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Towards Industry 5.0 and Digital Circular Economy: Current Research and Application Trends

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***Abstract*—Digital Circular Economy and Industry 5.0 have been two significant research attractions in the last years, due to the evolution of their predecessors into advanced technologies. Circular Economy (CE) has progressed into a sustainable digital approach, capable to be implemented into different scenarios. Industry 5.0 has turned from a fully automated application field into a balanced technological combination of A.I. and M.L. with the involvement of human factor, and promising enabler of Digital CE. As a result, a growing number of Digital CE models are introduced into the academic community. In this work, we collect and examine the latest research and application trends of Digital CE models, by studying their sustainable features, requirements, applications, and architectures.**

***Index Terms*—Digital Circular Economy, Digital Circular Economy Models, Digital Circular Economy Trends, Industry 5.0.**

I. Introduction

Over the last years, there are several technological breakthroughs in the academic community, related to the implementation of sustainable mechanisms and industrial applications. Such cases are the digitization of Circular Economy (CE) and the introduction of Industry 5.0 (I5.0), as well as their further development into unified solutions.

Integration of digital technologies into CE principles has proved to be an effective solution and enabler towards adding intelligence to business procedures and products while providing control and knowledge over the corresponding data to users and stakeholders. Data related to the condition of a product, or status of a service, assist the calculated predictions of health cycles and possible maintenance requirements while improving the potential reuse and recycling of their components [1].

The introduction of I5.0 can be considered a related enabler of Digital CE, due to its capabilities of integrating advanced technologies, such as Artificial Intelligence (A.I) and Machine Learning (M.L.) into the infrastructures, and the increased involvement of human factor, making I5.0 a human-centric application field, rather than its predecessor which is heavily dependent on automated approaches [2]. As a result, advanced A.I. systems utilize observation algorithms to replicate human actions, promoting the synergy between man and machine [3].

A combination of the two approaches enables the creation of circular business models, adopting the principles of both worlds, while leading to sustainable results. Such examples are the controlled amount of waste and its overall management at the end of a product's life-cycle, increased amount of reused and recycled material, and utilizing components for remanufacturing purposes. These operational factors create a trusting environment for customers and healthy competition between businesses and organizations [4].

The methodology followed in our research is a systematic literature review. Google Scholar platform was used to search published material focusing on the years between 2017 and 2022, and indexed by databases such as Elsevier, ScienceDirect and IEEEXplore. Main keywords used for the searching process were "Industry 5.0", "Digital Circular Economy", "Digital Circular Economy Trends", "Digital Circular Economy Models", "CE components", "Digital CE integration", "Digital CE Architectures".

As part of our contribution, we investigate the latest trends on Digital CE models and integration principles. Initially, we examine the concept of I5.0 and Digital CE features. We review the indicative functionalities and components required to support Digital CE infrastructures, and then, we examine solutions of different application fields, to provide a basis for the foundation of integration strategies and architecture designs. We close our paper with the respective conclusion on the findings of the Digital CE models, and our future goals for the corresponding research.

II. Related Work

Authors in [5] conducted research focusing on the creation of a CE framework, supported by digital technologies and implementation guidelines for stakeholders. The corresponding findings are the result of a systematic literature review of published material between 2000 and 2018, on digital technologies and CE principles.

In 2020, the researchers of [6] conducted a systematic literature network analysis, investigating the dynamic evolution of Digital CE literature, including cited and non-cited academic work. The goal of the particular paper is to analyze the focused research trends, principles of CE, and potential future research topics.

A review on the interconnection between Digital CE and I4.0 in the field of manufacturing can be seen in [7]. The authors focused on I4.0 approaches that could implement basic

CE principles, such as Reuse, Remanufacturing, Redistribution, and Recycle, while proposing a potentially functional framework.

Following a correlation analysis method, the authors in [8] investigate Digital CE trends, while examining different use-cases and identifying the most sustainable solution. Findings of the research support the appearance of conflict between the general and green economy, as well as the negative impact of digitalization in terms of growth rate for unprepared countries.

III. Industry 5.0

A. Principles

As supported by [9], I5.0 is expected to drastically affect the manufactory industry, due to the synergy of human interaction and smart systems functionality. By monitoring human actions, the smart systems are capable of repeating all the monotonous tasks, while the human factor is responsible for supervising the quality of the production process, and adding value to the produced products and services due to creativity.

Utilizing the fundamental aspects mentioned above, we provide Table I with the main principles of I5.0, taking into consideration the ones identified in [10] and [11].

TABLE I
I5.0 Main Principles

Principles	Description
Advanced Computing Systems	New hardware components are introduced to perform complex self-organizing computations, with the potential of expanding computing resources.
Internet of Everything	Considered as the evolution of the traditional term of Internet of Things (IoT), it connects people, data, devices, and processes.
Multi-Agent Systems	A network of agents, systems, and technologies equipped with proper sensory devices to solve complex problems existing in a common environment, while exchanging data to achieve their goals.
Knowledge Bases	They are connected to the Multi-Agent Systems in terms of approach since all the data collected are stored into Knowledge Bases. The Bases mainly include concepts, data related to problems, and solution approaches. They are also responsible for the advanced learning and adaptive behavior of smart systems and the prediction of possible approaches.
Emergent Intelligence	Another principle linked to Multi-Agent Systems. Systems perform unpredictable, but non-accidental patterns, due to decision-making and self-organizing processes and interactions with other agents, digital or human.
Evergetics	It is related to the human side of I5.0. It is considered a new type of science, where human agents have the resources to resolve complex issues, perform decision-making tasks, support education and learning between the rest of the agents to solve the corresponding problems, collaboratively.

B. Indicative Applications

As stated in the beginning of the section, I5.0 is defined by the healthy interconnection of digital systems and human interactions. As a result, the concept of a Digital Ecosystem is created by utilizing the collaboration of the two parties. Such ecosystems supported by the I5.0 principles create various applications fields, as seen in [12], [13] and [14]. In Table II we present some indicative examples of such I5.0 applications.

TABLE II
Indicative I5.0 Applications

Applications	Description
Healthcare	Evolving healthcare applications by utilizing smart wearable devices for real-time monitoring and recording data, M.L. techniques to predict diagnosis and human intervention by doctors with access to the corresponding data and performing a personalized treatment. All the processes are being performed collaboratively as a Multi-Agent System.
Cloud Manufacturing	Compared to typical manufacturing, a cloud is utilized to store and operate multinational data, control materials, and machinery, as well as take advantage of decision-making operations for proper scheduling and service organization. Such conditions are achieved through IoT sensory devices and A.I. - M.L. techniques.
Supply Chain Management	Proper technologies can be used to create digital copies of an industry's infrastructure, related to its supply chain management operations, including logistics and resources. Such replicas can be used to simulate real-time processes and predict the actions of real-life case scenarios. Similar approaches are adopted for an industry's production and manufacturing stages.

IV. Digital Circular Economy

A. Features

The main advantage of a digital version of CE is the benefits of Digital Technologies and CE implemented into a unified approach. Different types of products in the production stage can be optimized while increasing life-span, improving quality, tracking use-cycle, location, and condition status for proper decision-making strategies [15].

Another strengthening impact of Digital CE features is the utilization of data, during the stages of collection, analysis, and integration. Such benefits promote the creation and implementation of decentralized manufacturing and industrial systems, supporting the collaboration among stakeholders and clients while performing product and service evaluation throughout their life-cycles [16].

Installation of sensory devices upon products and services enable the functionality of predictive maintenance, optimizing the production process, and motivating the partnership among companies by monitoring the overall condition of a product. The particular partnerships are extended in clients as well, by offering the opportunity of purchasing only their required amount of service. Each level of sustainability is highly supported by open-source software improving the traditional CE approaches of recycling, reuse, remanufacturing, and re-sharing, by maintaining a unique digital passport [17].

B. Underpinning Technologies

Studying the functionalities that accompany Digital CE models, we researched the impact and roles of Digital Technologies in terms of their utility on the corresponding features. We provide Table III with the main technologies supporting CE models, considering the ones seen in [18], [19], and [20].

TABLE III
INDICATIVE I5.0 APPLICATIONS

Technologies	Utility
Internet of Things	Smart sensing for data collection and sharing among stakeholders. Monitoring and analysis of products and machinery. Enables features such as predictive maintenance, life-cycle and logistics monitoring.
A.I. - M.L.	Automatic functions during manufacturing, while providing feedback using decision-making techniques. Enables I4.0 and I5.0 applications, such as faster prototyping, copying human-thinking and actions, sorting waste and materials. Optimizing industrial systems and processes.
Big Data	Supporting analysis of massive amount of data, while being utilized in logistic stages. Assisting in the decision-making strategies for industrial actions. Supports automated processing for reuse purposes and business evaluation.
Blockchain	Providing an effective storage for encrypted data. Offering transparency and smart contracts among stakeholders, through transactions related to data ownership.
Cloud Computing	Providing alternative storage options for data access and management. Assists other supportive technologies and processes, for successful resources management.

V. INDICATIVE REQUIREMENTS

In this section, we discuss the required sustainable functionalities and components required for Digital CE models, as they are essential for understanding their operational concept and fundamental requirements.

A. Sustainable Functionalities

a) Supply Chain Management: Implementation of Digital Technologies in Supply Chains, evolves the traditional concept of CE, into an advanced system capable of providing data and information on processes of key importance, interruption alerts and scheduled objectives. The corresponding functionalities are supported by the fundamental CE features of cost optimization and a product's use and life cycles [21].

b) Smart Remanufacturing: Smart remanufacturing can be considered an expanded version of the traditional meaning, due to the optimized status offered by digital technologies. Simulating and utilizing Additive Manufacturing techniques during the process of remanufacturing, improves the decision-making strategies for efficient selection of disassembling and recovering components, considering their use frequency, as well as accessed data of data-driven models. [22].

c) Smart Recycling: As explained in [23], the main aspect of smart recycling is the availability of information between stakeholders for sustainable results and cost management of the marketplace. Such systems provide the available knowledge regarding regained and recyclable components and data, for value prediction and optimized decision-making, connected to the remanufacturing process.

d) Smart Reuse: Assisting data-driven CE models by reusing data for updating, improving and further developing sustainable processes and tasks, on production and supply chains for costs and resources management, and energy efficiency [18].

B. Component Requirements

Successful Digital CE models are defined by a variety of factors rather than just the implementation of advanced technologies for I4.0 and I5.0 integration. Taking into consideration [24] and [25], we study the required resources for sustainable CE business models.

An essential component is proper leadership management in the organization. Proper leadership can offer accurate guidance in the implementation of new sustainable approaches, and assist the preparation of the organization for the integration of new technologies and Digital CE models. It also guides the necessary management shifts from traditional models to technologically sustainable systems. Including empowerment of the personnel, by motivating them for the development of an innovative mindset over sustainable performance.

Strategic planning indicates alignment between organization changes due to CE models and new technologies integration. It supports the whole process of combining the technology integration into the new business plans, by preparing both the employees and the infrastructure for new supply chain equipment, sustainable knowledge, and skills. Such an approach can potentially lead to the creation of a specialized transition team, with proper communication over common goals, technical field knowledge, and communication principles.

Technological components, such as the Internet of Things and Big Data are essential enabling factors of remanufacturing, recycling, and reuse in the production and supply chains. Both disassembly processes and data control are assisted by decision-making strategies through reverse logistics and a combination of A.I. Cyber-physical systems reduce waste while producing only the required amount of products and services, without excessive expenditure of resources. Cloud Computing enables alternative storage options and capabilities such as additive manufacturing for energy, resources, and inventory management. Table IV provides an overview of the required resources and components.

VI. RELATIVE IMPLEMENTATION SOLUTIONS

As part of our contribution, the corresponding section is focused on studying and analyzing CE models supported by digital technologies, belonging to different application fields: energy management [26], supply chain management [27] and data-driven models [28].

TABLE IV
COMPONENTS AND RESOURCES FOR CE BUSINESS MODELS

Components	Effects
Proper Leadership	Accurate guidance for new sustainable approaches. Preparation for Digital CE models integration. Shifting management process towards new sustainable trends. Motivating personnel for the development of new skills and knowledge.
Strategic Planning	Alignment of organization goals and new technologies integration. Implementation of new technologies into CE business plans. Preparation of the infrastructure and personnel training. Creation of a specialized transition team.
Technological	IoT and Big Data for remanufacturing, recycling and reuse. Reverse Logistics and A.I. for disassembly, data-control and decision-making strategies. Cyber-physical systems for waste control. Cloud Computing for storage, additive manufacturing and resources management.

In Subsection VI-A we provide the respective description regarding the functionality of each model, in Subsection VI-B we examine each model according to their implementation strategies, in order to create an integration process basis, and in Subsection VI-C we study their respective architectures and components for a foundational design of a CE model.

A. Implementation Fields

Starting with [26], the authors of the work investigate the integration of Blockchain technology into energy management systems and smart grids, to enable sustainability and CE principles. The study takes into consideration the role of energy policymakers and the potential challenges that may accompany such transition. Both the barriers and process methods are categorized and analyzed through numerical analysis.

The authors of [27] study the connection between I4.0 and CE principles, as well as their practical implementation into business models and cases. A solution based on automated Closed-Loop Supply Chains is introduced while considering the implications on stakeholders and policymakers.

A data-driven model is proposed in [28], focusing on a sustainable and circular approach on information flow and life cycle management in the process of recycling. The model emphasizes the interconnection of stakeholders, enabling the features of resharing and reusing data.

B. Integration Strategies

In the case of Blockchain technology integrated with energy management, the researchers emphasize that Smart Grids are defined by their dynamic structure and energy management parameters, both technologically and socioeconomically, leading to changes in energy policy. The results of such changes is the shift of stakeholders from consumers to producers and the general Smart Grid consisting of a network of micro-grids for data exchange. Due to the importance of the energy sectors, the authors of the study support that a decision-making committee is essential for criteria recognition, determining upcoming challenges, and verifying the consistency of the potential implementation.

The proposed solution for I4.0 in Circular Supply Chains supports the positive impact of digital technologies on business' infrastructure since they enhance productivity, proper resources management, and the general implementation of smart equipment. The respective model is heavily based on the ReSOLVE framework by Ellen McArthur Foundation, and tested in three different companies. The researchers state the importance of identifying suitable digital technologies in an organization, and the two important factors for the model's integration: proper company preparation through training and motivation by technical experts, and guarantying the company's culture is suitable for enabling circularity principles in its infrastructure.

Finally, the suggested data-driven architecture studies a gradual approach of circular technologies into an organization's premises. Such examples involve changing the business perspective from hierarchies to distributed networks, adaptation according to tasks, implementation of cognitive and self-optimized systems.

Taking into consideration the information and data provided by the three respective framework proposals, we present Fig. 1 as a foundation of the CE integration process into a business model.

C. Indicative Architectures

Regarding the architectural framework of the Energy Management model, the circularity principles are supported by the role of prosumers. According to the researchers, prosumers are stakeholders that produce renewable energy and share the excess energy with the rest of the micro-grids for commercial purposes, while the whole infrastructure is supported by Blockchain technology. Blockchain provides efficient transactions through P2P, which also enhances the reduction of harmful emissions, smart contracts, and faster data evaluation.

The solution implementing I4.0 technologies for Circular Supply Chains proposes a two-part solution establishing sustainability. The first component is an Online Bidding Process, enabling automated matchmaking between clients and suppliers, through a matchmaker evaluating all the information provided by the clients' request and the suppliers' offers, until a final transaction is completed. The second component begins its operation through a Blockchain application, performing waste management tracking of the closed-loop supply chains, both for the client and supplier, with the data being logged as unchangeable transactions.

The data-driven model consists of three main layers. The Data and Information Collection Layer focuses on collected data from sources such as User Applications and Data Market-places, with cloud and decentralized storage options. The Data and Information Exchange Layer focuses on data exchange

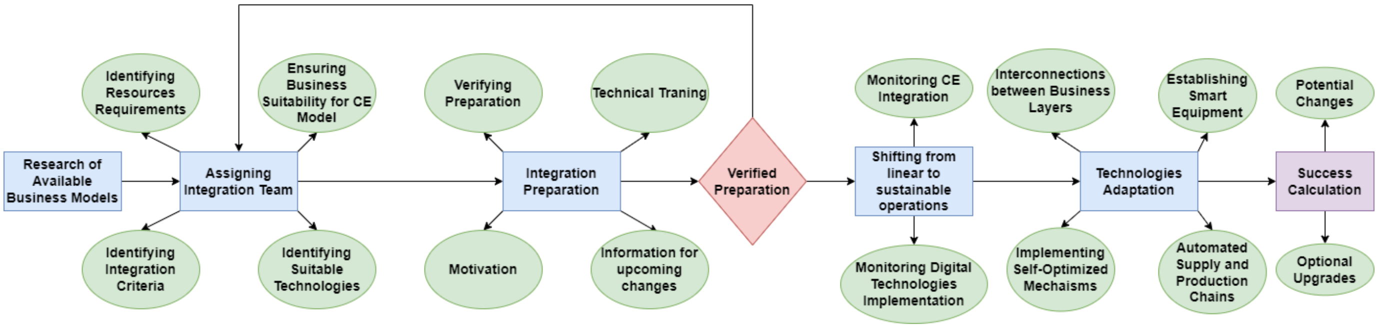

Fig. 1. Foundation model of CE integration process into business models

between stakeholders through smart contracts, with another implementation of Data Marketplaces. The two Layers are connected with RESTful data protocols for the data exchange. The last component is the Robot System Layer, which is the basis of the automated machinery and technologies, integrating a human-machine interface, for all the required CE operations.

Supported by the evidence presented by the three frameworks, we present Fig. 2 as a High-Level basis of a potential CE framework for business integration. Beginning with the production process, the organization's data can be stored in a cloud and perform the two phases of Data Collection and Data Exchange, between stakeholders and patterns, while enabling the feature of reuse. The implemented I4.0 and I5.0 technologies, such as IoT, A.I. and M.L. are implemented into the Automated Supply Chain processes, for the required distribution of products, services, and data to the consumers. Depending on the type of consumption, the consumer can have the option to share their data with other consumers or the company itself, through smart agreements, enabling the features of sharing and smart recycling.

VII. Conclusion

In this paper, we discuss the progression of I5.0 technologies and Digital CE, through their features and relative implementations. We investigated the recent research trends and preferences regarding CE business models while paying attention to studying integrations related to different industry fields and applications, by showcasing a potential foundation regarding implementation steps and CE framework. As part of our future work, further research on the integration process and architectural framework is required, for detailed necessary components and technologies for a fully adaptive solution to support our findings fully.

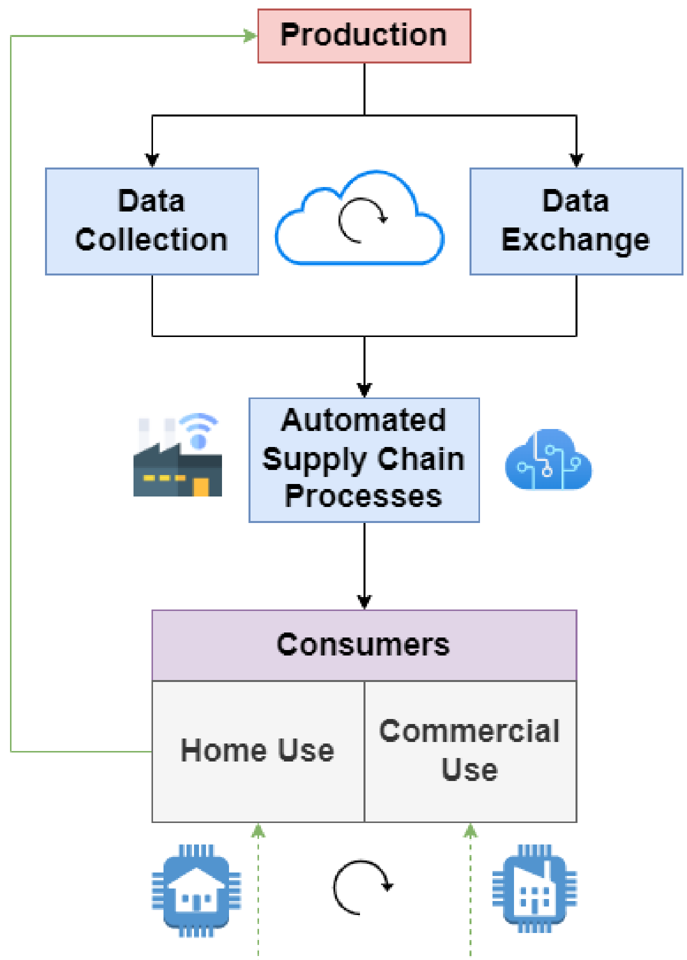

Fig. 2. A High-Level diagram of a potential CE framework

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