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Review

Information and Communication Technology Solutions for the Circular Economy

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Abstract: The concept of circular economy (CE) is becoming progressively popular with academia, industry, and policymakers, as a potential path towards a more sustainable economic system. Information and communication technology (ICT) systems have influenced every aspect of modern life and the CE is no exception. Cutting-edge technologies, such as big data, cloud computing, cyber-physical systems, internet of things, virtual and augmented reality, and blockchain, can play an integral role in the embracing of CE concepts and the rollout of CE programs by governments, organizations, and society as a whole. The current paper conducts an extensive academic literature review on prominent ICT solutions paving the way towards a CE. For the categorization of the solutions, a novel two-fold approach is introduced, focusing on both the technological aspect of the solutions (e.g., communications, computing, data analysis, etc.), and the main CE concept(s) employed (i.e., reduce, reuse, recycle and restore) that each solution is the most relevant to. The role of each solution in the transition to CE is highlighted. Results suggest that ICT solutions related to data collection and data analysis, and in particular to the internet of things, blockchain, digital platforms, artificial intelligence algorithms, and software tools, are amongst the most popular solutions proposed by academic researchers. Results also suggest that greater emphasis is placed on the "reduce" component of the CE, although ICT solutions for the other "R" components, as well as holistic ICT-based solutions, do exist as well. Specific important challenges impeding the adoption of ICT solutions for the CE are also identified and reviewed, with consumer and business attitude, economic costs, possible environmental impacts, lack of education around the CE, and lack of familiarization with modern technologies being found among the most prominent ones.

Keywords: ICT; circular economy; IoT; big data; blockchain; artificial intelligence

1. Introduction

Today's dominant "take, make and dispose" economic development model poses significant threats to the sustainability of the economies and of the natural ecosystems, which are of vital importance for humanity as a whole [1]. Circular economy (CE) comes as an alternative to the linear economy model [2,3] based on:

1. Smarter product manufacturing, efficient use of energy, materials, and resources, eliminating waste and pollution, and minimizing the use of virgin and non-renewable resources.
2. Keeping products and their parts at their highest value for a longer time, providing them with as many "lives" as possible, and optimizing their use not only during their first lifecycle, but during subsequent lifecycles as well.
3. Useful application of materials which are considered as waste, by regenerating natural resources and restoring finite materials to be used again.

Several authors summarize the main ideas of CE in various so-called "R" frameworks. 3R, 4R, 6R, or even 9R, are some of the most popular frameworks revolving around the CE [4]. CE principles 1, 2, and 3, mentioned above, are directly related to the "reduce", "reuse", and "recycle" concepts of the 3R framework respectively. All three concepts are interconnected. For example, reusing a product or converting a product's components into useful materials through recycling also leads to the reduced use of virgin materials.

The 4R approach uses "recover" as the fourth "R" to stress the importance of the recovery of the energy embedded in waste (e.g., through incineration). The 6R framework complements the 4R approach with the "redesign" and "remanufacture" concepts. "Redesign" refers to next-generation products, designed to use materials, components or resources recovered from the prior product lifecycle. "Remanufacture" includes new processing of used products in order to, fully or for the most part, restore them to their original state, by reusing as many parts as possible without a negative impact on their functionality [5].

Lastly, the 9R model complements the 4R framework with the concepts of "rethink" (maximizing how much a product is used, through sharing), "repair" (maintaining and repairing defective products, so that they serve their original purpose), "refurbish" (restore an old product and bring it up to date), "remanufacture" (same as in the 6R model), and "repurpose" (utilizing a discarded product or its parts in a product that has a different purpose or type of use).

All of the frameworks share a hierarchy, with their first "R" function (e.g., "reduce" in the 4R framework) being prioritized over the second "R" (e.g., "reuse" in the 4R framework), the second one over the third one, and so forth [6]. Close cooperation within and among different sectors of the society, encompassing governments, academics, non-governmental organizations, businesses and the general public, is of vital importance for supporting and implementing the concepts of each framework [2]. Other approaches for CE also exist, such as the popular "Regenerate, Share, Optimize, Loop, Virtualize, and Exchange" (ReSOLVE) Model [7]. However, further analysis of such approaches falls out of the scope of the present study.

In this paper, we considered the 4R Framework, which is in line with the core of the Waste Framework Directive 2008/98/EC [8], as the most suitable for the investigation and classification of information and communication (ICT) solutions that are designed to act as enablers for the CE. According to the definition used by UNESCO, the term ICT refers to various technological elements and solutions, which are used for the creation, transmission, storage, sharing and exchange of information [9]. Some examples of the technologies encompassed by the term are: computers, smartphones, internet, emails, telephony, satellite communications, broadcasting solutions, storage devices, software, robotics, etc. [10].

The current literature review has three main objectives. The first and foremost is to investigate whether ICT solutions of various kinds can play a role in the transition to CE models. The second encompasses identifying potential challenges and barriers faced while using ICT elements for the aforementioned transition. By creating a novel categorization of the solutions, the third objective of this paper is to suggest a new line for research works, which integrates ICT solutions from various technological sectors with different CE concepts.

The remainder of this paper is structured as follows: Section 2 presents all the solutions reviewed in the context of this paper. These solutions are classified into categories and organized in seven subsections. Section 3 revolves around the main challenges faced when adopting ICT solutions for the CE. In Section 4, we analyze the results of this literature review and draw conclusions.

2. Information and Communication Technology Solutions for the Circular Economy

To carry out this literature review, we searched for scientific publications (academic articles) utilizing the SCOPUS database and Google Scholar web search engine, for the most part. We reviewed 104 papers and analyzed 63 different ICT solutions. 41 papers were excluded due to their similarities with other papers that were analyzed or due to their unclear correlation with the purposes of CE.

In certain cases, we utilized a snowballing process for our review, where suitable academic articles referenced by other authors were also reviewed. We classified our results into seven different categories: (1) Communications, (2) Computing Technologies, (3) Cyber-Physical Systems, (4) Data Analysis and Artificial Intelligence Algorithms, (5) Data Collection and IoT, (6) Data Management and Storage, and (7) Software and Simulation Technologies. It is possible for some solutions to fall under multiple categories. The reader may also refer to Section 2.8, which summarizes all classifications.

2.1. Communication Technologies

The use of most, if not all, ICT solutions towards a CE would be impossible without a proper telecommunication infrastructure. Furthermore, more energy-efficient communications can lead to important resource savings. This is demonstrated in the solutions presented below in the form of novel communication protocols (e.g., link-layer or routing protocols) or techniques (e.g., cognitive radio, software-defined networking, virtualization, etc.) that are more eco-friendly and energy-efficient and, thus, more suitable for serving a circular model of economy.

Cellular mobile technologies all the way from 2nd Generation (2G) up to the current 5th Generation (5G) are being utilized as key building blocks for CE applications. Gutierrez et al. analyze a holistic solution for the integration of the discharges of small food companies into the urban sanitation system, leading to a reduction of water pollution as well as to a better quality of river and marine waters. The proposed solution makes use of the General Packet Radio Service (GPRS) network infrastructure as well as of Supervisory Control and Data Acquisition (SCADA) and Simulation Technologies [11]. Mishra et al. examine energy harvesting techniques in 5G mobile technologies. Such techniques offer controlled energy replenishment and subsequent energy and resources saving. They also assist in satisfying the Quality of Service (QoS) requirements of machine-to-machine (M2M) communications [12].

In order to strengthen their potential as CE enablers, communication technologies evolve to reduce their own environmental footprint, taking advantage of novel techniques such as virtualization, adaptive transmission, or caches. Hatzivasilis et al. propose a novel industrial internet of things (IIoT) protocol. This protocol was evaluated on a wind park's 5G industrial network, which utilized Software-Defined Networking (SDN) and Network Function Virtualization (NFV) technologies. The proposed solution was found to be substantially faster and more efficient, as compared to the existing standardized solutions [13]. The use of Adaptive Link Rate (ALR) technology is investigated by Gunaratne et al. as a way of achieving energy savings in the operation of an Ethernet link [14]. Cache-based networks coupled with SDN features represent a promising solution, offering higher data rates and energy efficiency, in comparison to the Long-Term Evolution (LTE) network [15].

Other advanced communication techniques and networking concepts, such as cognitive radio and peer-to-peer (P2P) communication, also serve well the advancement towards CE models. Cognitive radio is a type of wireless access programmed and configured dynamically, aiming at providing reliable communication whenever and wherever needed, as well as at efficiently utilizing the radio spectrum [16]. Grace et al. analyze the role that cognitive radio could play in more power-efficient and generally "greener" communications [17]. Orsini et al. describe a case study, in which a P2P energy market, backed by Blockchain technology, is driving the growth of community microgrids, which present benefits in terms of resilience, robustness and renewable energy utilization, compared to the traditional utility grid infrastructure [18].

Novel communication protocols and signal processing techniques are also being researched to relieve power consumption needs and facilitate the transition to CE models. Lu et al. describe how the design of algorithms and the exploitation of distributed computing can be leveraged to achieve more efficient communication protocols (such as routing protocols), leading to greater energy efficiency in the M2M communications domain [19]. Wang et al. analyze the Time-Reversal Wireless Signal Transmission technology and stress its contribution to the reduction of power consumption and interference alleviation [20].

2.2. Computing Technologies

Different types of computing, such as cloud computing, edge computing, and distributed computing, can have a catalytic role in the path towards a CE, as presented below.

Cloud computing represents a model for enabling easy access to a shared pool of configurable computing resources that can be managed dynamically [21]. Kallio et al. present a cloud-based rental service which uses sensors, networking and data analytics, contributing to the optimized use and smaller environmental footprint of tools [22]. Based on the main concepts of cloud computing, cloud manufacturing (CM) is a new business model, encompassing the componentization, integration and optimization of manufacturing resources and capabilities at a global scale [23]. Fisher et al. underscore the important contribution of CM to advancements in collaborative design, process resilience and automation, as well as sustainable waste management [24]. Moreover, the dematerialization possibilities offered by cloud computing can underpin the CE concepts. For instance, according to Lacy et al., dematerialized music in the form of Cloud-Based Streaming Services has the potential to lead to resources saving [25].

Not only cloud computing but also distributed computing (already discussed in Section 2.1 in the context of M2M communication [19]) and edge computing often act as facilitators of CE models. In edge computing, computation is executed at the edges of a communication network, i.e., closer to the sources of data [26]. Damianou et al. underline the contribution of edge computing in increasing performance and efficiency of internet of things (IoT) networks that use blockchain, as well as in mitigating the resources consumption and the waste production [27].

Another concrete example of the usage of computing for yielding CE benefits are the so-called "thin clients". Thin client computing systems offer the same applications and graphical user interfaces that are available on desktop computers, whereas the heavy computational load is centralized on powerful servers. In this way, administration costs are reduced, and a more efficient use of computer resources is achieved [28]. Coughlan et al. analyze the use of thin client computers, as a solution for repurposing end-of-life laptops with obsolete equipment from consumer waste electrical and electronic equipment (WEEE) [29].

2.3. Cyber-Physical Systems

Cyber-physical systems (CPS) are integrations of computation with physical processes [30]. Sharpe et al. demonstrate the implementation of a CPS, increasing the traceability and supporting decision-making within a WEEE refurbishment business. The proposed solution contributed to more accurate and more efficient refurbishment processes [31]. Romero et al. perform a preliminary conceptual development of a new generation of Green Sensing Virtual Enterprises (GSVEs). The main idea behind GSVEs is to dynamically create goal-oriented networks, which support short-term alliances between green enterprises, utilizing IoT, wireless sensor networks and CPS technologies. Thus, more efficient resources sharing/management is achieved [32].

Additive manufacturing (often referred to as 3D printing) is a specific type of CPS that provides a wide range of valuable contributions to a CE, including: multiple product life cycles, product attachment through personalization, resource efficiency through complex geometries, repairability, improved efficiency and local community empowerment through distributed manufacturing [33].

Closely associated to the notion of CPS is the so-called digital twin technology, which involves creating the virtual models for physical objects in the digital world, in order to simulate their behaviors [34]. Rocca et al. analyze a laboratory application which integrates digital twin and virtual reality technologies for virtually testing the configuration of a WEEE disassembly plant by means of simulation. This application offers better managing and optimizes the WEEE disassembly process [35].

Other uses of CPS in a CE context involve the deployment of ground or aerial robotic systems. Pellicciari et al. describe software tools for simulation as well as for scheduling of multi-robot stations in terms of energy consumption optimization [36]. Sarc et al. stress the importance of digitization and intelligent robotics for the optimization of waste management [37]. Based on unmanned aerial vehicles (UAVs) and IoT cloud-based analytics, Stegnos et al. propose a solution for preventing marine littering [38].

2.4. Data Analysis and Artificial Intelligence Algorithms

Solutions revolving around data analysis and artificial intelligence (AI) algorithms were extensively examined in the context of this paper. A wide range of technologies and methods employed in the corresponding solutions can be found and have been surveyed, including: big data analytics, case-based reasoning, data and model integration, data visualization, dynamic game theory, dynamic programming, evaluation models, fuzzy logic, heuristic algorithms, machine learning, recommender systems, semantic processing, and others. The use of these technologies for advancing CE is further presented in the paragraphs below.

Big data is one of the most popular CE enablers. The term big data refers to large-volume, complex and ever-growing (at an extremely fast pace) datasets, coming from various sources. Traditional definitions of big data refer not only to volume but also to variety and velocity as key aspects, usually referred to as "3Vs" [39]. 4V or 5V models are also popular, including data veracity and data value as the fourth and/or fifth "V". Jabbour et al. integrate aspects of the ReSOLVE model of CE with the 4Vs of big data management. In addition to this, they spotlight the importance for the CE of novel big data-based business models [40].

A significant aspect in the area of big data is data visualization. Data visualization refers to the representation of a huge amount of data in ways that enhance situation awareness, e.g., into pictorial or diagrammatic representation. Two very popular technologies using data visualization are augmented reality (AR) and virtual reality (VR). In AR, virtual objects are linked to the physical objects. AR can be implemented by devices ranging from micro-size to big screens. Mourtzis et al. propose an AR product customization application, enabling original equipment manufacturers (OEMs) to design their manufacturing networks in a more efficient and cost-effective manner [41]. Among other AR solutions, Behzadan et al. describe the potential of an AR-based system for excavators, enabling workers to detect and visualize buried utilities, thus helping prevent accidental utility (water/wastewater pipes, conduits, cables, etc.) damage and their subsequent severe economic and environmental impacts [42]. In VR, a user is submerged into a full 3D experience, in which the physical objects are linked to the virtual world [43]. A case of VR application for optimizing the WEEE disassembly process [35] is presented in Section 2.3.

Another popular technology in the CE domain is fuzzy logic. Fuzzy logic can be described as a type of many-valued logic which models vagueness and uses natural language to represent and handle partial truth in practical applications in a consistent manner [44]. Based on the main philosophy of fuzzy logic, Kang et al. demonstrate an analysis model of ecological suitability of land, using fuzzy comprehensive evaluation and geographic information system (GIS) data. The proposed solution can serve as a scientific basis for sustainable construction and development of cities [45]. Akinade et al. describe a waste analytics system which achieves accurate waste prediction and offers construction waste (CW) minimization opportunities. This system is based on the adaptive neuro-fuzzy inference system (ANFIS) technology [46].

Machine learning represents a major pillar in many popular applications nowadays, and the CE domain is no exception. Machine learning includes computer methods and algorithms, which can adapt, learn and improve through experience [47]. Taylor et al. explain how machine learning and data-driven approaches can improve corrosion management, enabling material efficiency and asset preservation [48]. Neves Da Silva et al. stress the contribution of monitoring centers for water, energy and waste management, using machine learning techniques in optimizing resource consumption of municipal, commercial and industrial clients [49]. Zhou et al. analyze a model for CE evaluation in major steel and iron enterprises, based on support vector machines with heuristic algorithms for tuning hyper-parameters. CE evaluation can provide valuable information for assessing adopted techniques from a circularity aspect as well as for better resource management [50].

Other algorithmic approaches, e.g., based on game theory or dynamic programming, are also applicable in a CE framework. Based on dynamic game theory techniques, Zhang et al. analyze a solution for versatile job shop scheduling in real time, substantially improving energy and production efficiency [51]. Hao et al. analyze a container multimodal transport system, based on dynamic programming for the optimized combination of transport routes and modes, leading to increased energy and resource savings [52].

To enhance decision support in CE models, a range of scientific approaches grounded in recommender systems, reasoning techniques or semantic technologies can also be found. Gatzioura et al. present a hybrid recommender system, which supports industrial users in identifying possible resources and symbiotic partners, improving overall performance [53]. Case-based reasoning (CBR) has also been utilized for solving problems and supporting decisions in the CE domain. CBR can be explained, simplistically, as the process of adapting old solutions to meet new demands. An example of a CBR model incorporates problem understanding, learning and solving and integrates all the above with memory processes [54]. Li et al. analyze a hybrid method that combines CBR with blockchain for the planning of a remanufacturing process. The proposed solution contributes to a reduction in emissions and energy requirements as well as to resource savings [55].

The use of semantics and ontologies has also been gaining ground in CE fields. Koo et al. introduce a new paradigm for establishing a semantic framework, which enables model integration for biorefining [56]. By supporting biorefining processes, this solution can lead to resources savings. Ontology engineering is another approach that has been followed and involves activities such as ontology development, construction and lifecycle management [57]. Trokanas et al. present the development of an ontology for biomass and biorefining technologies, which contributes to optimized use of resources [58].

2.5. Data Collection and Internet of Things

Various data collection and IoT technologies were reviewed for the purposes of this paper, spanning asset tagging, building information modeling (BIM), satellite imaging, GIS, SCADA, and others. The following paragraphs explain how these technologies act as enablers for CE.

Among the most widely used technologies are smart tags and radio-frequency identification (RFID). Smart tags are small devices combining memory, data processing and communication capabilities. They come in different shapes and sizes and can be used for various applications (e.g., object or animal identification, manufacturing, personnel security, goods transportation) [59]. Gligoric et al. demonstrate the use of smart tags technology for the unique identification of items and the tracking of the environmental conditions in which a product is maintained. Such a technology offers improved handling of resources and facilitates decision-making [60]. RFID tags, which have a small microchip on board, are very popular tools for the identification of objects, using electromagnetic fields [61]. Zhang et al. support that the development of an automotive recycling information management system (IMS), based on RFID and IoT technologies, would substantially improve the recycling/recovery rate [62].

Building information modeling (BIM) is another enabler of CE. BIM is a technology that creates an accurate virtual model of a building. Such a model visualizes what is to be built, enabling the identification of potential design, construction, or operational issues [63]. Swift et al. underline the role of RFID and BIM technologies in making building elements more traceable, adaptable and reusable in new designs [64]. Akanbi et al. analyze a disassembly and deconstruction analytics system for ensuring efficient materials recovery as well as for checking if building designs are compliant with the concepts of CE [65].

One of the major technological pillars of CE is IoT. IoT is a global network of interconnected objects which have unique addresses and can communicate using standard protocols [66]. Among other waste management solutions, Saha et al. describe an IoT-based smart solar powered waste compacting bin, contributing to the optimization of the collection routes and the reduction of unnecessary clean-up costs [67]. Forlastro et al. demonstrate an affordable IoT solution for video makers, which optimizes resource use by enabling users to transform traditional video equipment into smart objects and shoot through a mobile application [68]. Industrial internet of things (IIoT) encompasses various disciplines including energy production, manufacturing, agriculture, healthcare, retail, transportation, logistics, aviation, space travel, etc. [69]. Anttila et al. analyze an IIoT system for upstream management and improvement in the oil and gas industry. The specific system offered financially and environmentally beneficial results [70].

Another important technological pillar of CE is the geographic information system (GIS). GIS refers to computer systems which store, manage, analyze and display geospatial data [71]. Vadoudi et al. describe a new information strategy framework for sustainable manufacturing, based on the integration of GIS technologies with the current product lifecycle management (PLM) [72]. Iglesias et al. describe an example where the satellite infrastructure was utilized. In this example, WorldView-2 satellite images were used to map Typha grass in Hadejia valley irrigation scheme, contributing to the control of this plant as well as to the sustainable use of it for the production of biogas [73].

The use of Supervisory Control and Data Acquisition (SCADA) systems is also key in some CE applications. SCADA does not refer to a full control system, but rather to a supervisory software package, positioned on top of hardware and using interfaces via programmable logic controllers (PLCs) or other commercial hardware modules [74]. Jensen et al. refer to SCADA systems as integral parts of modern wind turbines, contributing to their normal functioning as well as to their lifetime extension [75].

The field of wireless sensor networks is also considered critical in many monitoring applications, including those relevant to CE. Tsakalides et al. underline the importance of wireless sensor networks in eliminating water leakages and contaminations and reducing their serious environmental impacts [76]. Dyo et al. analyze the design and deployment of an energy-efficient and sustainable sensor network for wildlife monitoring [77].

2.6. Data Management and Storage

Data management and data storage technologies were adopted within various solutions that were analyzed for this literature review, e.g., information management systems (IMS), blockchain, data privacy, data security, smart contracts. The use of these technologies is further elaborated below.

An IMS can be defined as a software system responsible for data storage, searching and retrieval [78]. Ping presents an IMS applied to tourism management in order to cover CE purposes. Some potential benefits of such a solution include more efficient information tracking and processing, improved security and customer relationships, as well as better control of supplies [79]. Together with various other solutions, Pagoropoulos et al. underscore the importance of relational database management systems (RDBMS) and database handling systems in waste handling, where they facilitate decision-making, leading to the re-planning of the value network [80]. Hatzivasilis et al. present main defense mechanisms for providing end-to-end data security and privacy, facilitating the integration of big data, Internet of Medical Things (IoMT) with the CE and contributing to the optimized use of assets [81].

Blockchain is an increasingly popular technology in the area of data management and storage. As expected, this technology has also raised the attention of CE researchers. Blockchain can be defined as "a distributed ledger maintaining a continuously growing list of data records that are confirmed by all of the participating nodes" [82]. A block is a record which contains data, a value with the hash (digital fingerprint of an amount of data of the block) of the previous block, and a value that represents its own hash. The meaning of the cryptographically linked chain of blocks through these hashes can be explained by the link between the hash of the current block and the hash of the previous block [83]. Balakrishna et al. analyze the potential to improve the effectiveness of the organic food supply chain, using the blockchain technology [84]. Dindarian et al. explore cases in which blockchain technology enabled traceability, and thus improved handling of electronic waste [85].

In conjunction with blockchains, smart contracts have been attracting significant research attention from the scientific community. A contract can be defined as a set of rules or clauses that parties have agreed upon, for governing the relationship between them. Smart contracts are just like contracts in the real world, with the difference that they are fully digital. They are small script programs, which are used and stored in blockchains, featuring a tamper-proof logic code within them [83]. Alexaki et al. describe a solution for regulated circular healthcare jurisdictions using the blockchain and smart contract technologies. Such a solution has the potential to contribute to more modular and interoperable healthcare services as well as to enable circularity by providing the necessary collaborating mechanism [86].

2.7. Software and Simulation Technologies

Software is an indispensable part of CE-related ICT solutions. Furthermore, simulation technologies play a catalytic role in the transition to a CE. We reviewed such solutions, encompassing digital platforms, PLM systems, simulation solutions, software tools and smartphone applications.

Digital platforms and relevant technologies represent a critical asset for CE development. The utilization of PLM systems in digital platforms can play an important role in the context of industrial symbiosis. One benefit of such digital platforms is that they facilitate the exchange of by-products between businesses, as well as the synergies in the context of industrial symbiosis [87]. Combining digital platforms and technologies such as open online education, technology-enhanced learning, open educational resources, serious games, massive open online courses, technological infrastructures and open schooling can foster analysis skills and lifelong learning for the CE [88].

The use of simulation models and technologies is equally important. Zheng et al. present a real-time simulation scheme for a photovoltaic generation scheme, based on Real Time Digital Simulator (RTDS) technology [89]. The proposed system can contribute to the normal functioning of the photovoltaic generation scheme, avoiding loss of energy and resources caused by system failures. Núñez-Cacho Utrilla et al. analyze a solution of simulation-based management of construction companies to measure key performance indicators (KPIs) related to the CE [90]. Based on the proposed solution, proper circular strategies can be identified and adopted.

Mobile application technologies are playing an increasingly important role in society today and can also contribute into CE development. Lönn proposes an AR-based smartphone application to raise awareness about the CE, thus facilitating the adoption of CE concepts [91]. Faria et al. present mobile applications used to sell, buy or loan clothes, supporting the CE purposes (mostly digitalization and reuse) [92].

Other software tools and solutions relevant to the CE domain also exist. Some additional examples that can be highlighted are the following: Amsel et al. analyze a software tool for estimating the energy consumption of software to inform users about the environmental friendliness of software systems [93]. Chamberlin et al. demonstrate design software tools, which are useful for the analysis as well as the guidance of business communications in the context of CE. These tools can lead to the adoption of the main concepts of CE by proposing different communication strategies, based on the behavior and motivations of people [94]. Alvarado-Morales et al. analyze computer-based tools for the design and analysis of sustainable bioethanol production [95].

2.8. Categorization Method

All of the solutions described in Section 2 are categorized in Table 1. We used a two-fold classification, focusing on both the technological categorization of each solution as well as the 4R concept that each solution is most relevant to.

Table 1. Categorization of the ICT Solutions for the Circular Economy (CE).

General Categorization	Subcategorization	Specific Technology	Circular Economy Concepts			
			Reduce	Reuse	Recycle/ Restore	All Four Concepts
Communications	Adaptive links		[14]			
	Cache-Based Transmission		[15]			
	Communication Infrastructure	5G	[12,13]			
		GPRS	[11]			
	Cognitive Radio		[17]			
	M2M Communications		[12,13,19]			
	P2P Communications		[18]			
	Routing Protocols		[19]			
	Wireless Transmission		[20]			
Computing Technologies	Cloud Computing		[22,38,70]			
		Cloud Manufacturing				[24]
		Industrial Cloud	[13]			
		Cloud Streaming	[25]			
	Distributed Computing		[19]			
	Edge Computing		[27]			
	Thin Client Computers			[28,29]		
CPS	Core CPS Technology		[32]	[31]		
	Additive Manufacturing			[33]		
	Digital Twin				[35]	
	Robotics		[36]		[37]	
	UAVs		[38]			
Data Analysis and AI Algorithms	Big Data Analytics		[81]			[40]
	Case-Based Reasoning			[55]		
	Data and Model Integration		[49,56]			
	Data Visualization					
		VR			[35]	
		AR	[41,42]			[91]
	Dynamic Game Theory		[51]			
	Dynamic Programming		[52]			
	Evaluation Models					[50]
	Fuzzy Logic		[45,46]			
	Heuristic Algorithms					[50]
	Machine Learning		[48,49]			

Table 1. *Cont.*

General Categorization	Subcategorization	Specific Technology	Circular Economy Concepts			
			Reduce	Reuse	Recycle/ Restore	All Four Concepts
		Neural Networks	[46]			
		Support Vector Machines				[50]
	Other Data Analytics		[22]		[65]	
	Recommender Systems		[53]			
	Semantic Processing					
		Ontology Engineering	[56,58]			
		Semantic Modelling	[58]			
Data Collection and IoT	Asset Tagging and RFID		[60]	[64]	[62]	
	BIM		[46]	[64]	[65]	
	IoT		[22,27,32,38,51, 60,67,70]	[68]	[37,62]	
		IIoT	[13,70]			
		IoMT	[81]			
	Satellite Imaging and GIS		[45,72,73]			
	SCADA		[11,49,75]			
	Wireless Sensor Networks		[76,77]			
Data Management and Storage	Blockchain		[18,27,84,86]	[55]	[85]	
	Data Privacy/Security		[81]			
	Information Management Systems		[62,79]			
		RDBMS			[80]	
	Smart Contracts		[86]			
Software and Simulation Technologies	Digital Platforms		[49,75–77]	[87]		[88]
	PLM Systems		[72]	[87]		
	Simulation Technologies		[11,35,89]			[90]
	Smartphone Applications		[92]			[91]
	Software Tools		[41,42,56,93–95]			
Other Smart Technologies	Smart Grids		[18]			
	Smart Products		[32,67]	[68]		

For the general technological categorization of the solutions, the seven categories identified and mentioned in the beginning of Section 2 were utilized, complemented by an eighth category containing other smart solutions which could not be categorized into any of our seven main categories. To make the results clearer and more usable, the general technological categorization was followed by a subcategorization. 46 subcategories were utilized for our purposes. In seven subcategories, a subsequent third subcategorization was used to indicate the specific solutions presented. Several solutions utilizing different technologies can be found in different technological categories and subcategories.

Regarding the relevance to the 4R concepts, we used 4 categories: (1) Reduce, (2) Reuse, (3) Recycle/Recover, and (4) Relevance to all four concepts. "recycle" and "recover" concepts were presented in the same column, as only a few solutions were relevant to the "recover" concept alone. Thus, we managed to keep the table less complicated. Lastly, for the CE concept categorization, each solution was categorized into only one of the four categories (the most relevant one).

3. Challenges

Despite the numerous benefits of ICT solutions for the CE, there are still several challenges and barriers regarding the use of ICT, in the way to a more restorative and regenerative economy. Mapping all the relevant challenges is a rather puzzling task, due to the diverse nature of the ICT solutions and the complex interconnections among the challenges. Table 2 contains representative examples of challenges frequently occurring in the scientific literature.

Table 2. Challenges in Adopting Circular ICT Solutions.

Challenge	Citation
Consumer attitude	[96,97]
Corporate responsibility	[98]
Cooperation and trust	[99,100]
Data uncertainty	[101,102]
Economic	[103–105]
Environmental impact	[106,107]
Information use	[108,109]
Lack of capacity	[99]
Policies	[110,111]
Product design	[112]
Security	[113]

As presented in Table 2, certain cases of customers with limited awareness of environmental issues can be a significant barrier to the adoption of CE technologies [96]. In addition to this, according to Gåvertsson et al., there is a widespread perception that re-used products are of lower quality than new ones [97]. Issues in relation to corporate responsibility have an equally damaging effect. Ormazabal et al. note that the lack of commitment on the part of the organizations' leaders is a major challenge for CE [98].

Trust and the added value of cooperation among different stakeholders can play a key role in the transition to a CE. However, since conflicting interests are present in many cases, the establishment of trust and cooperation can also pose important challenges. In particular, the lack of stakeholder cooperation, including service provider cooperation, impedes the smart waste management adoption according to Zhang et al. [99]. Antikainen et al. recognize that sharing of data between competitors, whilst ensuring property rights and privacy, as well as establishing trust constitute important challenges for the digitization in a CE environment [100].

Data uncertainty is identified as another obstacle for the CE. Van Schalkwyk et al. underline that some simulation models are imperfect and need to be enriched with further data [101]. Zhang et al. state that "Noise" in lifecycle big data might have a negative impact on the accuracy and reliability of decisions [102].

Moreover, costs related to investments for circular digital technologies might discourage businesses from adopting such technologies, in spite of the long-term benefits they might have [103]. Lack of support from public funds might be an additional burden [104]. Martin et al. recognize the challenge of the proper allocation of economic costs and benefits in an industrial symbiosis context [105].

One of the most important concepts of the CE is that the economy and the environment should coexist in equilibrium [114]. As a result, potential negative environmental impacts from CE technologies pose significant challenges. As a remarkable example, Despeisse et al. refer to the problem of 3D printing leading to increased resource consumption through higher demand for customized goods, higher rate of product obsolescence, and less eco-efficient localized production [106]. Makov et al. also highlight re-spending and imperfect substitution as two examples of the environmental rebound effect (ERE), caused by the smartphones' reuse [107].

Efficient information use is also of paramount importance for the success of CE models. Aid et al. argue that the lack of information or the ambiguities regarding what information is required by who may be obstacles for waste management systems [108]. Geng et al. refer to the inadequate use of systematic information systems by many companies [109].

Capacity-related problems, especially with respect to the lack of proper skills and training, represent an additional barrier. According to Zhang et al., there is limited knowledge, and consequently limited use, of smart-enabling technologies, including IoT, by many companies [99].

From a policy perspective, the lack of government laws and regulations is another significant barrier to the uptake of CE investments [110]. According to Watkins et al., current legislation does not adequately support the development of potential symbiotic products that make use of multiple residue streams of industrial processes [111].

From a product design perspective, in many cases, current approaches that are not CE-oriented lead to products that are hard to disassemble, reuse and recycle (e.g., products with a wide mix of materials, toxic glues, etc.) [112].

Last but not least, significant problems and discouragement from adopting CE-oriented technologies may arise in cases of data breaches and inefficient data security [113].

Addressing the aforementioned challenges requires collaborative efforts from different stakeholders. Training and capacity building around CE-related issues and technologies at the individual and corporate levels can have a catalytic role in the transition to a more regenerative economic model. If both businesses and individuals have a high level of environmental awareness and are familiar with CE-enabling technologies, then the adoption and support of new circular business models and environmental policies will be substantially less complicated tasks. As shown above, several technologies are not mature enough yet in terms of efficiency, security, sustainability, etc. Therefore, multidisciplinary research and development around CE technologies is of vital importance.

Furthermore, policies, laws and action plans for CE from governments can provide a multitude of benefits and address several challenges simultaneously. One important example referring to initiatives regarding the entire lifecycle of products is the recent European Union Circular Economy Action Plan. The core of the aforementioned plan can serve as a basis for similar initiatives across the globe. Some of the main aims of this plan encompass: (1) Promoting the development and widespread use of sustainable products; (2) Supporting consumers, public organizations and businesses in the "green" transition with proper legislation/non-legislation measures; (3) Focusing on key resource-intensive industries and products (electrical and electronic equipment, battery cells, plastics, vehicles, textiles, single-use packaging, tableware and cutlery, building materials, etc.); (4) Minimizing waste and dangerous substances, better waste management; (5) Supporting CE transmission through funding mechanisms; (6) Leading and proposing agreements, alliances and initiatives at a global scale [115].

4. Discussion on the Results—Conclusions

The present paper surveyed a wide range of ICT-based solutions that act as pillars or facilitators for the successful development and application of CE models. The most prevalent result from Table 1 is that the majority of the solutions are more relevant to the "reduce" CE concept. This is fully in line with the hierarchy of the CE frameworks. Prioritizing "reduce" over "reuse", "recycle", and "recover" is of great importance, as it aids in preventing several complications (quality deterioration sometimes present while recycling/reusing, use of resources to recycle/restore, etc.) As all of the concepts of the 4R model are strongly interrelated, finding a solution in a specific CE concept category does not exclude the possibility of one solution being relevant to another CE concept as well.

Another important remark is that many of the solutions employed several technologies from different categories. This can be justified by the fact that information and communication technologies are often connected with each other. Data Collection and IoT and Data Analysis and AI Algorithms were the two most popular general technological categories of all the analyzed solutions. IoT, Blockchain, Digital Platforms and Software Tools were the most popular technological subcategories.

The adoption of the analyzed solutions for the CE transition cannot always be clearly prioritized, due to their complex interrelations and sometimes unique contributions. However, from our analysis we can underscore the importance of some solutions in terms of their completeness in supporting all four concepts of the 4R framework: (a) Cloud manufacturing and new business model supporting industrial symbiosis [24]; (b) Big data in support of CE as a whole [40]; (c) CE strategy design and adoption evaluation [50,90]; (d) Education and training to raise awareness about and promote CE solutions [88,91]. As the aforementioned solutions support all four concepts of the 4R framework, they can play a more central role in the CE transition. Novel circular business models can pave the way for the adoption of several CE-related technologies. Similarly, education and capacity building activities can raise consciousness about CE with both businesses and individuals, leading to the greater development and support of relevant technologies. Lastly, evaluation models for the CE can provide useful information and recommendations for forming more efficient strategies as well as for prioritizing the adoption of various circular solutions.

Analyzing the papers in this literature review indicated not only the direct connections with the technologies utilized, but also the indirect ones. Technology and digitization have transformed the world's landscape. The form of today's businesses, manufacturing processes, healthcare, communication, education, mass media as well as of almost every other aspect of human lives has radically changed since ICT advancements began snowballing, a few decades ago. It would be a mistake to overlook the importance of all these advancements, even in seemingly irrelevant solutions. For example, designing an AR-based mobile application for supporting the CE today, would be impossible if it had not been for the advancements in computers, programming, communications, etc., of the previous decades. It would also be impossible if people had not been educated to use smartphones and the internet.

The CE model is radically different from today's linear model of economy. Currently, there are many obstacles and challenges regarding the adoption of ICT solutions for the CE. Several of these challenges were identified in this paper. Consumer and business attitude, economic costs, environmental impacts, lack of education around the CE, and lack of familiarization with modern technologies were some of the most critical ones, while there are also many interconnections among them.

In conclusion, the role of ICT solutions in the transition to a circular model of economy is fundamental and there is an ever-growing literature around this subject. Proper training and capacity building at the business and individual levels, effective policies, action plans and funding mechanisms from governments, as well as multidisciplinary research can facilitate this transition and help overcome the existing challenges.

Author Contributions: K.D. was the paper's initiator. He identified the need to systematically review the deployment of information and communication technologies in the context of circular economy operations. He researched relevant applications especially the ones related to artificial intelligence and data collection and management in various facets of the circular economy. E.D. performed extensive research on state-of-the-art ICT proposals, solutions and tools deployed towards the achievement of circular economy objectives. He identified relevant research opportunities and associated challenges. It is noted that both authors closely cooperated in order to achieve suitable information flow and harmonization across the entire paper. All authors have read and agreed to the published version of the manuscript.

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