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How Do Technologies Based on Cyber–Physical Systems Affect the Environmental Performance of Products? A Comparative Study of Manufacturers' and Customers' Perspectives

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Abstract: In the academic literature, there are studies that link the adoption of Industry 4.0 technologies with an improvement in product-related circular economy indicators. However, there are scarce studies carried out in business contexts that analyse the degree, the stage of the life cycle and the value given to these improvements by customers and Industry 4.0 technology manufacturers. To contribute to clarifying these fields, a multiple-case study of nineteen technology manufacturers has been conducted, with input from the experience of venture clients as users and active participants in a shared project. Both manufacturers and their customers agree that Industry 4.0 technologies have a positive impact on circular economy. Benefits depend on the type of technology and its application and are mainly concentrated in the manufacturing phase. Additive manufacturing appears to be the technology with the greatest potential to influence circular economy, but customers also highlight the influence of augmented/virtual reality. Most manufacturers and customers emphasise the biggest influence is on reducing material consumption. This serves to improve the critical variables of market positioning by reducing product costs. However, acquisition cost, as well as quality and safety specifications, are of greater importance to manufacturers and customers, which may limit the environmental benefits obtained.

Keywords: Industry 4.0; circular economy; environmental impact; life cycle thinking; sustainability

1. Introduction

Circular economy (CE) has emerged as a new economic model for sustainable development. It is a shift from the traditional linear model, based on "extract, make, use, throw away", to a model where the use of all available resources is maximized [1]. The paradigm shift in the way we produce and consume has sparked the development of numerous initiatives around the world, of various kinds and at different scales, such as: the European Union's Circular Economy Action Plan [2]; at a national level, China's Circular Economy Promotion Law (articulated through several action plans that provide more details for specific sectors) [3]; the German Circular Economy Act [4]; the development of an inclusive legal framework for the transition to a CE society in Japan [5]; the Netherlands Circular Economy Programme; Finland's 'Leading the Cycle' policy; and South Korea's 2016 Framework Act on Resource Circulation [6]. These are laws, policies and acts that seek to promote and drive towards more sustainable economic models by introducing changes to the structural asset base of the global economy, such as transport and communication infrastructures, building, manufacturing systems and energy generation [7]. According to the goals set by the UN in the 2030 Agenda for Sustainable Development [8], the decrease in waste generation through prevention, reduction, recycling, and reuse policies has special relevance. Therefore, it is necessary to work on reducing, as much as possible, the consumption of material resources (R1) that enter the system, as well as reducing negative results such as emissions and waste (R5) (see Figure 1). To achieve these objectives, it is necessary to work on the other 3 "R"s of the CE model: reuse (R2), recovery (R3) and recycling (R4) (see Figure 1) [9].

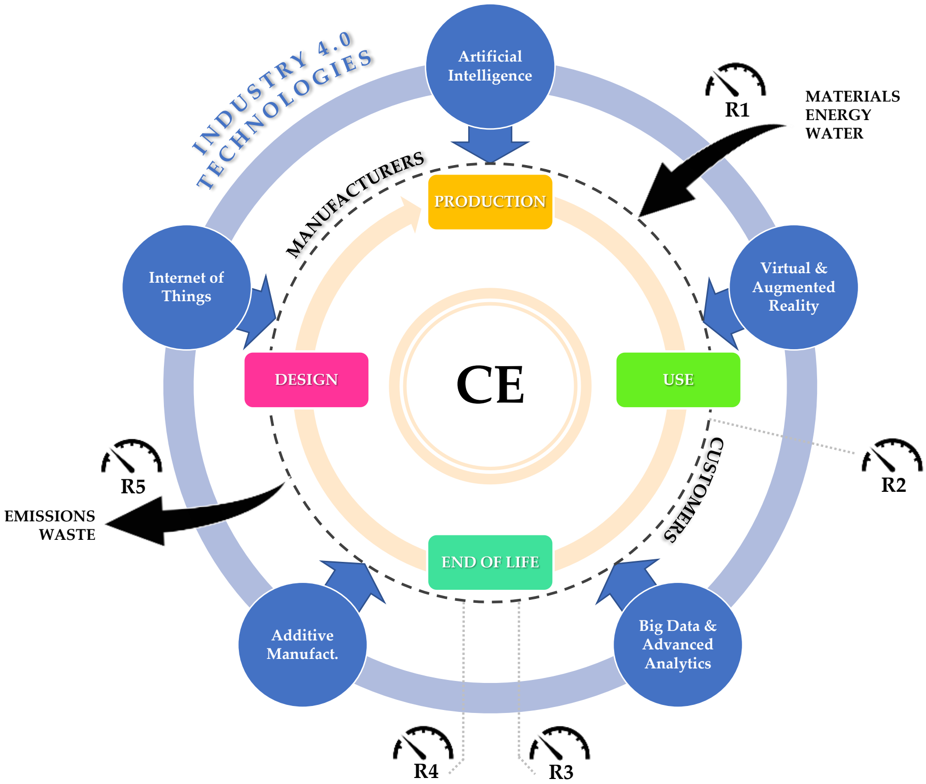

Figure 1. CE model for industry.

These strategies provide new opportunities arising from technological development and should take advantage of the technologies of the so-called Fourth Industrial Revolution (I40) [10,11]. Globally, countries such as China and Japan have introduced plans such as "China Manufacturing 2025" [12] and the "Fifth Science and Technology Basic Plan", together with "Society 5.0" [13], to develop and incorporate new technologies in the business fabric and take advantage of their potential to be able to better face future challenges. For its part, the German Federal Government presented the "High-Tech Strategy 2020" with digital economy and I40 among the priority lines of action [14]; in the United States, the "Advanced Manufacturing Partnership" was established [15]; and France has launched the "La Nouvelle France Industrielle" program [16]. Despite the commitment to new technologies by the world's leading economies, it is necessary to identify how new technologies can be developed in the interest of sustainable development as the goal. In this regard, academic work linking I40, CE and sustainable development are very few [17–21] and, moreover, there is some controversy about how I40Ts affect sustainable development in the long term [17]. Rosa et al. [11] and Bonilla et al. [20], for example, point out that I40Ts offer a wide range of possibilities that can help companies to improve their circular performance. The fact is that, from the product design phase, decisions are made that can significantly influence the degree of circularity of the system and, in this decision-making, investments in I40Ts are key [22,23]. However, Nascimento et al. [24], among others, claim that, in the socio-technological context of sustainable manufacturing, there is a disconnection between CE and I40.

On the other hand, as highlighted by Massaro et al. [21], recent studies propose to researchers the use and diversification of data sources to better understand the practitioners' point of view. Authors propose the study of academic but also practical sources, analysing the content of databases of professional documents, journalistic articles, press releases and specialised blogs. We have tried to approach this reality from a closer perspective, based on the case study methodology. The phenomenon is complex, and it is necessary to enrich current knowledge from the perspective of the main stakeholders and gather evidence that will help us to understand it better [25].

Considering this background, this research is focused on two main objectives:

1. Assessing the actual contribution of each technology to system circularity from the perspective of manufacturers and customers. This includes an analysis of the direct influence of each technology on each phase of the product life cycle, as well as the influence of the I40Ts in each of the key circularity indicators of the CE model (R1, R2, R3, R4 and R5);
2. Identifying the importance given by both manufacturers and customers to the circularity of resources in the selection process of I40Ts.

The paper is organized as follows. Following this introduction, a literature review and sections outlining the methodology are presented. Subsequently, the results of the research are shown and discussed. Finally, conclusions, limitations and future lines of research are summarised.

2. Literature Review

2.1. Circular Economy Strategies

The increase in global demand for resources in recent decades due, among other reasons, to the growth of the world's population and emerging economies, has led to a marked acceleration in the consumption of natural resources. This has led to supply disruptions and the price volatility of raw materials, materials, and resources [26].

Furthermore, from an environmental point of view, ecosystem degradation and the human-generated impact on nature has increased due to the current linear economic model and growth in demand [26]. This scenario makes our so far dominant economic model comprising non-renewable resources hardly sustainable [27].

The circular economy presents itself as an alternative to this current model of production and consumption, with the potential to solve environmental challenges. The circular economy is an alternative economic model in which, adopting a holistic and systemic approach, industrial processes are not seen as the inevitable cause of natural resource exploitation, environmental pollution, and waste generation, but rather, as contributions to sustainable development [28,29]. While the goal remains to make business operations profitable, a CE model aims to generate more economically, environmentally and socially responsible value in a resilient and competitive manner [28,30].

This is achieved by adopting innovative business models and regenerative product design, material management and value-retention approaches, and strategies that follow to continuously circulate flows of products, components, and materials to their maximum utility in production systems [31–34]. Actions should be taken to ensure that the life cycle of products and materials are maintained for as long as possible [31].

Furthermore, waste should be minimised, material (re)utilisation should be maximised, and resources should be repeatedly reintroduced into the production cycle to create value when goods reach the end of their useful life [34]. In this context, the concept of waste should tend to disappear. However, it is not always possible to avoid the generation of waste, which is why waste should be considered as a source of resources and value through its valorisation [35]. Refurbishment, remanufacturing and component recovery become key concepts in the cycle [26]. We are talking about strategies known as R-strategies. In the academic literature, we find different approaches that are similar to each other based on the multi-R system [36]. They differ mainly in the number of circularity Rs they present [37]. Thus, we shall start with a 3-R system [38]:

- Reduce (R1): Perhaps the most important R of the three [26]. It is about reducing the amount of waste produced while reducing input consumption, such as materials, energy and water.
- Reuse (R2): This is based on reusing objects and resources to give them a second useful life. This focuses on the reuse of products or components of the same type of product discarded by another consumer after they fulfil their original function.
- Recycle (R3): Perhaps one of the most popular methods: through separate collection and recycling, the need for new materials is reduced, but energy is required for their transformation and reuse. It would, therefore, be the last option to consider.

This system can be extended according to the proposals of Lieder and Rashid [28], Goyal et al. [35], Vermeulen et al. [37], Singh and Ordoñez [38], Merli et al. [39], Morseletto [40] or Gudde [41]. Considering the proposed systems, a 5-R model has been developed as a combination of the R-lists developed by Vermeulen et al. [37] and Gudde [41] (see Figure 1). Thus, two Rs have been added to the 3-R system so that the proposed model allows formulating circularity strategies while maintaining the primary function of a product:

- Recover (R4): This consists of finding solutions to recover products that appear non-recyclable, such as energy or water.
- Reduce waste and emissions (R5): This is a consequence of the other R. It should focus on resource recovery. At the end of the process, CE requires a waste and emission management strategy that should seek to reinforce the recirculation of resources, minimising environmental consequences.

2.2. Industry 4.0 Technologies

In 2011 at the Hannover Fair, the German government announced the fourth stage of industrialisation, known today as I40. Subsequently, in 2012, the multinational General Electric defined the creation of the Internet in industry as an integration of the physical and digital world [42]. In parallel, concepts such as “smart manufacturing”, “digital transformation” and “Fourth Industrial Revolution” have been used as synonyms [43].

The concept of I40 is based on the integration of information and communication technologies (ICT) and industrial technologies, mainly composed of the Internet of Things (IoT) and cyber–physical systems [44,45]. In other words, it mainly relies on the creation of a cyber–physical system to realise a digital and smart factory, which creates a highly flexible production model of personalised and digital products and services with real-time interactions between people, products, and devices during the production process [46].

The relationships between the typologies or classifications of technologies encompassed by I40 are currently not entirely clear [18]. Ghobakhloo [10], Tjahjono et al. [46], Awan et al. [47], Saturno [48] and Javaid et al. [49], among others, have made quite similar proposals. Some of the most frequently cited technologies identified are the following: additive manufacturing, advanced human–machine interface, artificial intelligence, industrial robots, big data and analytics, cybersecurity, cloud computing, horizontal and vertical system integration, industrial IoT, sensors, simulation, virtual reality, and augmented reality. In this paper, we have focused on additive manufacturing, artificial intelligence, augmented vision and/or virtual reality, big data, advanced analytics and the Internet of Things. Considering that there is no unanimously accepted classification of I40Ts, we have tried to address a sufficiently representative panel of the technologies that offer us the greatest possibilities of access to quality information of good quantity to achieve reliable, valid, and meaningful results:

- Additive manufacturing (AM): This is based on the 3D printing of plastic, metallic or other materials; 3D printing is called as such because of the process of adding to an object layer by layer [50].
- Artificial intelligence (AI): As indicated by Boden [51], AI technology can be understood as intelligence performed by "intelligent machines" so that they have reasoning

capacity and the ability to develop psychological capabilities. For example, developing perception, associating, announcing, planning and motor control.

- Virtual and augmented reality (VR/AR): This is a set of computer techniques that allow the creation of images, the integration of virtual objects in real space, and the development of interfaces in which the user uses glasses or helmets made by the manufacturer [52]. Some authors share this view and add energy consumption and reducing material resources to the potential capabilities of I40Ts [53].
- Big data and advanced analytics (BD/AA): Large data sets (big data or macro data) that are commonly found in research or business practices should be managed through advanced analytics. In big data, the three dimensions of data management or "3V" (volume, variety and velocity) are defined as variety, velocity and size [54].
- Internet of Things (IoT): This refers to the interaction of objects with the environment and the immediate response to changes [55]. In this way, IoT technology and smart devices help to improve decision-making in usage decisions by providing real-time responses.

2.3. Circular Economy and Industry 4.0

CE strategies must take advantage, among other elements, of the new opportunities being generated by technological development and the technologies of the fourth stage of industrialization [10,11]. I40 not only represents a qualitative leap in technological development but must also go hand in hand with a decoupling of economic growth and natural resource consumption [11].

It is necessary to work on and analyse how I40Ts can be developed for the benefit of sustainable development (Table 1). There is a debate on the long-term impact of I40Ts on environmental sustainability and the CE [56]. Nascimento et al. [24] state the lack of relationship between CE and I40 in the socio-technological context of sustainable manufacturing. Kamble et al. [56] found that the extensive use of sensors and smart equipment could increase energy consumption. In contrast, Stock and Seliger [50] and Lopes de Sousa et al. [1] claim that I40Ts have demonstrated their ability to give way to CE principles. In general, I40Ts and, in particular, AM and BDAA technologies [57–59], have been accepted as a good support for scrapping or reusing materials. AM can be useful to aid the re-manufacturing of products or components [60–62] and to re-filament them [63] by recovering parts with defects, although the additives that may be contained in the filament may limit the recovery [64]. Berman [65], Hermann et al. [66], Müller et al. [67], Yuan et al. [68] and others highlight the potential of I40Ts to reduce energy and material resource consumption. According to some authors, additive manufacturing technology has the capacity to reduce raw materials [69,70] and to reduce energy consumption [71–73]. Other studies claim that BDAA [74,75], IoT [76–80] and VAR [80,81] contribute to the reducing energy consumption. Prause and Atari [82] observed the existence of the influence of additive manufacturing and BDAA technologies on CE, but did not detect the influence of other technologies such as IoT, VR and VAR. Research on the potential of I40Ts to address environmental problems has intensified in recent years; Kamble et al. [56] compiled a systematic literature review of 85 articles on I40 technology and its impact on sustainable development. They stated that only 18% considered the vision related to sustainability and, specifically, I40Ts were analysed for their potential to reduce production waste and energy consumption. A few years later, the situation on this issue has not changed, according to the review conducted by Jamwal et al. [83].

Table 1. Main research on the relationship between EC and I40.

Authors	Year	Ref. No.	Research Gap	Main Contributions
Rosa et al.	2020	[11]	Connection between CE and I40.	It reveals how different I40Ts could support CE strategies and organisations.
Agrawa et al.	2022	[17]	Future research directions at the nexus of CE and sustainable business in the context of digitisation	Digitalisation could be of great help in developing sustainable circular products. Customer involvement is necessary to create innovative sustainable circular products.
Chiarini et al.	2021	[18]	Contribution of each technology to the overall environmental performance of manufacturing companies.	Sensors, radio frequency identification, artificial intelligence and analytics are most relevant to improve environmental performance. Simulation software contributes moderately. Additive manufacturing, cobots, robots, automated mobile robots and automated guided vehicles had a negative effect. Augmented reality had no effect and other technologies indirectly affected environmental performance. Lack of knowledge and scepticism about the application of technologies such as artificial intelligence and augmented reality.
Bonilla et al.	2018	[20]	The effect on the environmental sustainability of physical and virtual infrastructures inherent to I40.	Predominance of positive impacts that can be considered as positive side effects resulting from I40 activities.
Garcia-Muiña et al.	2019	[22]	Ecodesign as a tool to define the balance point between sustainability and circular economy.	Empirical validation of a circular business model as an operational tool to promote the competitiveness of enterprises.
Nascimento et al.	2019	[24]	Integration of emerging I40Ts with CE practices.	Positive influence on improving business sustainability by re-integrating waste into the supply chain. Recommendation of a circular model to reuse discarded electronic devices, integrating web technologies, reverse logistics and AM.
Prieto-Sandoval et al.	2017	[31]	Direct connection of CE with the goal of this paradigm: sustainability.	CE is not a "fad", it is a paradigm of action that has resulted from the evolution of the concept of sustainability and its application in the economy, society, and the necessary care of the environment around us.
Laskurain-Iturbe et al.	2021	[61]	I40 influence on CE.	Environmental impact improvements related to reducing material, energy consumption, waste generation and emissions. Important differences between the potential impacts of each technology.
Uriarte Gallastegi et al.	2020	[64]	Environmental implications of the technologies covered by AM.	Neither companies nor experts confirm an increase in energy consumption highlighted in the literature. Higher material consumption efficiency compared with traditional subtractive technologies. Low level of noise generated by AM. Possibility of integrating AF in environments where medium–high concentration tasks are carried out.

Table 1. *Cont.*

Authors	Year	Ref. No.	Research Gap	Main Contributions
Campbell et al.	2011	[71]	AM geopolitical, economic, social, demographic, environmental, and security implications.	AM manufacturing: • Reduces material waste and scrap; • Limits the amount of energy used; • More efficient use of raw materials; • Minimal harmful (e.g., etching) chemicals needed; • Environmentally friendly product designs possible; • Changes to design streamlined; • Carbon footprint of a given product reduced (via reduced waste and need for global shipping).
Kellens et al.	2017	[72]	Environmental dimensions and impacts related to AM manufacturing processes.	Parts made with AM can be beneficial for very small batches, or in cases where AM-based redesigns offer substantial functional advantages during the use phase of the product.
Rejeski et al.	2018	[73]	Environmental implications of AM.	There is a need for research: • New materials, quantifying the energy impacts of the products of AM; • Better risk assessment and management research related to AM; • Management at the end of life of products produced using AM; • Supply chain footprint of AM; Regulatory implications of bioprinting.
Shrouf et al.	2014	[76]	How IoT will improve energy efficiency.	Approach to adopt the IoT paradigm at production level to support energy management and increase the energy efficiency of production systems in smart factories (I40).
Tao et al.	2016	[77]	IoT applications in product life cycle's energy management.	IoT techniques can accompany the entire product lifecycle for better energy management.
Jamwal et al.	2021	[83]	Future research potential of Industry 4.0 technologies to achieve manufacturing sustainability.	Industry 4.0 has a significant impact on the sustainability of manufacturing at different stages. Very few studies discuss the relationship between sustainability and Industry 4.0 factors for business practices. AI and machine learning approaches are helping industries to achieve sustainability in manufacturing as well as the implementation of Industry 4.0. In blockchain-enabled supply chains, few studies have addressed environmental issues. Big data offers several opportunities for manufacturing industries in terms of production tracking and real-time optimisation.
Tavera Romero et al.	2021	[30]	Challenges and impacts on society and individuals for the transition from a linear to a circular economy.	Few studies address the impacts on individuals and society of a transition to CE supported by I40, and what strategies are available to avoid societal failure.

Table 1. *Cont.*

Authors	Year	Ref. No.	Research Gap	Main Contributions
Awan et al.	2021	[47]	How IoT can be part of managing the circular economy.	IIoT plays a crucial role in value creation, but there are few studies on the requirements of I40 to incorporate the circular economy of the supply chain. The literature has focused on digitisation as an enabler of the circular economy.
Piscitell et al.	2020	[84]	How to I40 can unlock the circularity resources within organisations.	This research topic is still in its early stage of attention and the full potential has not yet been fully explored. The choice to implement the CE model ultimately depends on the field of application of the I40 system.
Bag et al.	2021	[36]	Effect of I40 adoption on advanced manufacturing capabilities and its outcome on sustainable development (10R).	Companies with a high degree of I40 implementation lead to a positive development of 10R advanced manufacturing capabilities. 10R advanced manufacturing capabilities have a positive influence on sustainable development results. The I40 delivery system has a moderating effect on the degree of relationship of I40 adoption and 10R advanced manufacturing capabilities.
Massaro et al.	2021	[21]	How I40 can foster the impact of CE in companies.	Use of smart services in waste management, resource efficiency and collaboration, new business models and the mission of companies.
This research			How EC can benefit from I40Ts. Perspectives of the two main actors (manufacturers and customers).	Benefits are mainly concentrated in the manufacturing, logistics and transport phases. Manufacturers and customers do not consider environmental aspects to be critical variables in their decision-making processes, even though they give them a medium to high importance. Manufacturers and customers point out that the greatest influence exerted by these technologies is on R1 (reducing material consumption). Manufacturers: AM has a high or very high influence on the 5Rs. Customers: AM and VR/AR have a high or very high influence on the 5Rs.

Our research aims to show how CE can benefit from Industry 4.0-related technologies. We have approached the issue from a different and complementary perspective to that seen in the literature so far. Massaro et al. [21] are perhaps the authors closest to us, as they approach the issue from an academic and professional perspective by analysing professional documents, journalistic articles, press releases, specialised blogs and scientific articles from the Nexis Uni and Scopus databases. We have tried to approach this reality from a closer perspective, based on the case methodology, with the two main professional actors as protagonists: manufacturers and customers.

Therefore, based on the literature review and the stated objectives of our research, we pose the following research questions (RQ):

1. What is the actual contribution of each technology in each of the key circularity indicators of the CE model (R1, R2, R3, R4 and R5)?
2. To what extent does each technology directly influence each phase of the product life cycle?
3. How important is resource circularity in the selection process of I40Ts for both manufacturers and risk customers?

3. Materials and Methods

The methodological proposal is fundamentally determined by the nature of the perspective from which we intend to approach the central question of the research and the accessibility and quality of the sources of evidence. What do the manufacturers and their venture clients say about it? What evidence do we have? Is it consistent and sufficient to draw relevant conclusions?

In our case, we wanted to go a step further than Massaro et al. [21], and we have approached manufacturers and their venture clients and the projects they have shared. This level of approach, of access to sources of information, is difficult to obtain. Nevertheless, the small size of the population did not allow us to study it through statistical inference and, therefore, limited the possibilities for an adequate use of traditional quantitative analysis.

However, the case study methodology allows the phenomenon to be analysed in its real context, considering all aspects of the problem, and using multiple sources of evidence—quantitative and/or qualitative—simultaneously [25].

For the present research, we have opted to use multiple case studies to reinforce analytical generalisations with corroborated evidence (literal replication), which is essential to provide internal validity to the research. We are aware that in no case can we speak of statistical generalisation, which is characteristic of a random sample, since the set of cases studied does not represent or attempt to constitute a significant sample from a statistical point of view (see methodological design in Figure 2) [85].

The initial process consisted of a review of the literature. This allowed us to obtain a first approach to the research problem and to pose the central RQs.

Subsequently, to offer an exploratory approach to the phenomenon under investigation, fieldwork began with a survey which, although it did not provide us with the possibility of applying in-depth statistical analyses, did offer us the possibility of approaching the study phenomenon in the first instance. The analysis of the results allowed us to obtain very useful information to decide the unit of analysis (one per technology), as well as design the case protocol and the evidence collection plan in the preparatory phase of the case study. The case studies were also selected at this stage of the research. They were intended to be informative, to answer the research questions and to achieve a minimum representation of all technologies [86].

Thus, the survey was sent to all 134 companies (first four editions) from Europe, America, Asia, and Africa that were selected to participate in a public–private acceleration program specialized for the promotion of Industry 4.0 projects: BIND 4.0, winner of 'Improving the Business Environment' of the European Enterprise Promotion Awards 2020 (EEPA) [87]. These are manufacturers of technological products or services with application in the fields of advanced manufacturing, smart energy, health technology and food technology.

The initial version of the survey was designed in accordance with the objectives pursued. To avoid distortions due to different interpretations of the questions by the participants, all questions were asked using the same structure. A pre-test was developed, and the pilot questionnaire was sent to two academics in the knowledge area, a business consultant and two I40 companies. Responses and comments from the respondents were analysed and contacts were maintained to clarify various issues that helped us to outline the final questionnaire [88]. For the closed responses, a new Likert-type scale was initially established (−4 to +4, with −4 being a very negative influence, 0 no influence, and 4 very positive). The survey also offered participants the option of adding information through open-ended questions, so that new elements could be integrated into the study. A total of 104 responses were obtained, giving a response rate of 77.6%; specifically, 8 companies that develop additive manufacturing (AM) solutions, 28 artificial intelligence (AI) companies, 18 augmented vision and/or virtual reality (VR/AR) companies, 24 big data and/or advanced analytics (BD/AA) companies and 26 Internet of Things (IoT)-based companies responded. In no case were negative influences detected and, therefore, tables in Section 4, 'Results and discussion', show the influences with a scale from very low or none (○) to very high (●●●●).

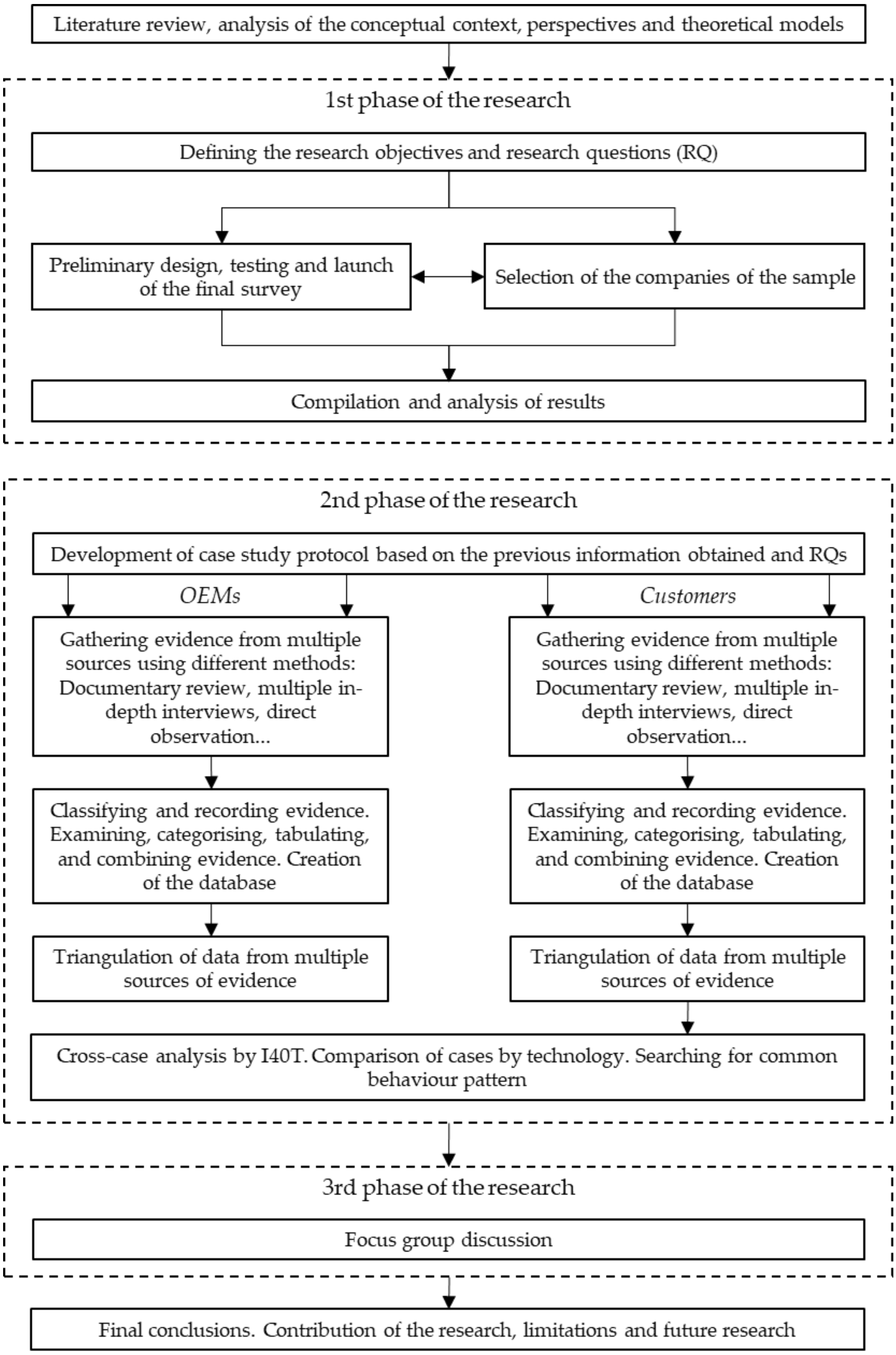

Figure 2. Diagram of the methodological process followed. Source: Compiled by the authors, based on Ivankova et al. [89] and Yu [90].

Subsequently, the second phase started. Nineteen original equipment manufacturing (OEM) projects that participated in different editions of the BIND 4.0 program were analysed: AM (4), BDAA (3), AI (4), AV (2) and IoT (6) (briefly described in Table 2). Semi-structured interviews were conducted with managers (11), managers and technical staff in the areas of design and development (11), environmental management (3) and after-sales service managers (2), and on-site visits were conducted at 11 of these OEMs.

Table 2. List of cases classified by type of technology.

Code—Brief Description	Source of Evidence		
	Interviews [1]	Visits [2]	Docs. [3]
AM1—Printing metal and plastic material for aircraft manufacturer suppliers	M, T, EM	✓	7
AM2—Minimization of biological waste in the food industry through atomic-level applications	T, SM	✓	2
AM3—Special coating using nanotechnology in the manufacture of brake discs	M	✓	3
AM4—Consultancy to implement AM in industrial processes	M	✓	2
AI1—Monitoring the construction of a wind farm using satellite-free images	T		2
AI2—Voice recognition technology for operators to search for or write down procedures	M	✓	2
AI3—Analysis of the data (heating, air conditioning) of the buildings/factories	M	✓	3
AI4—Analysis of camera data to optimize procedures	T		2
AV1—Quality inspection system for plastic film production	M, T	✓	5
AV2—Automation of parts inspection in industrial processes (mainly automotive parts)	M		4
BDAA1—Data processing to optimize the use of industrial machines	M, T	✓	4
BDAA2—Use of information systems to manage and optimize the factory	M	✓	5
BDAA3—Massive data analysis to optimize production machine indicators	T, SM		4
IoT1—Devices for monitoring the supply chain	T, SM		5
IoT2—Monitoring through sensors in the lube oil of the wind turbines	M	✓	4
IoT3—Data capture from industrial machines using sensors	M	✓	3
IoT4—Sensorization of industrial machines to optimize mainly energy consumption	T		2
IoT5—Use of wireless sensors to control the entire value chain (from supplier to customer)	T		3
IoT6—Movement control of workers by sensors to optimize routes and movements	T		3

Notes: [1] Semi-structured interviews with: M—general managers; T—technical staff in the areas of design and development; EM—environmental managers; SM—after-sales service managers. [2] (✓) On-site visits; [3] Documentation with significant evidence.

In addition, to gain customer insights, venture clients collaborating with the BIND programme were contacted. Considering the list of venture clients with which the selected manufacturers had collaborated, we wanted to contact those that also had a minimum of two years' experience working with I40T projects (see Table 3). In total, we had access to nine venture clients that had collaborated on one or two projects with one or more manufacturers. As with the manufacturing companies, on-site visits were carried out (5), and in-depth interviews were held with managers (9), managers and technical staff in the areas of design and development (6) and environmental management (2).

Table 3. List of customers sorted by type of I40 technology used.

Code—Brief Description	Source of Evidence		
	Interviews [1]	Visits [2]	Docs. [3]
AM1—Private foundation for the creation and promotion of connections between people, companies, and initiatives in the context of the use of ICT.	M, T, EM	✓	5
AM2—VR/AR Studio.	M, T	✓	2
AM3—Creation, design, and printing of 3D parts.	M, EM	✓	3
AM4—Goldsmiths and jewellery designers.	T	✓	2
BDAA1—Big Data Research Lab.	M, T	✓	4
BDAA2—Solutions for Internet TV, from the generation and administration of metadata to the complete management of video, interfaces, or user apps.	M		4
AI1—Solutions for Internet TV, from the generation and administration of metadata to the complete management of video, interfaces, or user apps.	M		3
AV1—Public company to boost economic activity related to the application of cybersecurity and strengthen the professional sector.	M		3
AV2—Design of immersive experiences in virtual environments.	M		2
IoT1—Solutions for Internet TV, from the generation and administration of metadata to the complete management of video, interfaces or user apps.	M, T		4
IoT2—Cybersecurity services covering identification, protection, detection, response, and recovery.	T		3

Notes: [1] Semi-structured interviews with: M—general managers; T—technical staff in the areas of: purchasing, engineering, production, or others; EM—environmental management. [2] (✓) On-site visits. [3] Documentation with significant evidence.

Following Yin [25], data were collected through passive and active observation (methodological triangulation), and documents such as project memories or technical reports were collected for analysis (data triangulation) (see Table 3). Data collection was stopped when no new themes emerged that would add to the existing results, in accordance with the principle of data saturation [91].

Once the characterization of the investigated cases was completed, individual and cross-case analysis was conducted by technology, following the guidelines developed by Miles et al. [92]. Specifically, each piece of evidence collected was examined, categorized, and tabulated, trying to determine the connection between the data and identify common patterns between cases.

Finally, a focus group discussion was created with the aim of obtaining a reliable group opinion that would reduce the degree of subjectivity in the assessment of the conclusions of the analysis of the results. Denzin and Lincoln [93] pointed out that when a finding begins to take shape, the researcher can contrast it with new informants, and they can act as judges in the evaluation of the main results of a study. Therefore, if each expert or evaluator interprets the information provided in the same way, then it is possible to speak of constructive validity [94] (see summary of measures taken to ensure validity and reliability of research in Appendix A Table A1). Furthermore, as Thurmond [95] points out, methodological triangulation allows researchers to deepen their understanding of the issues and maximize their confidence in the results of qualitative studies. The group consisted of seven members: participants from the previous stages of the research (3) and new ones (4): from academia (1), a technology centre (1), consultancy (1) and the public body (1) who were shown the results of the second phase. We wanted to have feedback from participants from previous phases and new ones to obtain different perspectives. According to O. Nyumba et al. [96], it is necessary to have participants from different disciplines, although the participation of experts from the same area of knowledge, but from different fields, is also beneficial, as is currently the case.

The results of the cross-case analysis are summarised in tables in Section 4, 'Results and discussion'. In Section 4.1, the impact of various technologies on each R concerning the circularity of materials, is assessed with details of the key source of evidence (in-depth interviews (I), documentation (D) and site visits (V)) and, in brackets, the cases from which these sources were obtained. Section 4.2 shows the phase of the product life cycle mainly affected by each technology.

Afterwards, Section 4.3 shows the relevance of circularity both for the manufacturer, in the development of the product, and for the customer in the choice of.

The tables have been drawn up considering the results of the analysis of the common patterns of the data obtained in the field phase (interviews, available documentation, external communications and visits) and show those that have aroused the consensus of the panel of experts.

4. Results and Discussion

4.1. Environmental Influence of I40Ts on 5Rs

In relation to the AM, it should be noted that the sample includes manufacturers and customers working with different sub-technologies oriented to the plastic and metal products sectors. However, this fact does not influence the high degree of agreement in valuing the contribution as highly positive. The manufacturers consider the effect on the 5Rs to be quite important and positive [64,73,76]. This perspective is shared by the client companies who consider that the circularity of materials is very high, reducing waste as much as possible, thanks to a greater reuse, recovery, and recycling of materials (see Table 4).

AI manufacturers and customers consider this technology to have a low-to-medium influence on the 5Rs, although other research has found it to be of greater relevance [97]. Manufacturers consider that its greatest contribution is that it allows a better dosing of material consumption. On the other hand, customers explain this fact by adding that, thanks to AI, they can reuse surplus materials. Customers agree that this technology has multiple applications and, therefore, the contributions on each indicator may vary depending on the processes, as the literature notes [98]. Specifically, a technical user of this technology pointed out that machines are capable of reasoning and psychological skills such as perception, association, prediction, planning and motor control, and thus can solve problems. This fact drives the standardization of processes and the development of environmental commitments based on the ability that comes from experience working with AI technologies.

On the other hand, the VR/AR manufacturers consider that the contribution of this technology is null or low, as reported in other studies [18], contrary to the customers who gave it a high and very high valuation. This difference in results may be due to the different fields of application of this technology. “If we take VR glasses as an example, we have that the glasses are produced by the manufacturer, and it is the customer who immerses the user in a synthetic world and manages to increase the sense of reality, without generating waste”, said one of the producers. In addition, as one of the customers confirmed, “VR/AR technology does not generate waste, as it does not require consumables, nor does it produce waste”.

Table 4. Influence of I40Ts on the environmental indicators of the CE model.

Technology	Stakeholder		Circularity of Materials [1,2] R1	R2	R3	R4	R5	Strategies	Main findings
AM	M[3]	Impact [3]	●●◕	●●◑	●●◕	●●●	●●◑	▪ Use recoverable (powder) or recyclable materials. ▪ Exploit the ability to create complex geometries of seamless objects, with more robust designs to cope with stresses.	▪ Reducing the weight of the parts by up to 50% in some cases. ▪ No wastage of material in the manufacturing process. ▪ Only the necessary material is used, and the rest is reusable in the process. ▪ It is possible to create products that can better withstand wear or high temperatures by increasing their life cycle.
		Source of evidence [4]	I, D, V (1,2,4)	I, D (1,2,4)	I, D (1,2,3,4)	I, D (1,2,4)	I, D, V (3,4)		
	C	Impact	●●●◑	●●●◑	●●●◑	●●●◑	●●●◑		▪ Reduction in the weight of the parts with appreciable effects. ▪ Only the necessary material is used, and the rest is reusable in the process. ▪ Less waste is generated.
		Source of evidence	I, D, V (1,2,3,4)	I, D (1,3)	I, D (1,3)	I, D (1,3)	I, D, V (1,3,4)		
AI	M	Impact	●●◔	●◕	●◑	●◔	●	▪ Drive digitisation. ▪ Modernising closed-loop supply chains in technological supply networks and controlling carbon and energy consumption.	▪ 100% reduction in paper usage. ▪ Savings of up to 50% in energy costs.
		Source of evidence	I, D, V (1,3,4)	I, D (1,3,4)	I (1,2,3,4)	I (1,3,4)	I, D (2)		
	C	Impact	●◑	●●	●	●◑	●		▪ There is no environmental impact as such, but a non-direct impact. ▪ Machine learning applied in systems to maximise energy efficiency and reduce carbon footprint.
		Source of evidence	I, D (1)	I (1)	I (1)	I (1)	I, D (1)		
AV	M	Impact	●●◕	●◔	●	◑	◑	▪ Optimising quality procedures and inspections. ▪ Improving re-manufacturing and logistics processes.	▪ Reduces the energy consumption of the industrial plant by avoiding the unnecessary use of energy to manufacture unneeded parts. ▪ Automating the quality inspection process helps to reduce the rework process. ▪ Digitise and automate tasks with more accuracy and less waste of misused material and energy consumption.
		Source of evidence	I, D (1,2)	I (1)	I (2)	I (1)	I, D (2)		
	C	Impact	●●●●	●●●●	●●●●	●●●◑	●●●◑		
		Source of evidence	I, D, V (1,2)	I (1,2)	I (1,2)	I (1,2)	I, D, V (1,2)		

Table 4. *Cont.*

Technology	Stakeholder		Circularity of Materials [1,2] R1	R2	R3	R4	R5	Strategies	Main findings
BD/AA	M	Impact	●●◔	●◕	●◔	●◔	●	▪ Increasing the efficiency of equipment and machinery use (predictive maintenance). ▪ Analysis of technologies for the adaptation of I40 in manufacturing companies. ▪ Control of management parameters.	▪ Avoid unnecessary use to manufacture unnecessary parts by improving machine utilisation from 50% of capacity to 80–100%. ▪ Application of algorithms in public lighting with energy savings of 20% to 32% and extension of the life of mercury lamps. ▪ Obtaining and exploiting information in real time to optimise the use of resources and raw materials. ▪ Nearly 100% paper savings due to digitisation.
		Source of evidence	I, D (1,2.3)	I, D (1,2)	I (1,2)	I (1,2)	I (1,2)		
	C	Impact	●●●●	●●●	●●	●●	●●		
		Source of evidence	I, D (1,2)	I, D (1)	I (1)	I (1)	I, D (1)		
			R1	**R2**	**R3**	**R4**	**R5**		
IoT	M	Impact	●◕	●◔	●	●	●◔	▪ Perfecting smart, collaborative and cooperative manufacturing. ▪ Creation of sustainable industrial value.	▪ Ecosystem of applications to improve the efficiency of production processes. ▪ Reuse cold chain control devices, about 30 times less e-waste. ▪ Reduction in waste in some applications such as diesel engine oil. ▪ Processing of machine data to provide information towards responsible consumption. ▪ Efficient management of transport systems, including maintenance of equipment and extending its life span. ▪ Extension of machine life cycle.
		Source of evidence	I, D, V (2,3)	I, D (1,5)	I (1,5)	I (1,5)	I, D, V (3,5)		
	C	Impact	●●●●	●●●◑	●●●	●●	●◑		
		Source of evidence	I, D (1,2)	I, V (1)	I (1)	I (1)	I, D (1,2)		

Notes: [1] The assessment provided summarise each aspect's rating in terms of influence level as a five-point Likert-type item, from very low or none (○) to low (●), medium (●●), high (●●●) and very high (●●●●); [2] R1—reduce materials; R2—reuse; R3—recycle; R4—recover; R5—minimise waste. [3] Impact-level assessment of the technology on each R of the circularity of materials. M—manufacturer; C—customer. [4] Source of significant evidence: I—in-depth interviews; D—documentation; V—on-site visits. The number of the source case of each technology for manufacturers and customers is shown in brackets.

With respect to the results of the BD/AA technology, the assessments of the 24 manufacturers place the influence of this technology on the 5Rs as low or medium, in contrast to the customers, who rate the level of influence as medium or very high, as noted by Bai et al. [97] and Chiarini [18], among others. Once again, it should be noted that the different uses of technology may be the reason for these disparate results. In the interviews held with clients, they highlighted that "big data", data intelligence or BD/AA form a set of technologies that will bring about a revolution analogous to the expansion of the Internet. In fact, one of the clients interviewed said that, in his opinion, BD/AA will change the way we think about business, health, politics, education and innovation in the coming years, in line with Jamwal et al. [83]. One of the customers gave, as an example, the case of the control and monitoring system of a bus line of a big city, which ostensibly improved the efficiency and effectiveness of the service. Through this technology, we could collect data from the bus line, in terms of the frequency of use of citizenship (users/day) and the required number of buses on the line. Subsequently, it was possible to reduce the demand for buses and optimize the service, increasing the number of users and their satisfaction. As stated in the report provided by the company, the combination of both technologies (BD/AA) contributed to a reduction in material and energy consumption (R1) and a reduction in waste generation and emissions (R5).

The last technology that has been analysed in the research is the IoT. The influence rating given by manufacturers to this technology is low. Among the results, the average of the ratings of the 26 manufacturers is between 1.25 and 1.75. However, customers explain that IoT technology and the use of smart devices helps improve decision-making and enables real-time responses, as Javaid et al. [53] point out. This contributes to a more positive assessment of the contribution of the 5Rs, considering that it has a very high influence on reducing consumption (R1) and the reuse of materials (R2). Specifically, one customer highlighted that "sensors deployed in a network with micro-services allow materials to be reused for various operation and maintenance tasks, saving costs and reducing the consumption of energy and materials". In the literature, in relation to the environment, reducing energy consumption is one of the most recurrent contributions of IoT [53,98,99].

4.2. Influence of I40Ts on Each Life Cycle Phase

In this section, it has been assessed whether there is an influence of each technology on each indicator of the CE model by phase of the product life cycle (1, procurement of materials; 2, manufacturing; 3, logistics and transport; 4, use and maintenance; and 5, end of life). We have found no references in the literature that specifically address this issue.

The unit and direct influence focuses on the study, phase by phase, of the increase or decrease in the circularity per functional unit of output of each phase. This implies that the effects of other phases are not considered, such as the influence derived from the optimisation of the use of material in the manufacturing phase and its effect on the need for a smaller amount of material in the material procurement phase.

Table 5 summarises the results obtained from the surveys and subsequent interviews held with the manufacturers and customers of the different technologies (phases I and II of the research process). The manufacturers and customers do not observe any direct influence of the technologies in the phase of obtaining materials and components. Although, in all cases, they recognize an indirect influence by the reduction in material needs, mainly in the manufacturing and logistics and transport phase, apart from BD/AA and IoT customers. There is agreement among the manufacturers that the positive influences are concentrated in phase 2 of manufacturing and phase 3 of logistics and transport. The manufacturers of AM technology consider this a high positive influence. They also point out that AM enables flexible, low-noise, short-run production and can even be integrated into environments with medium-to-high concentration tasks. This reduces transport requirements and facilitates logistics. Customers agree that the influence is positive in the manufacturing phase, except for the case of IoT technology. However, customers only share the manufacturers' perspective on AI, VR/AR and IoT technologies.

Table 5. Influence of I40Ts in each life cycle phase of the CE model.

Technology	Stakeholder		Affected Life Cycle Phase [1]	Strategies	Main Findings
AM	M[2]		❶❷❸❹⑤	▪ Reduction in waste and emissions. ▪ Reduction in material consumption.	▪ Possible to create products that can better withstand wear or high temperatures by increasing their life cycle. ▪ The required parts can be printed together with the process that requires it, reducing the need for transport and intermediate stocks. ▪ There are parts that are viable while in others there are still other more efficient manufacturing processes. Less waste is generated (including biological in some applications). Reduction in CO2 emissions from aircraft (engine components in aviation).
		Source of evidence[3]	I, D (1,2,3,4)		
	C[2]		①❷❸④⑤		
		Source of evidence	I, D, V (1,3,4)		
AI	M		①❷❸④⑤	▪ Optimise transport and logistics using autonomous machines. ▪ Increase the useful life of machinery (predictive maintenance).	▪ Decrease the impact on biodiversity by avoiding sending people, helicopters or drones into the area needed. ▪ Not having to look for the tokens/sheets reduces the time of the operations (between 7 and 15%) of the machines so the energy consumption is also reduced. ▪ Intelligent monitoring and management systems measure the levels of CO2, NO2 and VOCs in inhabited environments and proactively adjust maintain optimum levels, reducing the carbon footprint (emissions).
		Source of evidence	I, D (1,2,3,4)		
	C		①❷❸❹⑤		
		Source of evidence	I, D (1)		
AV	M		①❷❸④⑤	▪ Develop waste collection and treatment techniques. ▪ Reduce emissions and discharges.	▪ Applications in quality control processes help to reduce failure rates and reprocessing needs. ▪ The use of the RV/RA does not generate waste. ▪ Decreased energy consumption of machines (usually due to misuse), although not significantly.
		Source of evidence	I, D (1,2)		
	C		①❷❸❹❺		
		Source of evidence	I, D, V (1,2)		
BD/AA	M		①❷❸❹⑤	▪ Provide decision support and improve industrial symbiosis practices. ▪ Strengthen the flexibility of manufacturing resources to increase productivity.	▪ By calculating the mobility of the population in San Sebastian (Spain), it has been possible to optimise the use of services. For example, the bus service: fewer buses, less polluting emissions (CO2 and others) and less energy consumption. ▪ Energy savings of 20% or 32% in public lighting through smart-city management algorithms. ▪ In assembly lines, the aim is to reduce errors or improve efficiency. For example, in car assembly lines.
		Source of evidence	I, D (1,2,3)		
	C		①❷③④⑤		
		Source of evidence	I, D (1,2)		
IoT	M		①❷❸❹⑤	▪ Directly affect the safety of the production process and thus reduce material and energy costs. ▪ Promote automatic learning.	▪ Lube oil sensor monitoring to extend machine oil life and machine life. Reducing waste (oil) and extending the life cycle of machines. ▪ Exploitation of machine data to provide information of inverters and meters in connected machines. Optimisation of energy consumption by up to 30% in wind turbines.
		Source of evidence	I, D, V (1,5)		
	C		①②❸❹⑤		
		Source of evidence	I, D, V (1,2)		

Notes: [1] Lifecycle phases: procurement of materials (1), manufacturing (2), logistics and transport (3), use and maintenance (4) and end of life (5); ①②③④⑤ does not directly influence any phase of the life cycle; ❶❷❸❹❺ directly influences the phases coloured of the life cycle. Example: ①②❸④❺ directly influences the phases coloured of the life cycle, 3 and 5. [2] M—manufacturer; C—customer. [3] Source of significant evidence: I—in-depth interviews; D—documentation; V—on-site visits. The number of source cases of each technology for manufacturers and customers is in brackets.

Finally, in relation to the last two phases, use and end-of-life, there is agreement among manufacturers that there is no direct influence. However, customers consider that AI, VR/AR and IoT technologies have a direct and unitary influence on the use and maintenance phase and, in the case of VR/AR, also on the end-of-life phase. In any case, customers consider that this influence is not very relevant.

4.3. Importance of Resource Circularity in the Process of Technology Selection

Manufacturers consider resource circularity to be of medium importance in the selection of MA, BG/AA and IoT technologies, and slightly higher in the selection of AI and VR/AR (medium–high) (see Table 6).

Table 6. Importance of resource circularity in the process of technology selection by manufacturer and customer.

Technology	Stakeholder	Importance of the Environment in Decision-Making [1]	Strategies	Main Findings
MA	M [2]	●●●	▪ R&D, 2D and 3D simulations to improve process cycle time, ergonomic design and consumption. ▪ Making agreements to increase material recycling.	▪ Optimisation of material consumption and machine energy consumption. Development of more environmentally sustainable materials, such as PLA, or recoverable materials such as metal powder in laser metal deposition technology.
	C [2]	●●●●	▪ Ensure that products and materials are kept for as long as possible.	▪ Recoverable and recyclable material is used as much as possible, such as PLA left over from the farms, through a specialised company. ▪ The parts are analysed to reduce material consumption and surplus.
IA	M	●●●◐	▪ Integrating smart machinery. Automated production and production technologies that support design for circularity and interactive platforms for enhanced connectivity. ▪ Optimise production times and real-time problem solving.	▪ Although the environmental impact is indirect, it should be considered because the possibility of sabotaging the AI (accidentally or intentionally), for example, may result in occasional accidents with, among others, environmental implications.
	C	— [3]	▪ Create sustainable industrial value in social dimensions and economic sustainability.	—

Table 6. *Cont.*

Technology	Stakeholder	Importance of the Environment in Decision-Making [1]	Strategies	Main Findings
VA/RV	M	—	▪ Create value for the customer: shorter delivery time and higher product availability.	—
	C	●●●●	—	▪ The use of the RV/RA does not generate waste.
BG/AA	M	●●	▪ Execute analytical tools and analyse information objectively to optimise raw materials, lighting in the industrial plant and water management.	▪ The growth in storage capacities, analytical tools and data processing has been exponential in recent years, but the environmental impact has not been measured.
	C	●●●●	▪ Perform predictive analysis of material, energy, and machine usage needs.	▪ In 80% of the cases the environment is taken into account in the realisation of projects, e.g., in the development and management of public services in cities.
IoT	M	●●●	▪ Reducing energy and recovering, reusing or recycling material.	▪ Development of sensor systems deployed in a network with micro-services allows the reuse of operation and maintenance: saving costs and consumption of energy and materials.
	C	●●	▪ Analysis and reduction in spoiled products.	▪ Search for connected solutions to reduce the environmental impact in wind turbine operation.

Notes: [1] The assessment provided summarises each aspect's rating in terms of influence level as a five-point Likert-type item, from very low or none (○) to low (●), medium (●●), high (●●●) and very high (●●●●). [2] M—manufacturer; C—customer. [3] Not enough and/or well-founded evidence.

Customers consider that a higher importance is given to the selection process. This is to some extent in line with research findings in the literature [99–101], but these studies do not address the issue by technology, and usually consider a set of technologies with exceptions, such as the work of Tang et al. [102], which focuses on the blockchain technology.

Customers considered the circularity of resources to be of high importance in the selection process. However, both manufacturers and customers consider that costs, compliance with certain quality specifications and compliance with safety aspects are of greater importance. In this respect, it is noteworthy that, among customers, the importance of circularity was linked to costs. Specifically, on numerous occasions and for all the technologies, the clients highlighted that, with the aim of reducing costs, they implemented measures to change processes to obtain a better use of material and energy resources; that is, without having a great awareness, they established some procedures to measure and improve the circularity of the materials.

5. Conclusions

In recent years, we have witnessed a fourth technological revolution, in a context marked by the need for a change of economic model that will allow us to safeguard the development of future generations. This technological expansion has important environmental consequences, as it is accompanied by an increase in the consumption of products and services to which a growing population has access. However, it is not yet sufficiently known how I40Ts relate to CE, and what potential contribution I40 has on CE in the long term.

This research has analysed the problem from the perspectives of the manufacturers of technologies belonging to the I40 and their venture clients in relation to the essential indicators of CE, a perspective not addressed thus far. I40 technology manufacturers and venture clients share the opinion that:

1. I40 technologies have a positive impact on sustainability and CE indicators.
2. Its greater precision, speed of information, greater flexibility and greater energy efficiency mainly reduce consumption.
3. In general, the 5Rs are considered to be appropriate variables. However, they must be adapted to each case, and their measurement is complicated because the necessary information and resources are not available in the companies. This is because they are not normally considered a priority.
4. The environmental benefit offered by I40Ts depends on their use and the type of technology.
5. Benefits are mainly concentrated in the manufacturing, logistics and transport phases and, to a lesser extent, in the use, maintenance and end-of-life phases.
6. AM seems to be the technology with the greatest potential to influence the 5Rs of the CE, exerting a medium-to-high influence on all of them.
7. The greatest influence exerted by these technologies is on R1 (reducing materials consumption).
8. They do not consider environmental aspects to be critical variables in their decision-making processes.

From the technology manufacturers' perspective:

1. CE benefits are limited to the importance given by the customers to other critical variables such as cost, safety and quality.
2. CE benefits do not contribute to improving market penetration.
3. A decisive boost from public administrations to enforce compliance with requirements related to the circular economy would be a key factor to foster market penetration.

From the venture clients' perspective:

1. Customers share the opinion that AM is the technology that most influences the 5Rs, but they also highlight the influence of VR/AR. In their opinion, both technologies have a high or very high influence on the 5Rs.
2. They consider R1 an essential variable, since the reduction in consumption serves them, in turn, to improve critical variables in their market positioning, as well as reducing costs.
3. Environmental benefits cannot compromise the requirements of their products in relation to quality, safety or cost.

Among the limitations of this research, it is worth mentioning that we have not been able to measure more precisely the degree of influence of each technology on the environment. This is because, on the one hand, we would need a larger sample of companies (very difficult to increase the number of cases given the difficulties in accessing information from companies and their customers at the same time). On the other hand, we would have to concentrate the sample on very specific sectors, as the degree of potential environmental improvement varies greatly at the sectoral level. Additionally, with a significantly larger sample of companies, we could combine qualitative and quantitative methods so that it is possible to generate a set of hypotheses from the application of qualitative instruments and then test them quantitatively [84].

These limitations are the basis for future lines of research, which should focus on more specific sectoral analyses and extend to companies with different characteristics. We should also add a new research question to be answered, arising from the second phase of the research: are there synergies or combinations of technologies that improve the environmental performance of the product? A complex question, perhaps, that poses a challenge of possible interest to academics, businesses, and policy makers.

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Appendix A

Table A1. Measures adopted to ensure the validity and reliability of the case study.

	Reliability
Design	▪ Develop case study protocols based on the literature. ▪ Refinement of the case study protocol by conducting several pilot studies, test the form of questioning and its structure [25,85,103].
Case selection	▪ Selection based on theoretical sampling [25].
Data collection	▪ Provide the script to all interviewees prior to the interview. ▪ Develop a case study database (with all available documents: interview transcripts, archival data, etc.) [104].
Data analysis	▪ Third-party review of the processes followed in the research to see if they are in order, understandable and well documented, and if there are sufficient mechanisms in place to avoid bias [104].

Table A1. *Cont.*

Reliability	
Internal validity	
Design	▪ Establishing the theoretical framework prior to data analysis [25,85].
Case selection	▪ Sampling criteria in the case study protocol [25].
Data collection	▪ Records of factors that could serve as alternative explanations [92].
Data analysis	▪ Pattern matching (matching patterns identified in other authors' work) [25,92]. ▪ Use of triangulation techniques: multiple sources of evidence and data collection methods applied (different lenses and theoretical bodies of literature used as a framework for the research, or as a means of interpreting the results) [104].
Construct validity	
Design	▪ The use of multiple sources of evidence in the data collection phase, such as interviews, documents, or artifacts for protection against researcher bias [105,106].
Case selection	N/A
Data collection	▪ Peer review of transcripts and drafts [107].
Data analysis	▪ Establishment of a chain of evidence (use of verbatim transcripts of interviews and notes of observations made in companies that allow cross-checking of data from sources of evidence) [108] ▪ Review of the draft case study report. Let key informants and other supporting researchers or other researchers with ad hoc involvement in the research review the parts of the data analysis and draft report describing the results, and if necessary, change those aspects that are unclear [25].
External validity	
Design	▪ Justification for the selection of case studies (explanation of why this case study is appropriate in view of the research problem). ▪ Definition of the scope and limits in the research design phase, allowing reasonable analytical generalizations rather than statistical generalizations [109].
Case selection	▪ Description of business cases and contextual factors of the case study [25].
Data collection	N/A
Data analysis	N/A

Source: Adapted from Yin [25], Gibbert et al. [94], Riege [110], and Blome and Schoenherr [111].

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