tabulating and examining the evidence collected, in order to identify common patterns of behavior among cases. Projects in our case have been grouped by type of I40T.

Next, a cross-case analysis (comparative cross-sectional) was carried out by I40Ts and to determine the connection between the data and the propositions made by each technology (Miles et al., 2018). The results of the cross-case analysis are summarized in the Tables 2–9 presented in section 4.2. They indicate the detection method (DM) in-depth interviews (I), documentation (D) and on-site visits (V) of the different sources or types of evidence and the case or cases from which they were obtained. The evidence was assessed by significance of sources (SSE) and theoretical saturation (TS) obtained from the triangulation (Turner et al., 2015). Tables also show the assessment of the transferability of the

Table 1
List of cases classified by type of technology.

Code Brief description	Informant
AM1 - Printing metal and plastic material for aircraft manufacturer suppliers	M, T
AM2 - Minimization of biological waste in the food industry through atomic level applications	T
AM3 - Special coating using nanotechnology in the manufacture of brake discs	M
AM4 - Consultancy to implement AM in industrial processes	M
BDAA1 - Data processing to optimize the use of industrial machines	M, T
BDAA2 - Use of information systems to manage and optimize the factory	M
BDAA3 - Massive data analysis to optimize production machine indicators	T
AI1 - Monitoring the construction of a wind farm using satellite-free images	T
AI2 - Voice recognition technology for operators to search for or write down procedures	M
AI3 - Analysis of the data (heating, air conditioning) of the buildings/ factories	M
AI4 - Analysis of camera data to optimize procedures	T
AV1 - Quality inspection system for plastic film production	M, T
AV2 - Automation of parts inspection in industrial processes (mainly automotive parts)	M
CS1 - Shielding the entire computer system of an automotive company	T
CS2 - Protection of the IT system of a machine tool company including Blockchain technology.	T
IoT1 - Devices for monitoring the supply chain	T
IoT2 - Monitoring through sensors in the lube oil of the wind turbines	M
IoT3 - Data capture from industrial machines using sensors	M
IoT4 - Sensorization of industrial machines to optimize mainly energy consumption	T
IoT5 - Use of wireless sensors to control the entire value chain (from the supplier to the customer)	T
IoT6 - Movement control of workers by sensors to optimize routes and movements	T
RB1 - Robotic solutions with sensing technologies and flexible application software	M, T
RB2 - Implementation of intelligent robots in production processes	T
VAR1 - Training people who can use fire extinguishers	M
VAR2 - Integral support for the digitalization of water treatment plant maintenance processes	T
VAR3 - Training to optimize procedures in industry	T
VAR4 - Virtual training to train jobs with some risk element	T

phenomenon (TP), explained as the property of being transferable to other specific contexts by providing a coarse description of the sender and receiver contexts (case-by-case transfer) (Spencer et al., 2004). The impact level of the evidence (ILE) shows the assessment of in each *R* taking into account: the opinions expressed by the people interviewed in the cases, analysis of the available documentation, internal communications … and visits). Likewise, to reinforce the validity of the construction and as a reliability test, a group of experts (Yin, 2017) was involved in the elaboration of these two columns (TP and ILE): 2 academics, 3 researchers from 2 technology centers and 1 consultant.

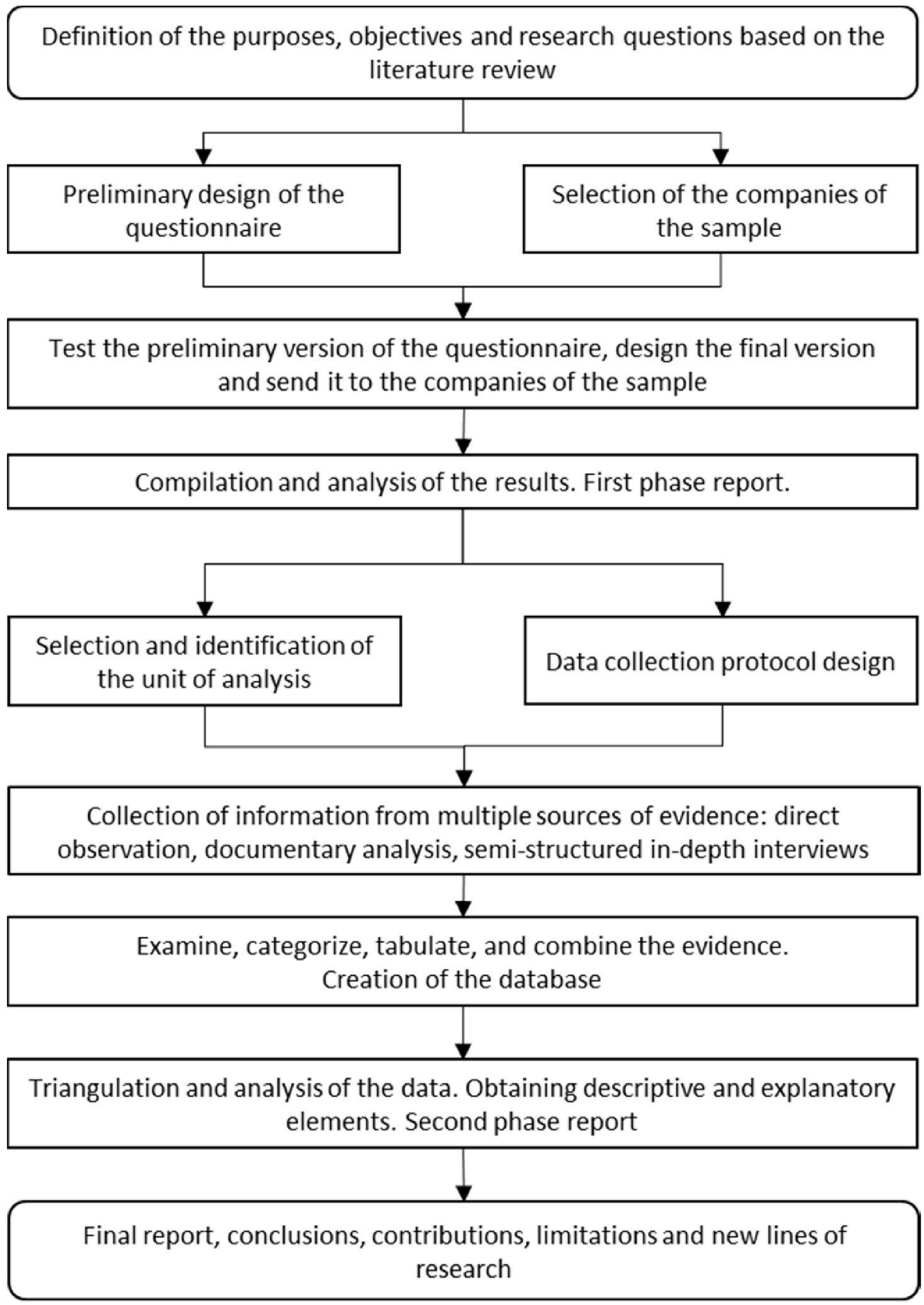

Fig. 3. Diagram of the methodological process followed. Source: Compiled by the authors, based on (Creswell and Clark, 2007; Ivankova et al., 2006).

4. Results

4.1. Preliminary study

The results of the preliminary study are based on 120 complete responses of the survey obtained from I40T implementation projects. Although a larger sample size for each type of technology is required for statistical analysis, the results have been a major source of information for the case study.

On one hand, the answers to the questions regarding the quantification of the responses about the impacts to the CERs (*RIC (Materials, Energy* and *Water)*, *Reuse*, *Recovery*, *Recycling*, and *RWE (Waste* and *Emissions*)) of each I40T were analyzed (see Fig. 4). All the mean values are positive. The responses reflect a generalized opinion that I40Ts have the capacity to positively influence circularity. With the exception of CS and VAR technologies, which are the technologies whose influences have been least valued, the averages of the *RIC-Materials* and *RIC-Energy* indicators vary in a range between 1.7 and 2.7, i.e., the value of the influence is considered to be medium-high. However, in all the cases the impact on the *RIC-Water* variable has been less valued than 1.7. In general, with the exceptions of AM and RB, *Reuse, Recovery and Recycle* score lower and move in a range between 0.5 and 1.5 (low influence). However, the ratings received in the AM responses are high and vary between 2.5 and 3, and those of RB are medium, varying between 1.5 and 2.2. On variables *RWE-Waste* and *RWE-Emissions*, I40Ts, AM, BDAA, AI and RB are considered to have a medium influence that is valued in a range between 1.7 and 2.5.

On the other hand, the answers to the open-ended questions were very useful to obtain evidence that could be evaluated in the case study. In addition, there were taken into account in the selection process of the

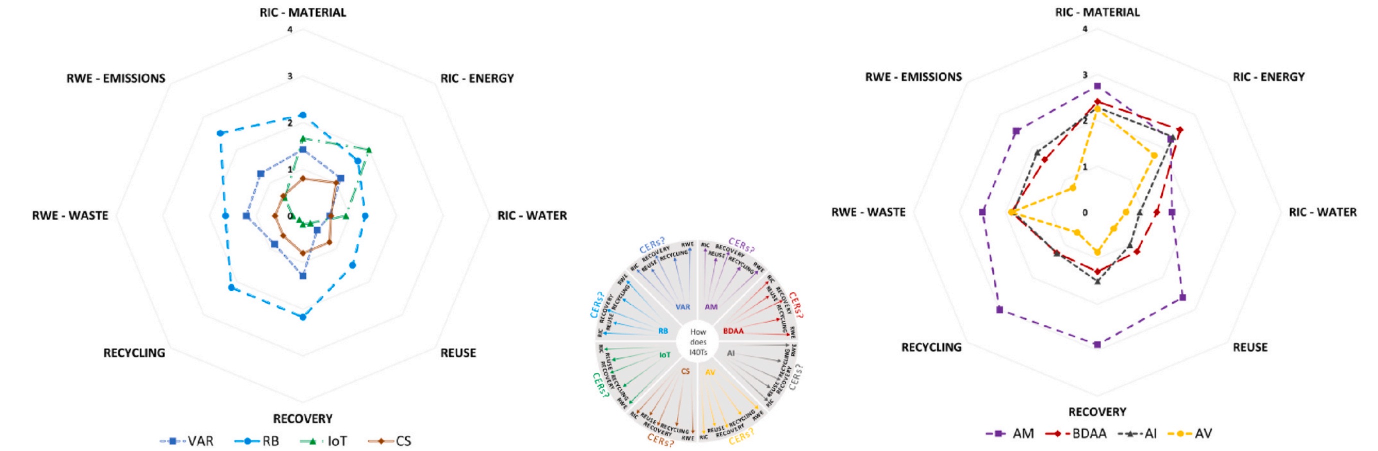

Fig. 4. Preliminary results on the influence of I40Ts on CERs. Note: Due to the fact that no global negative influences have been measured, influence assessment is presented on a five-point Likert scale (from no positive nor negative influence, expressed by 0 to very strong positive influence, expressed by 4).

case study projects.

4.2. Case study

4.2.1. Additive manufacturing

In the printing of metals and plastics, AM can achieve weight savings. Compared to conventional machining, depending on the product geometry, the reduction in material consumption varies from 20% to 85% (I, D). Rather than wearing material in manufacturing, material is added in layers and, for example, the 20 parts that made up the original fuel injector of an aircraft can be reduced to one. In the conventional manufacture of this product, the waste material from the production process of the 20 part components was 83% (I). However, in the new process, there is almost no waste material. In addition, the absence of welds and fasteners, combined with the possibility of creating complex geometries and topological optimization offered by this technology, has made it possible to reduce the weight of the injector by 15% (I, D) (AM1). In the automotive sector (AM3), such important reductions in material consumption have not been evidenced, although the material consumption of some parts can be brought down by 60% (I). It should be noted that in general these reductions are greater in short series or single parts. In addition, AM3 believes that this technology makes it possible to manufacture products that suffer less wear and withstand high temperatures better, and offers qualities very close to those of forging. This makes it possible to extend the product's use phase and reduces the number of spare parts that have to be manufactured. AM1 and AM3 agree that there are reductions in energy consumption in the manufacturing phase, but they are very small. AM4 highlights that one aspect that contributes to reducing energy consumption is the reduction of process noise (V). It allows being more efficient in plant layout, printing parts closer to the production line and thus minimizing the need for the internal transportation of goods. However, this technology has limitations. The size, type of materials and tolerances of the parts required are potentially some of the main ones. However, products usually require post-processing tasks mainly due to the brackets created in the processing phase.

The possibilities for the reuse, recovery and recycling of materials are quite substantial (AM1, AM3 and AM4). However, some AM technologies use a mixture of resins of unknown composition, which in many cases prevents their recovery and recycling (AM4).

AM2 pointed out that better material utilization implies waste reductions in the manufacturing phase but also, in the use phase; the products can enable waste reductions. For example, they allow atomic level coatings to be applied to the hoppers through which the product passes before being packaged in the food industry, reducing biological waste and sanitary problems. In addition, the AM1 technician pointed out that the reduction in aircraft weight helps to reduce CO_2 emissions and energy consumption in the use phase, which he quantifies as a 90%

Table 2
Results of the cross-case analysis for AM.

	Category	Main findings	DM	Case number	SSE[1]	TS[1]	TP[1]	ILE[2]
RIC	*Materials*	Achieve weight savings.	I, D, V	(1, 3)	●●	●●●	●●●●	+++
		Improve material utilization rate.	I, D, V	(1, 3)	●●●●	●●●●	●●●●	++++
		Extending the life cycle in the use phase reduces the material required.	I, D	(1, 2, 3, 4)	●●●●	●●●	●●	++
	Energy	A little less energy needed in manufacturing process.	I, D, V	(1, 2, 4)	●●●●	●●	●	+
		Reduction of internal transports.	I, D, V	(4)	●●●	●●	●	++
		Reduction in the use phase.	I, D	(1, 3)	●●●	●●	●	++
	Water	(No sufficiently strong or contrasting evidence has been found)						
	Reuse	Depending on the sub-technology used.	I, D	(3)	●●●	●●●	●●	+++
	Recovery	Remaining material can be used.	I, D, V	(3, 4)	●●●	●●●	●●	+++
	Recycle	Depends on the sub technology used (*Mixture of resins* hinders recycling).	I, D	(2, 3)	●●●	●●	●●	++
RWE	*Waste*	Radical reduction in material waste in the production phase.	I, D, V	(1, 2, 3, 4)	●●●●	●●●	●●●●	+++
		Extending the life cycle in the use phase reduces waste.	I, D	(2, 3, 4)	●●	●●	●●●●	+++
		Some additives used are pollutants.	I, D, V	(2)	●●●	●●●	●●●	++
	Emissions	Radical noise reductions depending on the technology.	I, V	(2, 3)	●●●●	●●●●	●●●●	++
		Reduction of CO_2 emissions.	I, D	(1, 3)	●●●	●	●●	+
Main limitations		The size, the materials and the tolerances needed.						
		Sometimes, post processing is needed.						

Notes: [1] The assessment provided summaries each aspect's rating in terms of level as a five-point Likert-type item, from very low or none (○), to very high (●●●●). [2] It captures the impact level of the evidence on the *Rs* as a nine-point Likert-type item, from very negative potential influence (- - - -), to very positive potential influence (++++).

Table 3
Results of the cross-case analysis for BDAA.

	Category	Main findings	DM-Case number		SSE[1]	TS[1]	TP[1]	ILE[2]
RIC	*Materials*	Exploiting objective information to optimize raw materials.	I, D, V	(2, 3)	●●●●	●●●	●●●	+++
		Almost complete elimination of the use of paper.	I	(2, 3)	●●●	●●	●●●	++
	Energy	Reduced energy consumption of the industrial plant.	I, D, V	(1, 2, 3)	●●●●	●●●	●●●●	++
		Optimization of lighting.	I, D, V	(1)	●●	●●●	●●●	+++
	Water	Water management parameters are controlled from the ERP.	I, D, V	(3)	●●	●●	●	+
	Reuse	(No sufficiently strong or contrasting evidence has been found)						
	Recovery	Clearer purchasing specifications.	I	(2)	●●	●●	●●	+
	Recycle	Clearer purchasing specifications.	I	(2)	●●	●●	●●	+
RWE	*Waste*	Fewer misused materials.	I, D	(2, 3)	●●●	●●	●●	+
	Emissions	Emissions reduction due to more efficient energy management.	I	(1, 2, 3)	●●●●	●●●	●●	++
Main limitations		Lack of knowledge of technology means that it is not always used correctly. Employees feel more controlled, which makes them reticent. Difficulty in reaching customers due to network security problems and lack of trust.						

Notes: [1] The assessment provided summarise each aspect's rating in terms of level as a five-point Likert-type item, from very low or none (○), to very high (●●●●). [2] It captures the impact level of the evidence on the *Rs* as a nine-point Likert-type item, from very negative potential influence (- - - -), to very positive potential influence (++++).

reduction (I). This aspect is also highlighted by AM3.

4.2.2. *Big Data and Advanced Analytics*

Obtaining and exploiting objective information on the real state of factories makes it possible to optimize the use of resources, especially energy and raw materials, and to a lesser extent water (BDAA2 and BDAA3). There is greater control over the status of processes and stockpiles, resulting in reductions of between 10 and 20% of deteriorated material (I). The use of paper in companies has been reduced by more than 80%, and can reach values close to 100% (I). Specifically, the fact of not having to search for sheets reduces the operation time (between 7 and 15%) of the machines (I), so energy consumption has been reduced in BDAA 2. However, this is not the only saving in BDAA1, BDAA2 and BDAA3 obtained more significant improvements in energy consumption, increasing the utilization rate of the machines at certain times, avoiding unnecessary use and reducing consumption caused by switching on and off. In addition, BDAA1 operates the lighting through algorithms to convert it into an intelligent system, obtaining energy savings of 30% in mercury lamps (I, D).

As for *Reuse*, *Recovery* and *Recycle* only, BDAA2 points out that this technology allows having clearer purchasing specifications and these can help to improve *Recovery* and *Recycle*.

However, in relation to reductions to consumption, waste reductions have been detected due to a greater optimization of the use of materials (BDAA2 and BDAA3). These experts added that this technology helps to manage energy resources by reducing emissions, using less energy and, in some cases, optimizing usage periods, allowing the use of cheaper and/or cleaner energy (renewable energy).

4.2.3. *Artificial Intelligence*

AI2 pointed out that AI has contributed to reducing paper consumption by almost 100%, replacing paper by screens (I). In addition, reductions in other materials were not significant (less than 5%) due to improvements in the production planning and management phases (I). However, energy consumption has decreased in all four projects. AI1 has reduced fossil energy consumption and the impact on biodiversity by reducing the dispatch of people, helicopters or drones to wind farms and fracking areas that are controlled via satellite. However, most of the times, good resolution images are in private hands and the budgetary constraints of the projects may be a hurdle. AI2 reduces the operation time and energy consumption of machines using automatic searches (between 7 and 15%) (I). However, in this case, workers' resistance to change could limit benefits. AI3 adjusts the air conditioning according to the outside temperature, achieving building energy savings of up to 50% (I, D). AI4 has been able to reduce energy consumption by optimizing procedures, adjusting data, and camera specifications.

Table 4
Results of the cross-case analysis for AI.

	Category	Main findings	DM -Case number		SSE[1]	TS[1]	TP[1]	ILE[2]
RIC	*Materials*	Less use of paper and plasticized sheets.	I	(2)	●●	●	●●	++
	Energy	Reduced internal and external transport.	I, D	(1, 3)	●●●	●●	●●	++
		Reduced machine energy consumption.	I	(2, 4)	●●	●●	●●	+
		Reduced heating and cooling energy.	I, D	(3)	●●●	●	●●●	+++
	Water	(No sufficiently strong or contrasting evidence has been found)						
	Reuse	(No sufficiently strong or contrasting evidence has been found)						
	Recovery	(No sufficiently strong or contrasting evidence has been found)						
	Recycle	(No sufficiently strong or contrasting evidence has been found)						
RWE	*Waste*	(No sufficiently strong or contrasting evidence has been found)						
	Emissions	Reduced transport.	I, D	(1)	●	●	●●	++
		Detects the levels of CO_2, NO_2 and other VOCs in the buildings and proactively adjusting the levels helps to improve carbon footprint.	I, D	(3)	●●	●	●	++
Main limitations		To maximize the benefits, the development of other technologies is required. Lack of training of employees and managers. Need to access through the network to elements, which when in private hands make the application more expensive.						

Notes: [1] The assessment provided summarise each aspect's rating in terms of level as a five-point Likert-type item, from very low or none (○), to very high (●●●●). [2] It captures the impact level of the evidence on the Rs as a nine-point Likert-type item, from very negative potential influence (- - - -), to very positive potential influence (++++).

No significant evidence of impacts of AI has been detected in *Reuse*, *Recovery* and *Recycle*. The case study has shown little potential for AI to reduce waste. AI2 notes that it contributes to improved stock-management and can reduce the percentage of materials that become obsolete. However, all four projects show more potential related to emissions reduction. In AI3, it can be seen that the carbon footprint decreases due to the reduction of CO_2, NO_2 and VOC levels (the reductions are up to 40% depending on the outdoor weather conditions) (I, D). In addition, the AI1 technician showed how AI technology can reduce the consumption of fossil fuels derived from air and road transportation by more than 50% (I, D).

4.2.4. Artificial Vision

The automation of the quality inspection process helps the customer to reduce the rate of poor quality items and therefore contributes to a slight reduction in material consumption (usually reductions of less than 2% in stable processes) (AV1 and AV2) (I). In addition, this I40T in a film manufacturing company has been crucial in digitizing and automating tasks more accurately while reducing energy consumption by more than 10% after the process adjustment is completed (AV1) (I). Its application in the automation sector also helps to reduce downtime and thus the resulting economic and energy losses (AV2). However, initially these projects raise doubts about the return on investment and this sometimes limits the results.

For *Reuse*, *Recovery* and *Recycle*, no major evidence has been identified. However, sometimes AI allows for an earlier detection of defective products or components, which has a positive influence on *Recovery* and *Recycle*, as it avoids subsequent treatments and assemblies involving mixtures of different materials that hinder *Recovery* and *Recycle* (AV2). Because of the improved use of materials and the small impacts on *Recovery* and *Recycle*, waste is reduced but at a low rate (less than 10%) (AV12 and AV2) (I, V). Emissions are also reduced as the increased control in the plant reduces the need for transport as it allows for better route planning (AV2).

Table 5
Results of the cross-case analysis for AV.

	Category	Main findings	DM	-Case number	SSE[1]	TS[1]	TP[1]	ILE[2]
RIC	*Materials*	Improve quality inspection process reduce material need.	I, V	(1, 2)	●●●	●	●●	++
	Energy	Reduction of rework processes.	I	(1, 2)	●●	●	●●	++
	Water	(No sufficiently strong or contrasting evidence has been found)						
	Reuse	(No sufficiently strong or contrasting evidence has been found)						
	Recovery	Reduce the mixture of different materials.	I	(1, 2)	●●	●	●	○
	Recycle	Reduce the mixture of different materials.	I	(1, 2)	●●	●	●	○
RWE	*Waste*	Improve quality inspection process reduce waste.	I, V	(1, 2)	●●	●●	●●	+
	Emissions	Reduce transport.	I	(2)	●●	●	●●	+
Main limitations		Sometimes the return on investment is not clear. To maximize the benefits, the development of other technologies is required.						

Notes: [1] The assessment provided summarise each aspect's rating in terms of level as a five-point Likert-type item, from very low or none (○), to very high (●●●●). [2] It captures the impact level of the evidence on the *R*s as a nine-point Likert-type item, from very negative potential influence (- - - -), to very positive potential influence (++++). The middle term expressed as ○ indicates there is no clear predominantly negative, nor positive influence.

4.2.5. Cybersecurity

In normal conditions, CS technology has zero or little influence on CERs (CS1 and CS2). The projects do not usually have direct or indirect impact on the studied items but CS1 and CS2 highlighted that they are critical in reducing potential CE problems. Cyberattacks can destroy the safety of the whole system of the company and can affect negatively all the items analyzed.

However, despite the fact that some companies are reticent about investing in CS, there is evidence that it is beginning to have an increasing indirect influence in combination with other technologies. For example, CS2 says that CS is needed in the development protocols of blockchain technology to ensure the traceability of products. In addition, CS2 indicates that the process of encrypting all information is a critical process that requires CS and is key, for example, to ensuring the provenance of raw materials and to prevent corporate "circularwashing". In addition, some companies are afraid to expose their information in the cloud and CS can provide confidence to companies and help spread good practices that promote circularity.

4.2.6. Internet of Things (IoT)

IoT technology has allowed companies to be more efficient in the consumption of materials, obtaining reductions of specific material (mainly materials used for maintenance operations) that vary between 5 and 30% in the 6 projects (I, D). This has been mainly because it has allowed them to have greater control over production and maintenance operations, thus reducing the percentage of defective products and extending the useful life of production resources. However, this requires changes in the customer in the way they use the product. In relation to energy consumption, the IoT3 and IoT4 projects by adjusting machine parameters with more data sources optimized energy consumption by

Table 6
Results of the cross-case analysis for CS.

	Category	Main findings	DM	-Case number	SSE[1]	TS[1]	TP[1]	ILE[2]
RIC	*Materials*	Potential lack of safety can increase the consumption of material.	I	(1, 2)	●●	●	●	+
	Energy	Potential increase in energy consumption in the foundries.	I	(1, 2)	●●	●	●	+
	Water	(No sufficiently strong or contrasting evidence has been found)						
	Reuse	(No sufficiently strong or contrasting evidence has been found)						
	Recovery	Ensuring traceability of recycled materials using blockchain technology.	I, D	(2)	●	●	●●	+
	Recycle	Ensuring traceability of recycled materials using blockchain technology.	I, D	(2)	●	●	●●	+
RWE	*Waste*	Potential lack of safety can increase waste.	I	(1, 2)	●	●	●	+
	Emissions	Potential lack of safety can increase emissions.	I	(1, 2)	●	●	●	+
Main limitations		Some companies are reticent about investing in CS as they do not perceive a return on their investment						

Notes: [1] The assessment provided summarise each aspect's rating in terms of level as a five-point Likert-type item, from very low or none (○), to very high (●●●●). [2] It captures the impact level of the evidence on the *R*s as a nine-point Likert-type item, from very negative potential influence (- - - -), to very positive potential influence (++++).

Table 7
Results of the cross-case analysis for IoT.

	Category	*Main findings*	*DMDM -Case number*		*SSE*[1]	*TS*[1]	*TP*[1]	*ILE*[2]
RIC	*Materials*	Extension of the life cycle reducing the material needed in manufacturing phase.	I	(1, 2, 4)	●●	●	●●●	+++
		Continuous control of the parameters reducing materials used for maintenance.	I, D	(2, 3, 4, 6)	●●●●	●●●	●●●	+++
		Less defective products, increasing the efficiency of the materials used.	I	(3, 4, 6)	●●●	●●	●●	++
	Energy	Data capture to optimize the energy used.	I, D, V	(1, 3, 4, 5)	●●●●	●●	●●●	+++
		Optimizations of transport reduce the petrol consumption.	I	(1, 2, 3, 4)	●●	●●	●●	++
		Optimization of the acclimatization of industrial companies.	I	(4)	●●	●	●●●	++
	Water	(No sufficiently strong or contrasting evidence has been found)						
	Reuse	Reuse of sensors and other machine components.	I, V	(1,3,4)	●	●	●	+
	Recovery	Recovery of sensors and other machine components.	I, V	(1,3,4)	●	●	●	+
	Recycle	(No sufficiently strong or contrasting evidence has been found)						
RWE	*Waste*	Extension of the life cycle reduces waste.	I	(1, 2, 3, 4)	●●	●	●●	++
		Fewer spoiled products.	I	(1, 2, 5, 6)	●●	●	●	+
	Emissions	Reduction of spoiled food decreases the greenhouse gas emissions.	I	(1)	●	●	●	+
		Reduction of petrol consumption.	I	(1, 3, 4)	●●	●	●●	++
Main limitations		The lack of maturity or scarcity of knowledge about new technologies, on the part of the managers or decision makers of many industrial companies.						
		The cost of the product and the investments required for installation and implementation.						

Notes: [1] The assessment provided summarise each aspect's rating in terms of level as a five-point Likert-type item, from very low or none (○), to very high (●●●●). [2] It captures the impact level of the evidence on the *R*s as a nine-point Likert-type item, from very negative potential influence (- - - -), to very positive potential influence (++++).

30% (I) and IoT6 with constant monitoring using low-power wireless sensors, and introducing some constant parameters in its planning, is reducing fossil fuel consumption (less than 5%) (I). However, technology providers pointed out that the lack of knowledge about new technologies, on the part of the managers or decision makers of many industrial companies limit the obtained reductions.

In relation to *Reuse*, *Recovery* and *Recycle*, some evidence of medium importance has been detected, such as the reuse and/or recovery of materials before they were definitively unusable. For example, in the market, most of the devices used to control the cold chain are single use but the new model (if properly maintained) can be used 30 times, thereby reducing electronic waste (IoT1). However, some project managers have highlighted that the cost of product recovery and the necessary investments may limit the results (Iot3, IoT4). In addition, evidence of waste reductions linked to product and component life-extension and the reduction of spoiled products and components have also been obtained in other cases. Emission reductions have been significant. Specifically, IoT1 achieved a reduction in greenhouse gas emissions by reducing organic waste and IoT6, by introducing some parameters in its planning through low-power wireless sensors, is reducing fossil fuel consumption by 5–10% (I).

4.2.7. *Robotics*

In the projects, it has been possible to collect evidence of reduction in material consumption, once the processes have stabilized. These reductions are not very relevant, in general, they are less than 0.5%, but they increase in repetitive processes (I). They are mainly obtained by reductions in the number of defective products and the extension of the tool life. Reduced energy consumption has also been identified. It is true that certain robots have an energy consumption that cannot be overlooked, but small energy reductions (less than 5%) have been obtained by optimizing processes and internal transports (I, D). In addition, there are cases where robots allow local production processes to be competitive because the cost of direct labor is reduced. This allows for a reduction in the international transportation of goods.

As for *Reuse*, *Recovery* and *Recycle*, RB2 is integrating activities with robots to optimize material sorting. These activities mainly favor recovery and recycling, and to a lesser extent reuse. In addition, because of greater constancy and consistency in the work of the robots, waste generation is reduced by extending the useful life of tools, decreasing the proportion of defective products and making better use of the material in certain processes. However, although these are compelling reasons for a strong reduction in waste, reductions of more than 10% have not been detected (RB1, 2) (I). With regard to emissions, RB1 has managed to reduce them significantly by facilitating the extraction of toxic dust and fumes and helping to filter them. In addition, as mentioned above, it has managed to increase local production and reduce the use of fossil fuels in transportation.

4.2.8. *Virtual and Augmented Reality (VAR)*

In all four cases, VAR helps to complement the typical understanding of interaction, facilitating learning and safety in the working relationship between man and machine. It has led to a reduction in poorly processed products and, consequently, in material and energy consumption. The quantification of these improvements is difficult to measure but in all cases, they have been considered to be insignificant

Table 8
Results of the cross-case analysis for RB.

	Category	Main findings	DM -Case number		SSE[1]	TS[1]	TP[1]	ILE[2]
RIC	*Materials*	Less material usage by using robots.	I, D	(1, 2)	●●	●	●●	++
	Energy	Small energy reductions by optimizing processes.	I, D	(1)	●●	●	●	++
	Water	(No sufficiently strong or contrasting evidence has been found)						
	Reuse	Robot assistance to recover material that can be reused, recovered or recycled.	I, D, V	(2)	●	●	●●	+
	Recovery		I, D, V	(2)	●●	●	●●	++
	Recycle		I, D, V	(2)	●	●	●●	++
RWE	*Waste*	Less material waste from using robots.	I	(1, 2)	●●	●	●	++
	Emissions	Reduction of dust and toxic fumes.	I	(1)	●	●	●	++
		Reduction of international transport.	I	(1)	●	●	●	++
Main limitations		Manual work remains the most flexible solution.						
		The investments required for installation and stabilization of processes.						

Notes: [1] The assessment provided summarise each aspect's rating in terms of level as a five-point Likert-type item, from very low or none (○), to very high (●●●●). [2] It captures the impact level of the evidence on the Rs as a nine-point Likert-type item, from very negative potential influence (- - - -), to very positive potential influence (++++).

Table 9
Results of the cross-case analysis for VAR.

	Category	Main findings	DM	-Case number	SSE[1]	TS[1]	TP[1]	ILE[2]
RIC	*Materials*	*Less material usage due to improved manual operations.*	I, D, V	(1, 2, 3, 4)	●●●	●●	●●	+
	Energy	*Less energy consumption due to operations improvements.*	I, D	(1, 2, 3, 4)	●●●	●●	●●	+
	Water	(No sufficiently strong or contrasting evidence has been found)						
	Reuse	(No sufficiently strong or contrasting evidence has been found)						
	Recovery	(No sufficiently strong or contrasting evidence has been found)						
	Recycle	(No sufficiently strong or contrasting evidence has been found)						
RWE	*Waste*	*Less waste from defective products.*	I	(1)	●	●	●	+
	Emissions	*Reduction of transport by remote order.*	I	(2)	●	●	●●	+
Main limitations		To improve its performance, it is necessary to invest in and integrate with other technologies.						
		The extensions are mostly aimed at objectives related to improving competitiveness, quality and safety, but the focus on applications aimed at improving circularity is weak.						

Notes: [1] The assessment provided summarise each aspect's rating in terms of level as a five-point Likert-type item, from very low or none (○), to very high (●●●●). [2] It captures the impact level of the evidence on the *Rs* as a nine-point Likert-type item, from very negative potential influence (- - - -), to very positive potential influence (++++).

(VAR 1, 2, 3, 4). In addition, the management of maintenance interventions in some cases is done with "zero paper" (VAR 2) and unnecessary trips are avoided thanks to the remote assistance system and online training (VAR 3 and 4).

As for *Reuse*, *Recovery* and *Recycle*, no significant evidence was detected in any case. Finally, RWE is considered to be positively influenced, but only slightly (VAR 1, 2, 3, 4). The reduction of waste generated by defective product materials and the amount of paper consumed are the most outstanding. In terms of emissions, the reduction of transport caused by tele assistance is the most important. In addition, it has been highlighted that it helps to minimize potential accident risks, impact is greatest on emissions and biodiversity (VAR 2, 3).

5. Discussion

This research has focused on analyzing the influence that each I40T exerts on each CER in order to respond to the 40 RQs posed (see Fig. 5). The findings highlight that, in general, the I40Ts have a positive impact on the CERs, but there are large differences between the level of influence exerted by each I40T and the degree to which each CER is impacted.

First, each I40T has a positive impact on RIC. Specifically, sufficient evidence has been obtained to consider that AM exert a very strong impact. These results come to confirm findings from previous studies regarding the positive influence exerted by AM (Campbell et al., 2011; Mellor et al., 2014; Oettmeier and Hofmann, 2017; Prause and Atari, 2017; Kellens et al., 2017; Rejeski et al., 2018). The impact of BDAA and IoT is considered strong. In the literature, there are articles related with the positive impact of BDAA (Rüßmann et al., 2015; Bahrin et al., 2016; Prause and Atari, 2017) and IoT (Shrouf et al., 2014; Lin et al., 2016; Tao et al., 2016; Wan et al., 2016) but Prause and Atari (2017) did not detect evidence for IoT. On the other hand, the medium-level positive influences of AI, AV and RB, and the low-level positive impacts of CS and VAR on RIC, have been assessed. These results differ from those obtained by Prause and Atari (2017) because they did not detect evidence for RB and VAR. Among the indicators, water consumption has not been considered a relevant variable within RIC.

Second, only the influence exerted by three I40Ts on *Reuse* have been evidenced. Specifically, as in the studies developed by Bloomfield and Borstrock (2018) and Marconi et al. (2019), it has been confirmed that AM exerts a strong positive impact on reuse. Likewise, low positive influences of IoT and RB have been found. However, the evidence detected by Bloomfield and Borstrock (2018) regarding the positive influence of BDAA on reuse could not be confirmed.

Third, a strong positive impact of AM, a medium-level influence of RB and a low-level impact of BDAA, CS and IoT has been identified on *Recovery*. For these reasons, with respect to AM, the results are consistent with those of the studies developed by Lahrour and Brissaud (2018) and Leino et al. (2016), and on the possibility of recovering material by converting it into filament as pointed out by Wittbrodt et al. (2013). However, the use of additives for some sub-technologies limited this possibility. On the other hand, little evidence has been detected to confirm the positive influence of BDAA identified by Marconi et al. (2019).

Fourth, AM and RB exert a medium and BDAA and CS low positive influence on the recycling variable. As in the previous cases, the impact of AM collected in the literature (Pavlo et al., 2018; Sauerwein and Doubrovski, 2018; Woern et al., 2018; Zhong and Pearce, 2018) is confirmed and the positive influence of RB is added due to its possible application to material separation. In addition, little evidence for BDAA linked with the definition of specifications support a little the results of Lin (2018). In terms of another I40T, VAR, no positive evidence has been detected, as reported Van Schaik and Reuter (2016).

Finally, it is noteworthy that RWE is the second variable on which all the I40Ts exert a positive impact. AM exert a strong positive influence. These results are in agreement with those obtained by Mellor et al. (2014) for AM. In addition, impacts that were exerted by BDAA, AI, IoT and RB have been evaluated as medium-grade influences. These results are in line with those predicted by Waibel et al. (2017) who highlighted that BDAA, AI and IoT served to avoid the waste of obsolete products to which the reduction of defective products and generation of emissions should be added. Moreover, the results share with Caggiano (2018) and Herterich et al. (2015) that RB contributes to reduce waste. Finally, although they also exert a positive influence, AV, CS and VAR technologies are considered to have a lesser degree of impact. However, CS is considered to be a key technology for the future due to the potential risks it avoids and the importance it can have in the development of new technologies such as blockchain. This combination of technologies will be necessary to guarantee the traceability of recycled materials or products in general and to avoid circularwashing.

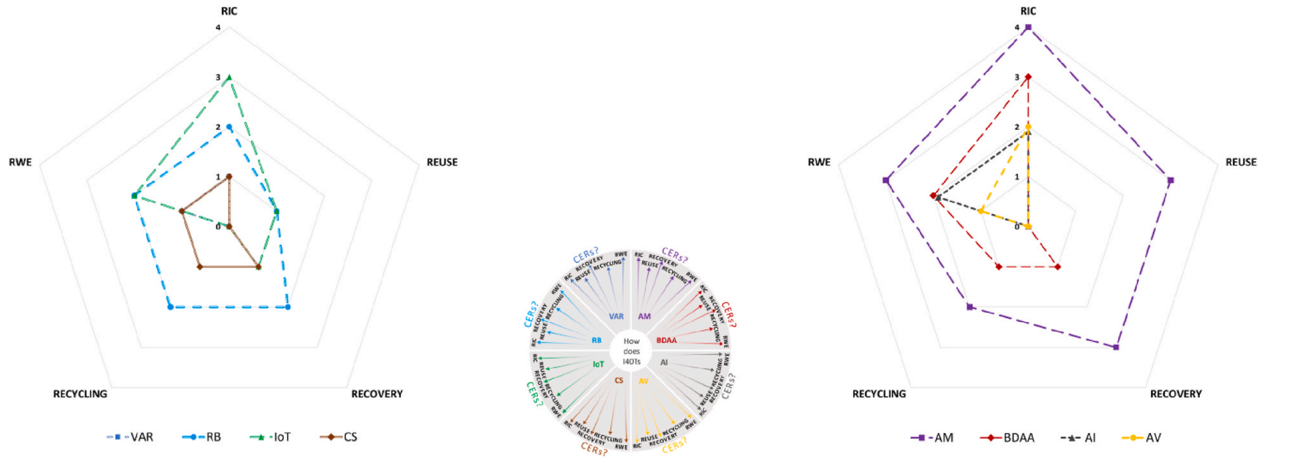

Fig. 5. Research questions analysis. Note: Due to the fact, that no global negative influences have been measured, influence assessment is presented on a five-point Likert scale (from no positive nor negative influence, expressed by 0 to very strong positive influence, expressed by 4).

Therefore, in general, the results are in line with those obtained in the literature analysis. There is more evidence of the influences of I40Ts on RIC and RWE than on reuse, recovery and recycling. In fact, for all the I40Ts the level of impact evidenced for RIC or RWE is equal or higher than that evaluated for the rest of the variables, corroborating the World Economic Forum (2019). Furthermore, it has been observed that the people involved in the adoption processes of I40Ts consider the variables reuse, recovery and recycling less relevant, although these variables are necessary to reinforce the closure of the CE loop.

Overall, the results partially confirm the literature review developed by Rosa et al. (2020). AM was presented as one of the I40Ts with the greatest influence on CERs, perhaps because it is more difficult to assess the impact of the other I40Ts on the improvement of any of the CERs and to quantitatively attribute a value to that contribution. AI, AV, BDAA, CS, IoT, RB and VAR are enabling technologies that allow for the improved performance and the exploration of new possibilities of other existing technologies in the industry. This research also added evidence of the positive impact of RB on all CERs and, in contrast to Prause and Atari (2017), who only found evidence of the influence of AM and BDAA on all CERs.

6. Conclusions, implications, limitations and future research lines

The 21st century has been characterized by an acceleration of technological development worldwide. This development has been accompanied by an increase in the consumption of resources and the generation of waste and emissions. For these reasons, it has become increasingly necessary to accelerate the process of transformation from a linear economy to a CE. This transformation is deeply dependent on its relationship with technological development and therefore, it must take into account the opportunities and threats that this technological revolution generates.

Nevertheless, both business and academia have focused on the influence of I40Ts implementation on competitiveness, and less attention has been paid to issues related to CE. In addition, there are varied opinions on how I40T can impact the CE. Our findings suggest that in general, I40Ts have a positive influence on CE. The most relevant contributions of I40Ts are those affecting the RIC and RWE indicators. Consumers and retailers are found to consider these variables as a higher priority than other, less affected, variables (i.e. reuse, recovery and recycling). In fact, AM and RB are the only two I40Ts that have a medium or high influence on these variables. This aspect must be considered when defining strategies corporate levels, as reuse, recovery and recycling must be improved in order to reinforce a closed CE loop. In addition, policy makers and other stakeholders should take note of these influences and promote policies that encourage companies to strengthen their actions focused on the use of I40Ts and thus take advantage of their influence on the CE.

Another relevant aspect to consider in the development of public policies should be the promotion of the application of different I40Ts to manage environmental risks. This is an issue that has not been sufficiently researched and yet can be very significant. This study is pioneering in analyzing the impact of CS on CERs. It considers CS as a technology without relevant direct influence, but taking into account the risks generated by the need for increased connection to the net, it may have strong implications and therefore needs to be further investigated to determine its potential in reducing current and future environmental risks.

In relation to the limitations of the study, the main one may be the transfer of findings. Although qualitative methodology allows for a deeper understanding of the object of study, it is necessary to develop quantitative studies. Case studies are highly dependent on the sending and receiving context, even when they involve multiple cases with a single unit of analysis. In particular, the dependence between technology categories critically influences the improvement capability of individual technologies and limits the generalization of the results. For this reason, future research should take into consideration that industrial companies are incorporating a combination of I40Ts into their processes that have a synergistic influence on CERs. Therefore, although individually some technologies seem to have a more positive impact than others (AM and RB), it is necessary to consider the combination of all of them to measure the real impact on CE, but the complexity of the problem may limit its realization. In addition, it would be interesting to contrast the perspectives of different stakeholders, such as customers, suppliers or policy makers. This line of research would be enriched by conducting research that divides companies by sector, size or according to their experience in dealing with I40Ts or environmental management systems.

CRediT authorship contribution statement

Iker Laskurain-Iturbe: Investigation, Methodology, Writing – original draft, Writing – review & editing. **Germán Arana-Landín:** Supervision, Investigation, Project administration, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Validation. **Beñat Landeta-Manzano:** Conceptualization, Methodology, Data curation, Validation, Formal analysis, Writing – review & editing, Visualization. **Naiara Uriarte-Gallastegi:** Investigation, Writing – review & editing.

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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