IoT and Digital Circular Economy: Principles, Applications, and Challenges

Konstantinos Voulgaridis[a], Thomas Lagkas[a], Constantinos Marios Angelopoulos[b], Sotiris E. Nikoletseas[c,d]

[a] *Department of Computer Science, International Hellenic University, Agios Loukas, Kavala Campus, 65404, Greece*
[b] *Department of Computing & Informatics, Bournemouth University, Fern Barrow, Poole, BH12 5BB, UK*
[c] *Computer Engineering & Informatics Department, University of Patras, University Campus, Rion, 26504, Achaia, Greece*
[d] *Computer Technology Institute Press "Diophantus" (CTI), N. Kazantzaki Str, Rion, 26504, Achaia, Greece*

Abstract

The research interest in Digital Circular Economy models is constantly growing, especially by studying the impact and implications of circular principles and Internet of Things technologies in modern society. Up until now, Industry 4.0 has been recognized as a vital enabler of circular approaches, building the first step towards sustainable Industry 5.0 solutions, while creating new growth opportunities. To fully understand digital Circular Economy each field needs to be investigated. We achieve that by conducting a systematic review with a thorough analysis on the Internet of Things, Digital Circular Economy, and their collaborative relationship independently, by studying business models, architectures, applications, and their respective features.

Keywords: Digital Circular Economy, Industry 4.0/5.0, Internet of Things, systematic review

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1. Introduction

Internet of Things (IoT) has been proven to be a research spotlight for the last decade, through numerous scientific publications, research projects, and innovations. Up until now, the academic community has provided thorough contributions to its concept and utilities, the wide perspective of applications fields, architectural models, and features.

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Industry 4.0/5.0 has attracted the majority of attention among the corresponding application fields, due to the technological and scientific breakthrough that accompanies them. The need for Cyber Physical Production Systems (CPPS) introduced the term of Industry 4.0 in 2011, implementing real-time smart communication and collaboration among manufacturing processes. Embracing such technologies, the European Commission published the concept of Industry 5.0 in 2017, aiming for the evolution of a digitalized and Artificial-Intelligent (AI) Industry 4.0 to a more human-centric and resilient approach [1].

At the same time, Circular Economy (CE) is considered another state-of-the-art and impactful concept, focusing on reusing or recycling materials and reducing waste, rather than following a traditional linear approach resulting in disposal. Its importance is thoroughly examined through a wide spectrum of scientific perspectives and possible use cases, as well as global initiatives, such as the ReSOLVE framework by the Ellen McArthur Foundation [2] and the Green Deal Action Plan by the European Commission [3]. Moreover, the combination of Information and Communication Technology (ICT) systems and their corresponding mechanisms such as Big Data, Cloud Computing, and IoT start influencing a digitalized version and implementation of CE into the modern society, while influencing the nature of ecosystems, business models, and technological structures [4].

The ongoing capabilities of IoT, opportunities of CE, and their combination, ensured the creation of new technological architectures, IoT Circular strategies and designs. Enhanced systems of reuse, remanufacturing, and recycling supported by IoT technologies, as well as their corresponding challenges are examples of such research topics [5]. Industry 4.0 and 5.0, specifically, focus on the digital transformation of manufacturing, and promote new perspectives in terms of production and consumption, by incorporating circularity principles [6]. Additionally, the combination of the two concepts is considered a key enabler for models and systems of reduced costs, increased efficiency in monitoring resources, and maintained high-quality during the lifecycle of products and services [7]. From a technological perspective, IoT technologies have the potential of utilizing algorithms and platforms, developed for the process and analysis of the generated circular data, as well as providing optimized decision-making actions for proper circularity [8].

The methodology followed in this work is systematic review. The Google Scholar platform was used to search for the recent relevant publications, and the majority of the academic papers are indexed by well-known databases, such as IEEEXplore and ScienceDirect. Different keywords were used for each section of the article: “IoT Applications”, “IoT Architectures”, “IoT Features”, “Digital Circular Economy”, “Digital Circular Economy Features”, “IoT Circular Economy”, while focusing on the years between 2016 and 2021. Once the total number of papers were gathered, they were separated into four categories: 6 papers were used for “Introduction”, 35 for “IoT – Industry 4.0/5.0”, 15 for “Digital CE” and 23 for “CE – IoT”.

In this article, we carry out an analysis of prior work on the topics mentioned above. Our contribution is focused on the detailed investigation of the different topics related to IoT, Digital Circular Economy, and their interconnections, adopting a step-by-step approach and forming the layout of the study as follows:

In Sections 2 and 3 we examine similar academic literature reviews conducted in the topic of Digital Circular Economy,while presenting a table of differences between our research and the previously published work, and proceed by stating the defined terms of Internet of Things, Industry 4.0 and Circular Economy. Section 4 is focused on IoT, stating different categories of applications, fundamental architectural models and the functionality of their corresponding layers, and a thorough analysis on IoT principles, features, security mechanisms, as well as major communication protocols. Section 5 focuses on the concept of Digital CE,with a background analysis on the traditional term of CE, researching the impact of digital technologies upon CE and the current Digital CE technological enablers. Section 6 is a combination of the two different topics, the principles and effects of Digital CE, indicative barriers and challenges, integration challenges and the available proposed models. We conclude our article with a discussion on the findings of our review and the respective conclusion on the merging of IoT and CE principles.

2. Related Work

In 2020, a literature review was conducted by Nobre and Tavares [9] on the role of Big Data and IoT technologies in the transition to a CE model, involving ICTs. The publication is a two-part research article, studying the debate of CE as a business strategy and turning theoretical circularity principles into practical solutions. The authors of the articles define that the particular review acts as the initial step to the creation of a solid circular framework with the required fundamental technologies. Their methodology involves a thorough analysis of the ReSOLVE Framework by the Ellen McArthur Foundation from a technological perspective. The conclusion of the research is the lack of CE frameworks involving ICTs, due to the short lifespan of modern technologies making a potential framework short-term.

A similar approach was conducted the same year, examining a variety of proposed CE frameworks with implemented ICTs, focusing on the field of Industry 4.0 [10]. The authors state that although Industry 4.0 and digital CE are two separate scientific research fields, there are attempts of unification into a singular system, providing new study attempts for the future. According to the study, the existing frameworks are designed depending on the dedicated area of the application, which is either CE or Industry 4.0 based.

Authors in [11] conducted a literature review on CE models, based on Industry 4.0 applications, examining the potential of unveiling circularity principles into business models and production industries with the support of enhanced digital technologies. Also, the study investigates the possible capabilities of Industry 4.0 assisting CE strategies for decision-making processes, since its attention and interest have increased during the last decade. A significant conclusion of the research is the necessity of Industry 4.0 technologies for a fully functional CE plan, regardless of business or industry field.

A new study was published in 2021 on the co-existence of CE and ICTs, with Industry 4.0 approaches [12]. The authors realize that there is a significant number of papers published on the collaboration and combination of CE and Industry 4.0 technologies, but they also emphasize the lack in the academic literature regarding the challenges that society may face upon transition to a CE model. The study analyzes a variety of research papers on Industry 4.0 technologies into CE plans in a step-by-step manner. However, they highlight the lack of technical preparation of individuals for such transition, as well as the challenges that economies of developing countries may face.

Another research published in 2021 states that the interest in the corresponding scientific fields started gaining attention in 2014 [13]. The authors' approach focuses on the analysis of the literature about the implementation of IoT, and its Industry 4.0 capabilities, into a CE management plan. The study highlights the importance of proper understanding and the meaning of a possible transition to a CE model, from different potential stakeholders and possible expectations of the supported technologies. However, it is stated that more research is required on stakeholders' influences, the role of

Big Data capabilities into CE models, and its impact on circular and strategic manufacturing options.

Table 1 presents a summary of the prior related work on the combination of IoT technologies and CE, and Table 2 compares our work with previous published surveys. We mark as "+" the submitted content and "-" the non-existent. Our study researches IoT applications, architectural layers and the required principles of IoT models on features, security aspects and protocols. We proceed by investigating the theoretical circularity concept, the digitalization of CE and its underpinning technologies. We complete our research by investigating the relations of CE and IoT, assessing the implications of CE and IoT and their barriers, integration strategies, architectural CE – IoT business models and applications.

3. IoT - CE Definitions

3.1. IoT and Industry 4.0 Definitions

In 2012, the International Telecommunication Union (ITU) provided the officially recognized definition of IoT as followed: "*Internet of Things is defined as a global infrastructure for the information society, which activates advanced services, connecting physical and digital components, based on existing and evolving interoperable information and communication technologies*" [14].

Defining Industry 4.0 proved to be complicated according to Christoph Jan Bartodziej in 2017 [15]. According to the author the first attempt in defining Industry 4.0 was the following and published in 2011: "*The fourth industrial revolution, a new level of organization and control of whole value chains over the entire life-cycle of products. This cycle includes the fulfillment of individualized customer requirements and extents itself from idea, real order, development, and manufacturing, delivery to the customer and the recycling process with the involved services. The basis for the development is formed by the availability of all necessary information in real-time through interconnection of all instances, which are involved in value creation as well as through the ability to derive the best possible value stream based on the resulting data. Through the connection of people, objects and systems, dynamic, real-time optimized, self-organizing, cross-company value networks will evolve, which can be optimized based on different criteria such as costs, availability and resource efficiency.*"

Table 1: Summary of Related Work on IoT and Digital CE

Authors	Title	Aim
G. Nobre and E. Tavares	"Assessing the Role of Big Data and the Internet of Things on the Transition to Circular Economy: Part I" and "Assessing the Role of Big Data and the Internet of Things on the Transition to Circular Economy: Part II"	Researching the incorporation of ICTs into CE strategic plans, and extending the technological approaches through analysis of the ReSOLVE framework.
P. Rosa et. al.	"Assessing relations between Circular Economy and Industry 4.0: a systematic literature review"	Analyzing the CE and Industry 4.0 approaches and frameworks.
G. Piscitelli et. al.	"Circular Economy Models in The Industry 4.0 Era: A Review of The Last Decade"	Reviewing Industry 4.0 approaches combined with CE strategies, for the decision-making process of sustainable operation management.
C. Romero et. al.	"Synergy between Circular Economy and Industry 4.0: A Literature Review"	Examining the relationship of CE techniques and Industry 4.0 approaches, while stating concerns regarding the technological preparation of individuals for a CE transition.
U. Awan et. al.	"Industry 4.0 and the circular economy: A literature review and recommendations for future research"	Identifying Industry 4.0 stakeholders' interests on IoT technologies utility into CE models.

Table 2: Comparison of Related Work on IoT and Digital CE

Related Work	IoT Applications	IoT Architectures	IoT Features	Digital CE Analysis	CE Technologies	CE—IoT Relations	Implementation Strategies
G. Nobre and E. Tavares [7]	-	-	-	+	+	+	+
P. Rosa et. al. [8]	-	-	-	-	+	+	-
G. Piscitelli et. al [9]	-	-	-	-	-	+	+
C. Romero et. al. [10]	-	-	+	-	+	+	+
U. Awan et. al. [11]	-	-	-	+	-	+	+
Our Work	+	+	+	+	+	+	+

However, a more accurate definition was published later in 2013: "*The technical integration of CPS into manufacturing and logistics and the use of the Internet of Things and Services in industrial processes. This will have implications for value creation, business models, downstream services and work organization.*"

3.2. CE Definition

Similarly, the European Commission provided an official definition on Circular Economy in 2015, connecting it to its Green Deal initiative. "*The circular economy is a model of production and consumption, which includes the sharing, rental, reuse, repair, renovation and recycling of existing materials and products as much as possible. As a result, the product life cycle is extended. In practice, this means reducing waste to a minimum. When a product reaches the end of its life, its materials are kept in the economy where possible. These can be used productively over and over again, thus creating further value.*"[16].

4. Internet of Things

In this section we discuss the fundamentals of IoT, as they are essential for understanding the Digital CE interconnections. Examples of different smart use-cases are mentioned, architectural archetypes with their respective layers, and detailed analysis on IoT principles.

4.1. Application fields

As stated by the official ITU definition, IoT's foundation is based on the interconnection of physical and digital components, utilizing the Internet and ICTs. As a result, IoT technologies are implemented globally in different sectors, depending on the application, system, and objective requirements. Due to the multiple phases and approaches of IoT systems, utilization of IoT for one sector can also benefit another, motivating the demand and acceptance by industries and consumers [17].

In this section, we describe a variety of IoT application fields, studying examples from the existing literature and providing Table 3 with an overview of the related content.

4.1.1. Environmental Applications

As environmental applications are defined a wide spectrum of applications that can be separated into different subcategories. Such types are the surrounding environment of the user or an object, and applications such as Smart Agriculture. Due to the constant need for controlling and monitoring wide areas, and most importantly for fauna and flora, IoT solutions are being developed for thorough and real-time evaluation of soil state, atmospheric conditions, and biomass [18]. Examples of monitoring variables for a controlled surrounding environment are temperature, humidity, shock, vibration et al. [19]. Collection of such environmental data is usually achieved through wireless technologies, combined with several sensing and cloud components, faster deployment, longer lifespan, and high quality [20].

Smart Water Supply is one of the environmental application fields, focusing on monitoring the existence of adequate supply for buildings and residents, or potential water loss through leakage. Such results are achieved through the utility of a wireless network system installed in pipelines, while reporting pipe flow measurement data and alerts if the water supply is outside the predefined range [21].

Another example focusing on environmental principles is the project called LOFAR-agro, specifically designed for monitoring soil, plant, or crops. The system calculates and monitors humidity and temperature variables using a wide-scale Wireless Sensor Network (WSN). Projects using such mechanisms were developed for the irrigation of olive trees, by measuring temperature, humidity, solar radiation and rain, and calculating levels of air pollution in the atmosphere by monitoring micro-climate changes [19]. A similar approach was conducted by [22], through the development of a smart solution for strawberry irrigation in greenhouses, by collecting and maintaining the data in the edge of the corresponding networks and assisting the maintenance of their ownership.

4.1.2. Healthcare Applications

According to [23], IoT technologies can be customized to be adapted to the challenges of modern-day healthcare systems, and specifically into three separate environments: a) hospitals, b) small-scale clinics, and c) non-clinical environments, also known as Patient-Centric Care (PCC). Advances in IoT approaches take advantage of components such as microfluidic biochips and wearable biosensors, providing improved and more efficient clinical diagnostics fpr chronic diseases, while there are optimistic theories of potential point-of-care molecular testing for cancer patients [24].

Moreover, a more recent indication of IoT supporting healthcare systems is due to the global pandemic of COVID-19. The scientific community has contributed by researching and developing different solutions for monitoring and controlling COVID-19. Such example is presented in [25]. The authors analyzed and researched the requirements of IoT systems that can be implemented into COVID-19 applications. Patients can use the corresponding services for heart rate, blood pressure, and glucometer monitoring. As well as real-time location monitoring of medical equipment for minimum delays and instant treatment.

4.1.3. Social Applications

The seamless trading of data and information has led to the evolution of IoT and the increasing utility of autonomous agents. Such developments provided the creation of multiple social applications that assist the concept of Smart Cities. The corresponding category contains applications and approaches that improve and support the daily social life of citizens. Related examples are a) smart homes with interconnected sensors and actuators to control temperature, lighting, and air conditioning, b) smart surveillance with real-time monitoring of dangerous areas and data collection through cameras, and c) smart mobility for providing available parking locations to drivers and traffic monitoring for public transportation systems [26].

Social applications are also expanding to a more interactive manner between individuals. IoT gateways are utilized in social media networks for tracking the location of individuals labeled as friends, suggesting meeting points and social events. Moreover, smart shopping models are gradually being developed through smartphone applications that can connect to the main grid of a smart home and provide a refrigerator check-list, product location in a supermarket or convenience store, and complete transactions through online credit cards [27].

4.1.4. Energy Management Applications

A state-of-the-art IoT solution that gathers more and more attention is related to energy management. Combining IoT technologies and regulations regarding energy management provides the concept of a Smart Grid. According to [28], "*Smart Grid is a communication network on top of the electricity grid to gather and analyze data from different components of a power grid to predict power supply and demand which can be used for power management*".

Smart Grid applications have the capability of being utilized in different types of sectors and IoT application fields, due to their energy management features [29]. Such examples incorporate a Smart Grid system into a) a Smart Home infrastructure for lighting and temperature control, b) warehousing and manufacturing for control of industrial processes, c) monitoring and controlling microgrids of power generation such as solar, wind, and hydro energy generators, d) conversion of energy storage into electricity [30].

4.1.5. Industry 4.0 - Industry 5.0

According to the available literature, several researchers consider IoT technologies as a subcategory of Industry 4.0, while the majority of them consider Industry 4.0 an application domain of IoT. In this article, we follow the same principle and recognize Industry 4.0 as an application field of IoT.

The initial step of describing the impact and appliances of Industry 4.0, requires a short introduction to Industrial IoT (IIoT). IIoT shares similar principles and features with IoT, with the difference that is heavily applied on industrial machinery and manufacturing equipment. Due to its industrial focus, manufacturing chains become smarter yielding increased consumer value, predicted machinery maintenance, and advanced service lines [31].

Industry 4.0 utilizes computing techniques combined with IIoT applications, creating a smart manufacturing environment by automating the industrial processes after completing a real-time data analysis through the network of the interconnected machinery[32]. Generally, a variety of smart sensors, artificial intelligence (A.I.), and data analytics are combined to create the concept of Industry 4.0 [33]. Moreover, supportive technologies, such as Blockchain, are implemented into the overall infrastructure of I4.0 for enhanced security and immutability of the related industrial applications, and a wide range of application fields [34], while providing additional supportive functionalities in different I4.0 aspects (e.g., production and supply chain solutions, technological upgrades, overall infrastructure management) [35].

However, this technological evolution has expanded into new approaches with the introduction of Industry 5.0, focusing on combining A.I. and the human intellect into a technological approach that will be part of the individual's daily life, making Industry 5.0 a more human-centric domain [36]. The researchers of [37] propose that a safe built-in exit should be considered for a safe and smooth transition from the fully automated Industry 4.0 to the humanly involved Industry 5.0.

The authors of [38], predict that Industry 5.0 is based on a healthy synergy and interaction of human and automated machines while promoting a visualization of automating machines observing and monitoring human actions through Deep Learning techniques, to reach a supportive human-like state. The researchers of [39] theorize that applying such technological advancement requires carefully designed Digital Platforms that can enable data sharing between systems that are part of a wider ecosystem with significant interconnections.

A thorough analysis of the potential Industry 5.0 outcomes was conducted in [40]. The researchers list some of the significant features that can be provided such as a) Smart Additive Manufacturing, b) Predictive Maintenance, c) Hyper Customization and d) Cyber Physical Cognitive Systems. They also provide the technologies that can support or be supported by the corresponding approach, such as a) Edge Computing, b) Digital Twins, c) Cobots, d) IoE, e) Big Data, f) Blockchain, g) 6G.

However, there is also a statement of uncertainty about the actual results of Industry 5.0, but not ignoring the fact that it will be the reason for interconnection between the physical world and virtual or digital assets [41].

Table 3: Key IoT Applications

Application Type	Functionality
Environmental	Smart Water Supply Smart Agriculture Environment Monitoring
Healthcare	Heart Rate Monitoring Blood Pressure Monitoring Glucometer Monitoring Real-Time Location of Medical Equipment
Social	Smart Homes Smart Surveillance Smart Mobility Smart Social Interactions Smart Shopping
Energy Management	Smart Grid
Industry 4.0	Automated Machinery Smart Manufacturing
Industry 5.0	Synergy of Human and A.I.

4.2. Architectures

The research community has devised a variety of architectural designs, depending on the application goals of the IoT system. Each architectural design accompanies several attributes, with neutral or component-focused characteristics. However, all architectural models follow the same principles of four layers: a) Perception Layer, b) Network Layer, c) Application Layer, d) Management Layer. Depending on the system's requirements, an architectural design may include additional substitution layers, as explained in [42]. A summative architectural design and its components can be seen in Fig. 1.

a) Perception Layer: The Perception Layer is considered the base of the IoT architecture and focuses on the technological functionalities of the design. Implemented with the necessary technologies to support sensory capabilities, processing of the collected data, and communication between the interconnected devices. As mentioned about the possibility of additional layers being required depending on the system's functionality, the Perception Layer can be divided into two sub-layers: i) Perception Nodes, that are related to the physical sensors collecting the data, and ii) Perception Network, transmitting the collected data of Perception Nodes to IoT gateways for further transmission [43].

b) Network Layer: The Layer connects the Perception and Application Layers, by using wired and wireless communication protocols and technologies to transmit the collected data to the information processing unit, while supporting the Management Layer operations. Just like Perception Layer, it can be organized into three-part sub-layers. i) Access Network, functioning as a communication interface between user and service providers, ii) Local and Wide Area Network, being responsible for the interconnection of close-range devices through LAN and longer range through WAN, and iii) Core Network, also known as the Internet and the main system supporting the IoT infrastructure, [43].

c) Application Layer: The Application Layer is responsible for depicting and providing the end-user with the collected data and services of the IoT infrastructure. It is also responsible for the total management of an application, its functionality, provided services, and operation of the applications described in Section 4.1. It can be separated into two sub-layers: i) Application Support Layer, for the computation and data processing, and ii) IoT Application, providing the user with collected information, analytics, and real-time decision-making techniques [44].

d) Management Layer: Its responsibility is the total management of the IoT infrastructure and architectural model, as well as monitoring the functionality of the layers that are interconnected into the unified system. Depending on the application's functionality, the Management Layer of the architectural design can be programmed to provide thorough operational analysis, detailed graph depictions, as well as supporting the decision-making process [44].

e) Virtual Layer: Some IoT applications and models may require additional layers apart from the fundamental four layers mentioned above. An example can be seen in [45], a research on a simulator analyzing the functionality of IoT applications. The authors of the particular study include one more layer on the architectural design, the Virtual Layer, programmed to visualize physical entities into cyber representations, stored on cloud infrastructures. Its technological design enables data analytics for IoT applications with past and real-time requirements.

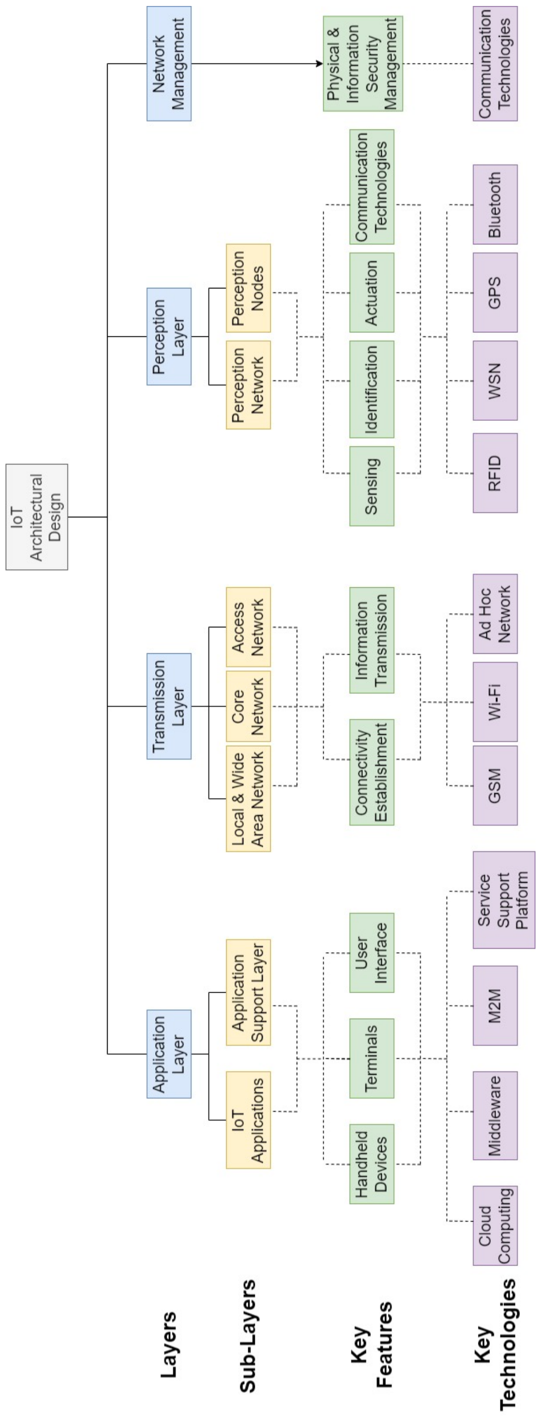

Figure 1: Summative IoT Architectural Design

4.3. Principles

4.3.1. Features

In [46], the authors conduct thorough research on the features provided by a fundamental IoT system, their strengths, and weaknesses regarding security and privacy, and potential solutions. According to the study, the foundational features of an IoT infrastructure are presented below. Table 4 provides a summation of the features and their corresponding descriptions.

a) <u>Interdependence</u>: It refers to the automated control of the IoT components, their behaviors, and functionalities, either from a human factor or other internal devices connected to the system's framework.

b) <u>Diversity</u>: Advancements in technologies provide IoT infrastructures with a multidimensional approach on protocols and networks, through cloud platforms that enable the users to customize their system according to application goals and requirements.

c) <u>Constrained</u>: IoT hardware components vary in terms of size, power, lifecycle, and processing capabilities. Different requirements utilize specific components that are either limited or efficient. The particular feature is described by the authors as a constrained environment.

d) <u>Myriad</u>: The automation and state-of-the-art technologies that are utilized by IoT infrastructures, process and collect enormous amounts of data, compared to traditional means of technology.

e) <u>Unattended</u>: It describes the wireless technologies that are gradually introduced and implemented upon IoT systems. Application use cases may require the installation of hardware in locations and conditions with minimal to no wired connections.

f) <u>Intimacy</u>: It refers to the personal use of IoT devices that monitors a user's bodily and biological functions, as well as environmental conditions and surrounding environments.

g) <u>Mobile</u>: Progression of IoT systems provides mobility to the infrastructure. Such a case is achieved through the requirements of IoT models to adapt to different networks, locations, and functionalities.

4.3.2. Security and Privacy

The major functionality of IoT systems is collecting and processing various types of data, some of which can be private, sensitive, or critical. Such conditions require solid approaches to implementing security and privacy mechanisms, both for shielding the collected data and protecting the user overall. The authors in [47] study security approaches from the perspective

Table 4: IoT Features

Feature	Description
Interdependence	Control from users or interconnected devices
Diversity	Adaptation with supported cloud platforms
Constrained	Limitations depending on requirements and utilized components
Myriad	High amounts of processed data
Unattended	Capabilities of wireless functionality
Intimacy	Biological and environmental monitoring
Mobile	Mobility for installation in different applications

of an IoT system, and defined major and minor security requirements that should be considered upon designing an IoT architecture. Below, the most significant security requirements are listed.

a) Data Confidentiality: Ensuring that the collected data are protected by passive attacks such as eavesdropping, and unauthorized users, while remaining private. It is achieved through data encryption during the collecting process.

b) Source Authentication: Authenticating the source of the transmitted data as genuine and not of malicious origin.

c) Data Integrity: Guarantying that the collected data have not been edited by accident, processed by unauthorized users, or corrupted with malicious intentions.

d) Availability: Ensuring the availability of the interconnected node system for data transmission and communication with the rest of the unified network, even during denial-of-service attacks.

In regards to the security aspect of combining IoT and CE, the corresponding requirements are exceptionally important to organizations implementing CE principles, due to the involvement of digital technologies, and potential concerns about unauthorized data exposure [48]. Protection and privacy of circular chain stakeholder need to be guaranteed for trustworthy routines, tracking of circular data, protection of end users, and preventing intrusions to production, supply chains, and the end products or services [49]. Therefore, the researchers of [50], clarify the importance of creating new encrypted solutions for safe data sharing among actors, prevention of data leaks, as well as considering the implementation of regulations and standards for additional protection of circular chains.

Taking into consideration the security requirements of an IoT system, [51], [52], [53], and [54] study the potential and most common threats that IoT infrastructures are susceptible to, and their corresponding solutions. Table 5 consists of a thorough list of security threats and their respective solutions according to the literature.

4.3.3. Protocols

IoT protocols are essential for the general functionality and adaptation of an IoT system. Depending on the features, architecture, and security requirements of an IoT infrastructure, the suitable protocols are selected to be implemented upon the system, for efficient communication among the interconnected components and successful data transmission. The authors of [55], [56], [57], and [58] have conducted detailed research on protocols of major importance, five of which are presented in this section.

a) Wi-Fi: It can operate under two modes. The infrastructure mode allows WiFi stations to connect through Access Point (AP) and interconnect the stations through the same AP. The totality of APs forms a Basic Service Set (BSS) that links to the MAC address. The Ad-Hoc mode is dedicated to wireless connections, forming a peer-to-peer network, functioning as a client and AP simultaneously. Data transmission is achieved via transmission channels, which is a narrow frequency band, utilizing radio or infrared waves. However, more technologies have been developed to avoid technical interference, such as frequency hopping spread spectrum and direct sequence spread spectrum.

b) ZigBee: It is designed to perform short-range communication by functioning as a simpler version of Wireless Personal Area Network (WPAN). It supports low-power functionality, high-security standards, and increased scalability with a large number of nodes. The architecture of the ZigBee protocol consists of three components: i) Coordinator, for receiving, transmitting, storing, and processing data., ii) Routers, for a maintained data flow throughout the network, and iii) End Devices, which is an optional part of the infrastructure. Generally, the number of components depends on the application requirements and topology.

c) LoRaWAN: It is designed to perform long range wireless communication. It supports low-power functionality while focusing on bi-directional, end-to-end security, mobility, and localization. It forms a star-of-stars topol-

Table 5: Security - Privacy Threats and Solutions

Threat	Description	Solution
Wormhole Attack	Component disruption through network traversal	Node behavior analysis, IDS anomaly detection, Cryptographic key management
Spoofing Attack	System infiltration through disguise or counterfeit credentials	Signal strength monitoring, channel estimation
Eavesdropping	Unauthorized data access, such as RPL routing attacks	Node behavior monitoring, signature authentication
Jamming	Disruption of wireless communication channels	Monitoring packet delivery ratio, packet encoding with error correcting code, frequency changes
Malware	Malicious coding disrupting proper system functionality, such as Sybil attacks	User behavior analysis, lists of trusted and untrusted users
DDOS	Disrupting functionality by utilizing multiple origin attacks	Centralized Software Defined Networking (SDN) controllers
Reverse Engineering	System dissection discovering functional weaknesses	Access control, non-linear key algorithms, IPSec protocols

ogy, where the data are transmitted between end-devices and a central server via standard IP connections, while promoting confidentiality, authentication, and integrity, making it highly suitable for IoT applications [59]. Its security properties are supported by end device-to-network and end-to-end encryptions, and keys that are Activated By Personalization (ABP) .

d) Sigfox: It started by supporting only uplink communication, but it was later upgraded by incorporating downlink communication as well. It has low requirements on propriety hardware but uses a significant number of vendors. Moreover, Sigfox has limitations in terms of utilization, since its architecture is specifically designed for small and infrequent amounts of data. Despite its low functional capabilities, it is considered one of the most secure protocols by incorporating build-in behavior monitoring and mainly operates in offline mode.

e) MQTT: MQ Telemetry Transport (MQTT) is an open standard protocol and utilizes three components i) Publishers, ii) Subscribers, and iii) Brokers. Publishers and Subscribers remain in a constant exchange of data, transmission and communication, through the Broker communication channel that performs the authorization process to ensure reliability. However, It is not suitable for Low Rate WPAN applications, since action needs to be taken to keep the connectivity in an online status for the Subscribers to receive notifications and alarms on network changes, which leads to slow data transmission.

f) NB-IoT: Narrowband IoT (NB-IoT) is a radio access network protocol created by The Third Generation Partnership Project (3GPP), supporting deployment of large number of devices and less complexity in the overall design, while maintaining high coverage functionality with long battery life and low cost for radio chips. The protocol's functionalities are similar to those of LTE systems. Moreover, the network elements of a LTE system can receive software updates for NB-IoT support. One of the key characteristics of NB-IoT is the power saving principles of the devices through sleep, and waking up with a programmed periodicity to receive incoming data [60].

5. Circular Economy

5.1. The Circularity Concept

As mentioned in section 4, Circular Economy was heavily promoted by the European Commission, as an attempt to adopt global economic growth while following sustainable environmental approaches. The general unsustainable model, according to [61] is a linear approach of extraction, production, utilization, and then dumping material waste. The researchers of the respective study state that Circular Economy is the beginning of promoting cyclical flows that don't simply focus on actions such as recycling, but material reuse, remanufacturing, repairing, refurbishing, and upgrading, while maintaining the goal of reducing material waste to minimal. Fig. 2 provides graphic depiction of the original CE conceptual model.

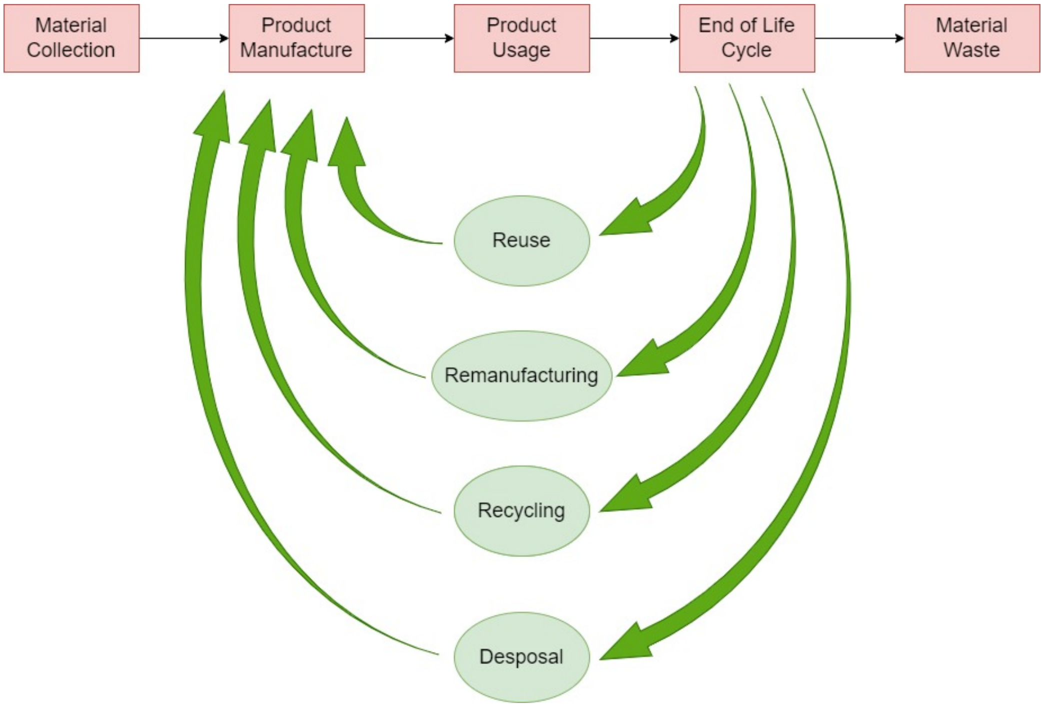

Figure 2: The traditional CE model, depicting the differences between linear chains and CE by implementing disposal, recycling, remanufacturing and reuse, in the end of the product's life cycle.

The academic community has conducted a significant amount of research on the science behind CE, including its impact on different sectors and applications. Moreover, due to the attention of this environmental evolution, both public and private sectors have funded or proposed CE solutions in the form of initiatives, to promote the corresponding sustainable future. Such an example is [62] where the authors performed thorough research on publicized CE initiatives, especially those that were recognized by the EU. The results of the study identified an instability regarding industries that adopt CE mechanisms into their infrastructures. More specifically, industries such as waste management, electricity, and electronics adopt the CE influence, when others like mining and health equipment proved to follow a slower approach.

In [63], the researchers follow similar principles, in a manner of applied CE strategies. The particular study investigates how local governments implement traditional CE methodologies and their corresponding success rate. However, the results showed a lack of knowledge regarding CE and its benefits, and competing interests among industries and businesses for its potential utilization. Another interesting finding is the misinterpretation of CE models, which require proper knowledge and training.

5.2. Digitalization of CE

Due to circular features provided by the concept of CE, academic studies support that Information Technologies (IT) are the most suitable to be combined with circularity principles while maintaining the benefits of both worlds and following the paradigm of initiatives such as the ReSOLVE Framework, which can result in the development and production of new technologies and sustainable systems. Moreover, statements supporting the idea of manufacturing principles and IT, concludes in the potential endorsement of a CE shift [64].

According to [65], for proper Digitalized CE integration, there are fundamental technological requirements for a successful transition that can be described in the concept of Process-Based Information Systems (PBIS). The particular systems are formed by a combination of IT solutions that simplify the integration of Digital Technologies upon changing business requirements. Similar support is provided by the concept of Digital Intelligence, for building a solid foundation on the circular models, by implementing automated monitoring, control, and optimization of the resources. Examples of such implementations are digital tracking, modeling devices, and digital sensors supporting recycling, reuse, and remanufacturing for electrical waste monitoring, virtual engineering objects, and automated optical sorting for recycled materials.

Some additional examples are provided in [66]. Cyber-Physical Systems can maintain data through the entire lifecycle of the product, store information on material composition and footprint. The collected data can be shared among companies for practical and efficient solutions on logistics and use. IoT can be utilized for platforms depicting the recycling availability of products and leading to the reuse of their materials.

Although there are many opportunities available with the incorporation of Digital CE, the work in [67] clarifies the upcoming challenges of the particular sustainable transition. Such obstacles are related to the requirement of new business models, data integration, sharing, and ownership. The researchers state that Digital Circularity transitions require financing, regulations on data sharing, ownership and privacy among competitors, and proper training for the CE implementation. However, solutions are suggested by sharing knowledge and expertise from different sectors, as well as co-creation and networking.

Regarding the impact of Digitized CE, the authors of [68] state that Digital Technologies affected positively CE models in three specific architectural layers: data collection, data analysis, and data integration, promoting the creation of decentralized manufacturing and enterprise systems. Such models are capable of offering collaboration among the stakeholders, while evaluating their actions during the lifecycle of a product, throughout the value chain.

Following the impact scope, researchers in [69] examine the potential benefits of a digital form of CE. Predictive maintenance is enabled through smart sensory installed in products and services, which is also connected to the production of products as a service. Such scales motivate partnership among companies by monitoring the condition and lifecycle of a product, while the customer purchases only the required service according to his needs. Moreover, sustainable consumption patterns, recycling, and recovery of materials are getting more attention, utilizing open-source software for sharing information about the materials used in production and their general digital passport.

Moreover, recent efforts of establishing digitalized versions of CE can be seen through significant research projects. The DigiPrime project [70] focuses on the development of a CE-based digital platform, enhancing secure and safe data exchange between actors of circular chains, while providing real-time data for recycling and waste management. KYKLOS 4.0 [71] is dedicated on the development of an ecosystem utilizing state-of-the-art technologies, such as A.I. and Cyber Physical Systems, for the improvement and additional support of re-functionalities in circular manufacturing, and the production of environmentally friendly personalized products.

Overall, both digital and non-digital CE focus on the implementation of re-functionalities in the production and supply chains. However, traditional

CE is restricted to utilization of physical resources, product parts, and materials, aiming on the production of environmentally friendly products made of recycled parts [72]. Digital CE is considered an enhancement of the traditional concept, providing additional insights for optimized product creation, by utilizing digital technologies for the collection, analysis and sharing of the data provided by the circular chains [73].

Taking into consideration the impact of Digital CE, we realize there are specific requirements for the implementation of Digital Technologies into Digital CE infrastructures. Table 6 represents the findings regarding Digital Technologies, related to their utilization in CE approaches and models.

6. Digital CE and IIoT

Undoubtedly, IoT and CE are two research areas that have attracted much attention in the last 5 years due to their constant improvements and appliances. Progressively, the digital form of CE enables to develop synergies with the IoT technologies, creating new systems that incorporate the strongest principles of both worlds.

In this section, we examine the current relations between CE and IoT, with an emphasis on I4.0, and the proposed integration strategies suggested in the literature.

6.1. CE and I4.0 Relations

6.1.1. Digital CE Areas

The authors of [81] investigated the main resources contributing to the collaboration of I4.0 approaches and data-driven CE, informing that such a combination is beneficial for both manufacturers and consumers while enabling the green concept. Moreover, the importance of digital technologies is highlighted for green product development, since they act as an interface of conventional manufacturing technologies, and feature a global environmental challenge for businesses to transition into digital CE models. This infusion aims at the restoration of sustainability and promotion of green manufacturing [82].

Moreover, the researchers of [83] emphasize the importance of data spaces as an implemented solution for sharing circular data among stakeholders. The decentralized nature of the respective technology, combined with IoT functionalities for additional data interoperability [84], is capable of supporting sector-specific data sharing requirements, while being compatible with

Table 6: Functionality of Digital Technologies in CE

Technology	Utility	Sources
A.I.	Supports Data Analytics, resource optimization for product design, enhancement of business models. Enables Industry 4.0 (I4.0) utilities, such as remote monitoring during manufacturing, faster prototyping, learning through repeated cycles. Assists waste sorting and material reprocessing.	[74] [75] [76]
IoT	Supports business models, product and tool tracking, condition and logistics monitoring, predictive maintenance, lifecycle monitoring. Enables utility of machine data during product development, optimization of supply chains, and waste management. Promotes collaboration and the implementation of smart industrial environments.	[68] [76] [77] [78] [10]
Big Data	Assists in overcoming operational risks and return flow uncertainties. Enables efficient decision-making through Data Analytics from various sources. Supports the creation of automated processing, open-source toolkits, and services for reuse and assessing business models.	[68] [79] [80] [78] [10]
Cloud Computing	Efficient access to maintenance services and supports increased demand with decreased resource flow while allowing access to large volumes of data.	[77]
Machine Learning	Supports processing and system optimization. Analyzes and controls industrial systems and processes.	[80]
Blockchain	Offers visibility, transparency, and smart contracting. Promotes security through transactions and solutions to data ownership.	[68] [69] [66]

cross-sector data exchange with proper configuration of the infrastructure. Such results support the overall cooperation between circular chain actors, by providing constant and controlled data flow both of public and sensitive data, flexible access, and integrity.

Before mentioning the results of this digital transformation, it is essential to list the principles of the sustainable transformation to a digital CE model. Table 7 lists the corresponding principles and requirements to accept the transition [85].

Table 7: Principles of sustainable transition

Principle	Description
Interoperability	The utility of Cyber-Physical Systems to unify the entire network of a manufacturing business.
Virtualization	Depiction of the Cyber-Physical Systems used in the Green Manufacturing context, in a virtual copy, for prediction of human error, work environment safety, support of technical complexity.
Decentralization	Devices provide information on the production processes and the specific stages that need to be followed for customization and complex CE environments.
Real-Time Capability	Ongoing collection of data and information of hardware, software, supply chains, and logistics in real-time.
Service orientation	Availability of Cyber-Physical Systems services, products, businesses, and human services, to other stakeholders and consumers for the creation of general sustainable product service.
Modularity	Support of collaboration among the parties of logistics and supply chains, as well as stakeholders for a successful and solid transition.

Utilizing these principles, we provide Table 8 with the CE and I4.0 effects, considering the ones identified in works [10], [86], [87] and [88].

Also, Table 9 shows an indicative list of industrial and non-industrial IoT applications, with their relevance to the functionality of Digital CE.

Table 8: CE and I4.0 transition effects

Transition Effect	Description
Lifecycle Management	Supported by suitable technologies, such as Additive Manufacturing, it offers an overall efficiency in CE functionality, managing energy consumption, and optimization of product development.
Remanufacturing 4.0	Offering decision-support utilities that can promote cost reduction strategies, while maintaining performance and innovation. In the context of CE, cases of innovation are also related to emerging sustainable business models where consumers can use the service for the required timeframe, rather than complete purchase. The corresponding models improve the general functionality of service and aftersales.
Resource Efficiency	Management of natural resources and waste, optimizing circularity principles of disassembly and reuse of materials, while receiving data in real-time. The particular functionality enables the concept of smart materials, utilizing the type and amount needed, as well as assisting Lifecycle Management by optimizing production timeframes.
Asset Utilization	Enables easier equipment upgrades, infusing sensory technology into components for real-time data collection, inventory, and stock management for average, unused, and excessively used materials. Corresponding utilities assist phases of monitoring demand, for accurate supply readings and reduction of excessive raw material needs.
Quality Improvement	Overall improvement of quality in products, services, and processes. Resource efficiency and asset utilization offer minimized consumption of raw materials while performing optimized supply chains and logistics for high-quality products with longer lifecycles. Labor productivity is also improved with reduced routine labor work through digitized functionalities requiring new skillsets.

Table 9: Relevance of IoT applications with Digital CE

Applications	Relevance
Smart Agriculture [89]	Utilization of digital technologies for proper crop management and resource use efficiency, aiming on reduction of agriculture impact on climate change.
Smart Healthcare [90]	Development of decision-making algorithms for smart healthcare disposal of infectious waster material, while utilizing circular economy aspects for recovery of reusable components and sharing data feedback to the rest of circular chain actors.
Smart Buildings [91]	Utilization of IoT sensory devices and smart Building Management Systems for efficient and sustainable consumption of resources (e.g., smart water and power consumption, smart lighting).
Smart Grid [92]	Introducing the concept of "prosumers", once consumers receive the generated energy, they can decided whether they will use electric waste for commercial purposes to other consumers, or return it to the producer.
Smart Manufacturing [93]	Utilization of digital technologies and Blockchain for waste tracking in manufacturing, while sharing the generated circular data with the rest of the stakeholders.

6.1.2. Indicative Barriers and Challenges

Transitioning to a circular model can be an unstable process if not thoroughly prepared, and unpredictable once fully implemented into the targeted business model. In this section, we discuss the different types of risks and barriers addressed by the academic literature.

The authors of [94] investigated a case study on turning a traditional palm-oil industry in Malaysia, into a sustainable circular business. Taking into consideration the findings of the particular research, there was a high number of insecurities regarding the role of I4.0 on CE implementations. Such examples are the high data flow of IoT systems for cyber security and privacy, the lack of automated virtualization, and the combination of different computational models into a unified framework, as also supported by [95]. However, there are also moral challenges, such as a lack of global standards, vision, mission, and data ownership while sharing information in collaborative platforms [96].

Additional challenges were addressed by [97], related to additional costs for the essential operation of a CE model before the adaptation phase, and reassembling products and materials that went through the disassembly phase of CE models. The disassembly problem also caused fear of complexity due to the different types of material and nature collected, while not ensuring the quality of performance but environmental security [98].

Regarding the societal and interactive aspect of CE, the issue of trust has been a crucial concern for the research community. According to the authors of [99], the implementation of digital technologies into circular infrastructures has raised questions about the integrity and trust of the data flow, while emphasizing the importance of ensuring transparency between the actors of circular chains, through agreements about data ownership, access, and privacy. Potential solution to the corresponding issues is the integration of Blockchain technology due to its decentralized and authentication principles in the form of smart transactions, by shifting the required circular data to the corresponding participants of the circular chain [100].

6.2. Integration and Implementation Strategies

6.2.1. Integration Strategies

Assigning a new sustainable model requires suitable series of steps as proposed in [101].

a) Research of available business models is essential for the supply chains, logistics, vision, and mission of the organization. Calculating the organization's capacity for CE integrations is also dependent on the available resources of the business. A proposed solution related to the particular phase is suggested by [102], utilizing the Lean Production methodology, by selecting strategically suitable activities by implementing circularity principles for optimization, rather than applying directly potential opportunities for the resources management.

b) The availability of resources, organization's goals, and current infrastructure's designs determine the collection of I4.0 technologies that can be applied or can be adjusted for suitable integration.

c) Shifting from traditional to sustainable operations and decision-making adjustments for all the surrounding processes of product development and logistics. Such operations are related to monitoring and management for the implementation of CE principles and their corresponding features while utilizing the I4.0 technologies mentioned above.

d) This combination of operations and technology leads to adaptation of the integration strategies between supply chain layers and interconnects them with products, services, stakeholders, and consumers in real-time. Such a statement is also supported by [103]. The interconnection is achieved through data transformation levels, resource optimization capabilities and data flow processes.

e) Finally, implementing calculation mechanisms of success indications regarding the smooth integration and implementation of true CE functionalities. Such mechanisms assist the organization with suggested changes or optional updates and upgrades. Similar approach is followed in the framework proposed in [104].

6.2.2. Digital CE Models

For better understanding and practicality of the CE and I4.0 combination, in this section, we examine proposed business and architectural models of the literature, inspired by these circularity principles.

In [105], the authors propose a circular architectural model, combining blockchain and IoT technologies, supported by edge computing mechanisms. The infrastructure contains IoT nodes installed in a digital circular environment, supported by Blockchain applications that verify the data collection, storage, and sharing in the form of transactions. Due to the high demand of Blockchain for memory and the nodes being fully dedicated to the circular data processes, the researchers utilize edge computing to cover the memory requirements, by providing separate nodes for local storage, The communication protocols used in the particular architecture are LoRaWAN and SigFox, that were also examined on subsection 4.3.3 The respective design can be seen in Fig. 3.

Similar to the solution above, in [106] the researchers suggest Blockchain as means to support circularity frameworks. More specifically, they propose three variations of Blockchain utility. The first one acts as an enabler of repair and reuse, with blockchain collection lifecycle and usecycle data, and sensor implementation for decision-making about the possibility of reuse or remanufacturing. The second one includes the recycling phase and the system is adapted for decision-making in the end-of-life stage, where the system selects the materials that can be reused, remanufactured, or recycled. The last variation includes the involvement of consumers, using their devices for data collection of the respective products and materials, sending them to the main framework of the infrastructure, and assisting the resource economy through smart contracts.

Researchers in [107] developed a framework utilizing forward and reverse logistics, by implementing IoT principles for achieving circularity features. The particular strategy reduces waste generation by performing the foundational CE loops while avoiding a linear approach. The researchers assume that the products are implemented with IoT technologies such as sensors and modules for monitoring through 5G networks. The respective design monitors usecycle and lifecycle of a product, with modules being installed before the parts of the product are fully coupled. The sensory devices collect the data during the use of the product, transmitting it back to the Decision Support System, which is also supported by an Intelligent Material Circularity Detector. Fig 4 depicts the specific architecture of the model.

The authors in [108] follow a similar approach with the framework above, utilizing forward and reverse logistics in a green manufacturing environment, with a technique called Organization Information Processing Theory as a basis. The researchers hypothesize that the implementation of RFID technologies on materials and products can be used to monitor of usecycle for the required data collection for inventory management. Moreover, they proceed with the hypothesis that installing IoT technologies in interconnected logistics components acts as an enabler of green manufacturing, decision-making processes, and smart resources management according to customer demands.

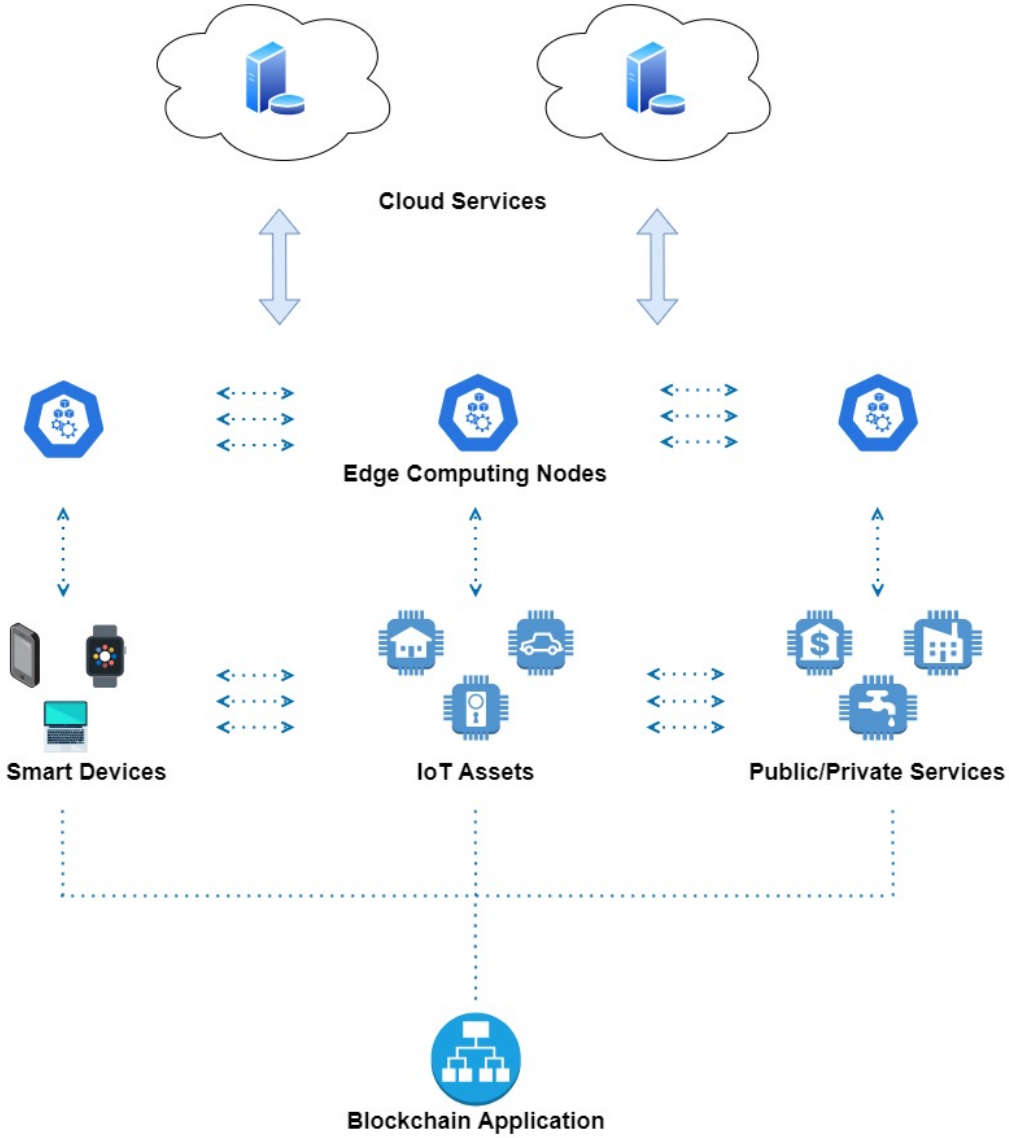

Figure 3: Blockchain model utilizing IoT and Edge Computing

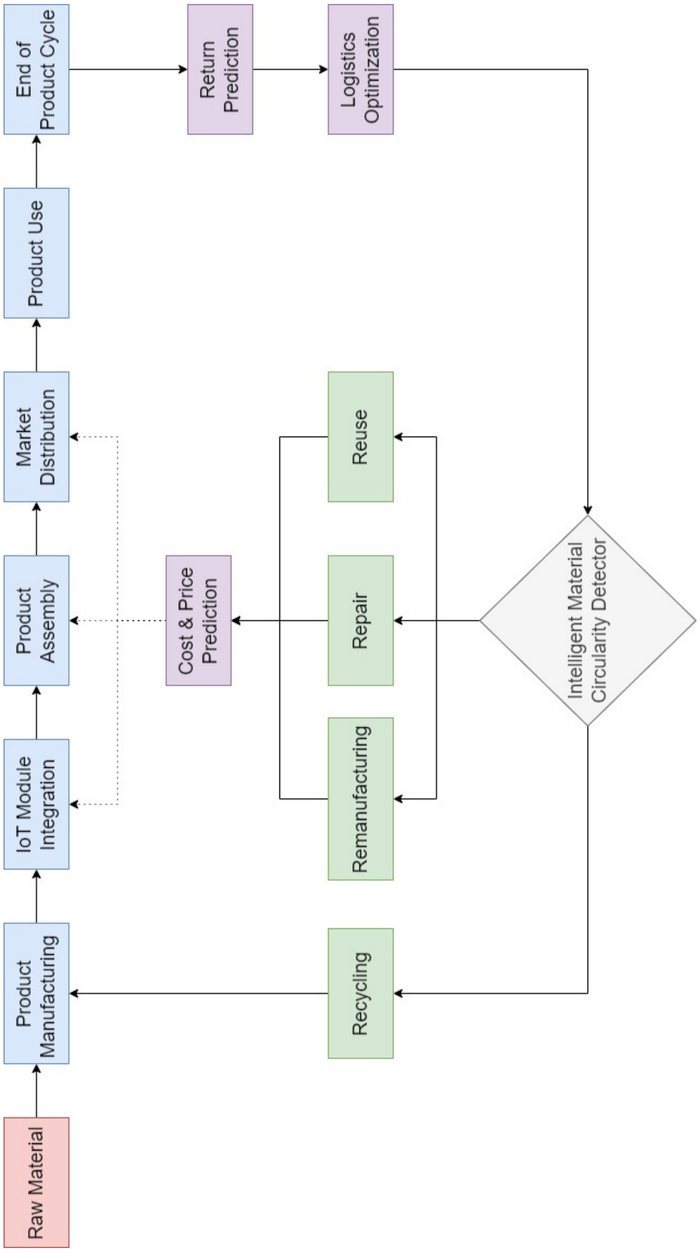

Figure 4: Model using Forward and Reverse Logistics approach, utilized with IoT technologies

6.2.3. Indicative Digital CE Applications

In the corresponding subsection, we study indicative Digital CE Applications that have been proposed by the academic community, while we classify them into two different categories, depending on their circularity concept, Open Loop and Closed Loop applications. Open Loop applications are defined by the availability of re-functionalities benefits for the rest of the circular chain participants when Closed Loop applications are focusing on functionalities used by the producers. Similarly, we define each application as a case of single or multiple sector CE, according to their potential of being used in application fields other than their original purpose. Table 10 provides an overview of the applications regarding their open/closed loop and sector category.

Starting with the Open Loop applications, an example of a circular business model can be seen in [109]. According to the study, a Northern European retailer provides household machinery and devices, implemented with a product service business model. The circularity features are achieved through optional subscriptions providing pay-per-use services while reducing resource consumption. The subscription offers the ability to access the appliance performance, using an IoT kit provided by the retailer, interconnecting the devices, monitoring and controlling them.

The authors of [110] study the process followed by the company called Arup for the construction of circular buildings. Utilizing Building Information Modelling (BIM), the construction was built with easy disassembly, recycling, and remanufacturing materials and components enabling data communication between stakeholders for the whole lifecycle of the construction. It also enables visualization of the building, before the actual physical construction, allowing contractors to contribute with their information on the building's design.

SmartTags is a proposed solution utilizing IoT technologies while aiming at the consumer's contribution. The solution is the creation of digital passports for products, involving data sharing, through printed sensors with modified GS1 barcode standards in QR codes for identification, data collection, and monitoring of usage and lifecycle. The ink of the printed QR codes undergoes visible changes depending on the environmental conditions. The result of the data collected depicts potential recyclability and reuse, by calculating frequency and way of usage [111].

The solution presented in [93] utilizes an application with Blockchain technologies, for waste tracking. The application is provided to all the available stakeholders, enabling tracking capabilities for all the stages of the circularity loop. The depicted data are related to the type of the exchanged materials in the form of transactions, using Blockchain technology, all the related transportation information, and available stakeholder information. The whole process is automated through smart contracts, specifically developed for circularity usage.

Regarding Closed Loop application examples, the researchers of [112] investigate the combination of IoT technologies and data-driven CE through an Indoor Space Usage Monitoring System (ISUMS), providing a more sustainable environment. The model utilizes an IoT system that provides thorough data on presence rates of a shared space, using the LoRaWAN protocol. The data can be used for the formation of sustainability action plans for smart circular buildings and adaptive space management.

A similar solution on waste management is suggested in [113], in the form of seven circular phases. The solution starts with calculating the lifecycle of the product and collecting the waste after the end of the lifecycle. It proceeds with sorting the waste into recyclable materials, categorizing them according to their type, and then undergoing physical and chemical processes, using them as input for 3D printers. Utilizing this input, the 3D printer performs the concept of a digital twin by printing the product's parts. The parts are coupled to form the finalized product, made by recycled materials and performing the circular loop from the beginning.

7. Discussion

The main focus of this article has been to assess the relationship between IoT technologies and Digital CE principles into unified systems, by researching the available literature of the academic community. Starting with the IoT technologies, we believe it is essential to analyze the available application fields, architectural models and features, to understand better the present solutions and proposals of a circular IoT system. Regarding the application fields, it is realized that most of the available studies on energy management and industrial applications, such as Industry 5.0 (I5.0), are based on hypothesis form and less on practical applications, due to the requirements on extensive research and resources. Moreover, although there are various types of architectural models available, the majority of them are based on the

Table 10: Indicative CE applications overview

Application	Open/Closed Loop	Sector Case
Household machinery service model [109]	Open Loop	Single sector
Circular building construction [110]	Open Loop	Single sector
Smart Tags [111]	Open Loop	Multiple sector
Blockchain waster tracking [93]	Open Loop	Multiple sector
Indoor Space Usage Monitoring [112]	Closed Loop	Multiple sector
Multiple phase waste management [113]	Closed Loop	Single sector

foundational layers of IoT models, while using protocols such as LoRaWAN and SigFox.

Regarding the Digital form of CE, there is a mixture of opinions regarding its integration into existing infrastructures. There are positive statements promoting sustainability and growth utilizing new technologies and mainly combinations of IoT, ML and AI, while dedicating Big Data for the massive amount of analytics due to the circularity principles. However, statements are suggesting otherwise, although they are fewer. This opposition is supported in terms of the upcoming costs regarding proper preparation of facilities and individuals, the requirement of new devices, and the period of adaptation for the new circular operations. More solutions can be applied by repurposing, existing data and dark data, beyond their original function. Such cases are capable of providing overall efficiency and maintenance costs, or redirecting the existing resources for side operations and adopting new business perspectives for data-driven products.

Connecting the two concepts, the relations between Digital CE and IoT are mainly on the application field of I4.0, when the involvement of I5.0 is minimal due to the lack of applicable solutions as an independent field. The involvement of stakeholders and consumers enables business models to utilize Blockchain for secure transactions of circular services. Although Digital CE is not only data-driven, there are proposed innovative solutions for a loop of turning physical materials into data input and reusing or recycling the original physical products. Moreover, it is realized that there is a lack of practical applications combining CE and IoT technologies, but several industrial business models.

8. Conclusion

The article assessed the interconnection between IoT technologies, focusing on I4.0 approaches, and Digital CE principles. The research was separated into three sections for proper understanding and analysis of each field independently: IoT, Digital CE, and the relationship between the two.

Results of the analysis showed that Digital CE is heavily dependent on I4.0 approaches for its enabling while promoting positive outcomes for lifecycle and usecycle monitoring. The majority of the architectural models and applications are specifically designed following the traditional principles of CE, such as remanufacturing, reuse, recycling and reassembly. More recent applications involve consumers in their business models for successful circular transitions.

Last but not least, we note that the most common technologies used in such appliances are IoT sensory devices for monitoring, AI for automation, Big Data for analytics, and Blockchain for security and transactions. A positive conclusion of the research is that more and more propositions are slowly turning from theory-based propositions into practical applications.

As part of our future work, further investigation is required regarding applicable integration strategies and Digital CE models, for the creation of a unified CE framework that can be applied in various use case scenarios. Including the architecture designs and technologies to support the collection, processing and organization of the circular data, according to the corresponding use case's requirements.

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