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Emerging Technologies Enabling the Transition toward a Sustainable and Circular Economy: The 4R Sustainability Framework

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Abstract

A Circular Economy is an emerging economic model, restorative and regenerative by both intention and design. By keeping materials at their optimal use and value continually, the system is considered to be optimized. The Circular Economy evolves in a repetitive cycle, where waste is returned back into the life-cycle of the product by recycling and reusing materials. The Circular Economy represents a sustainable and productive economy model that is financially, economically, and socially feasible. It is widely regarded as an acceptable and desirable solution to achieving prosperity whilst acknowledging ecological and social boundaries.

Opposed to the unsustainable Linear Economy, it draws on complexity and systems thinking by imitating nature that does not produce any waste. However, the implementation of the Circular Economy in industry is slow paced, mainly due to barriers caused by complex sustainability transitions and innovations needed to cover a systemic and system thinking approach.

In the last few years, the concept of a Circular Economy and the transition from a linear, take-make-waste system to a cyclic system that reuses, remanufactures, and recycles materials, have gained increased importance and attracted considerable attention from both scholars and practitioners. Research that examines the role of emerging technologies in supporting this transition is therefore imperative. It has also become a key policy objective due to the increasing pressure on policymakers and governments to introduce measures to ensure sustainability, bio-based products and sustainable processing.

This study discusses the concept of the Circular Economy as well as the transition from a linear to a closed-loop Circular Economy based on resource regeneration and ecosystem restoration. It unfolds the role and importance of emerging technologies related to Industry 4.0 and Industry 5.0 in this transition by analyzing their adoption and implementation in the context of Circular Economy. The key benefits of transformational change include increased engagement, improved performance, and higher levels of creativity and innovation.

The ultimate and implicit aim of this paper is to increase awareness of the actions needed from every single individual on earth and to increase understanding of the fact that the use of emerging technologies is not a magic stick to address the ecological challenges but a tool for supporting the transition to a cleaner environment. To obtain an authentic and genuine transition, a fundamental social and cultural shift needs to pave the way.

Keywords: Circular Economy, Sustainability, Blockchain, Artificial Intelligence, Internet of Things, Sustainable Development Goals

1 Introduction

The economy of today is wasteful. We are using the equivalent of 1.6 Earths to maintain our current way of life, meaning that natural resources are consumed to an extent that exceeds what the Earth can generate each year[1]. A

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[1] https://euagenda.eu/news/710876

shift in the way we use resources, materials and energy within the economy should urgently be made to come up with more sustainable solutions; hence, a social and cultural shift is required, as it has been pointed out in the 2030 Agenda for Sustainable Development[2].

No waste is produced by nature. Biodegradation breaks down dead plants, animals and the things produced from them so that invaluable nutrients are released into the environment to be reuse by other organisms. The whole planet is an interconnected complex and adaptive system thanks to this principle [37]. On the contrary, since the industrial revolution, design, production, and consumption systems have predominantly been based on a linear system that extracts, uses, and then discards resources at the end of their life. This trend is also called "*take-make-dump/take-make-dispose/take-make-waste*". The closed-linear system, powered by finite fossil fuels resources, such as oil and gas, depends heavily on immense consumption. It leads to resource scarcity and pollution and has a profound environmental and social impact. This outdated worldview is based on the 18th century enlightenment period, which comprehends natural systems through a mechanistic approach [52]. Unsustainable consumption, resulting in increased extraction of raw materials, manufacturing, and production, is contributing to environmental deprivation and acceleration of climate change.

The European Union (EU) binding recycling target[3], which indicates progress toward using more waste as a resource, can be mentioned as an attempt to address these challenges. However, recycling rates of packaging waste, municipal waste and electrical and electronic waste are progressing at a very slow pace in Europe. A surprising result is that the rate of progress is has been slowing down lately, with packaging waste recycling even decreasing in the past 5 years. The majority of waste ends up in diverse disposal operations including incineration and landfills. This clearly indicates that a fundamental social and cultural shift is a must. Circular Economy (CE) strives to prevent waste and pollution from being created in the first place. In contrast to the Linear Economy, the CE concept derives from a systemic and system thinking approach that tries to imitate natural systems which are considered as open, diverse, adaptive, complex, resilient, and optimized [9; 12; 15]. CE thinking has increasingly been encouraged in business, policy, and academic discussions to address environmental sustainability that aims to minimize waste and make the most of resources [7]. CE can be seen as a systems solution framework that tackles global challenges, such as climate change, biodiversity loss, waste, and pollution. It keeps materials, products, and services in circulation for as long as possible. The CE is a promising approach for addressing challenges of the Anthropocene and a key principle for accomplishing the Sustainable Development Goals (SDG)[4].

Figure 1: Linear, Recycling and Circular Economy regarding the amount of waste created

Figure 1 shows the differences in the amount of waste in the Linear, Recycling, and Circular Economy.

Studies have showcased that CE is steadily gaining ground and is leading to significant economic benefits [e.g. 8; 48]. Conceptual research has also identified diverse drivers and barriers to the transition [44]. The most noteworthy barriers are regulatory, market, technological, cultural, and organizational barriers. The regulatory, organizational, market and cultural barriers are likely to be reduced by increased awareness, as well as compensatory and punitive actions. Innovation is a crucial aspect of CE [21], together with changes in consumer behavior, design approaches, and material choices. In particular, awareness of acceptable consumer behavior in the light of CE needs to be cultivated.

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[2] https://sdgs.un.org/2030agenda & https://sdgs.un.org/goals
[3] https://www.eea.europa.eu/ims/waste-recycling-in-europe
[4] https://www.un.org/sustainabledevelopment/sustainable-development-goals/

The emphasis of this paper is on the transition from a linear to a closed-loop Circular Economy based on resource regeneration and ecosystem restoration. More specifically, this paper unfolds the role and significance of emerging technologies in this transition. The main contribution of this study is the development of insights that contribute to the adoption and implementation of emerging technologies related to Industry 4.0 and Industry 5.0 and their integration into CE to minimize the effects of resource scarcity through innovative alternatives. This study also contributes to raise awareness of threatening ecological challenges and to increase understanding of the underlying social and cultural factors that need to be nurtured and encouraged to accomplish the transition to a CE.

The remainder of this study is organized as follows. In the following section, we introduce prior work regarding the CE. The amplified challenges, particularly the ones relating to the urgency of transitioning to a CE are discussed as well as the role and importance of emerging technologies in achieving this transition. It continues by presenting different emerging technologies through the lens of sustainability and CE. The 4R Sustainability Framework is outlined in Section 4. Finally, conclusions and future research directions are provided.

2 The Circular Economy

The definition of the Circular Economy was given by the European Union in December 2022[5]: ”The *Circular Economy (CE) is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible”*. The definition is followed by an explanation “*In practice, it implies reducing waste to a minimum. When a product reaches the end of its life, its materials are kept within the economy wherever possible. These can be productively used again and again, thereby creating further value*”. In practice, this means a sustainable development that meets present needs without compromising future generations’ needs.

The EU produces more than 2.5 billion tons of waste every year[2]. By 2050, worldwide municipal solid waste generation is expected to have increased by roughly 70 percent to 3.4 billion metric tons[6]. The Circular Economy aims to tackle global challenges, such as climate change, waste, pollution and biodiversity loss, by implementing a design-based approach regarding three basic areas, namely: waste and pollution, circulation of products and materials, and regeneration of nature. Three main actions, called the 3R Principles, related to CE are Reduce, Reuse and Recycle[7]. The 3R initiative was launched by the G8 summit in Tokyo in 2005 with the “*aim to shift the global consumption and production patterns towards building a sound-material-cycle* society” [7].

The Finnish Bio-economy 2035 strategy, updated in 2022[8] as seen in Figure 1, includes three overlapping circles, namely Ecologically Functional (Biodiversity, Carbon capture, Solutions to Global Problems), Economically Rational (Double value added, Advanced technologies), and Socially Sustainable (Equity, Well-being, Jobs).

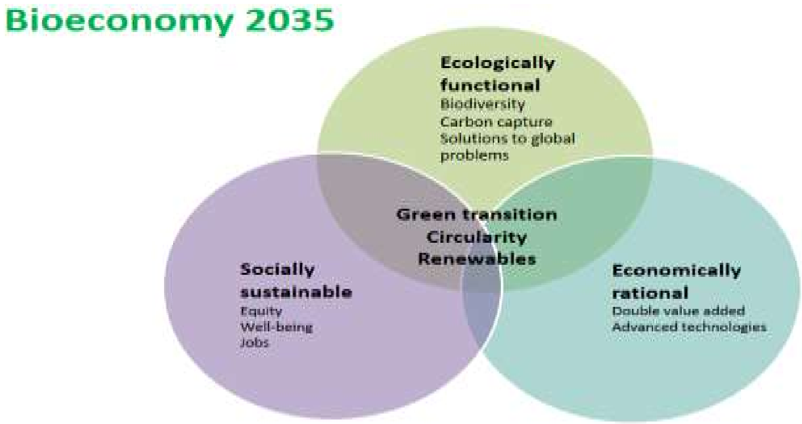

Figure 2: Finland’s Bio-economy 2035 strategy

[5] https://www.europarl.europa.eu/news/en/headlines/economy/20151201STO05603/circular-economy-definition-importance-and-benefits
[6] https://www.statista.com/topics/4983/waste-generation-worldwide/
[7] https://uncrd.un.org/content/3r-initiative
[8] https://www.bioeconomy.fi/facts-and-contacts/the-finnish-bioeconomy-strategy/

The common area of the three overlapping circles includes equivalent weightings from the three circles and is expressed as Green Transition, Circularity and Renewables. In other words, the common area articulates the transition from a linear economy to a greener, renewable, and circular future.

Both the CE and Circular Business Models (CBMs) are conceptualized and depicted in various ways leading to increasing divergence and a growing semantic dissonance which are intensively detrimental to the implementation of CE principles [7]. For example, Pieroni et al. [39] argued that the existence of different CE propositions without a consensus might hinder the knowledge consolidation in the field. They claimed that it is fundamental to establish a common discourse and a common language in order to facilitate the dissemination and adoption of circular objectives collaboratively both at an interorganizational and at a societal level.

3 Transition from a Linear to a Circular Economy

Taking part in the CE is a necessary step toward sustainability and fighting climate change. Sustainability can be said to be an approach to systems level that includes economic, social/societal and environmental/ecological factors and the assessment of their interaction [33]. The Triple Bottom Line business concept (Economy, Society and Environment, also called the three Ps: Profit, People, and Planet) suggests that to create increased business value, businesses should commit to measuring their performance in a broader perspective by including social and environmental impact in addition to their financial performance [53].

Some scholars have been critical regarding the CE concept in reference to the following:

i. Contradictory definitions of CE [23];
ii. Theoretical robustness of the CE concept developed by policymakers and businesses [45];
ii. Eco-efficiency may lead to more consumption, the so-called "*Jevon's paradox*" [24];
iii. Long-lasting products may not be environmentally friendly (disposal difficulty) [32];
iv. Prolonged use of eco-inefficient products [3].

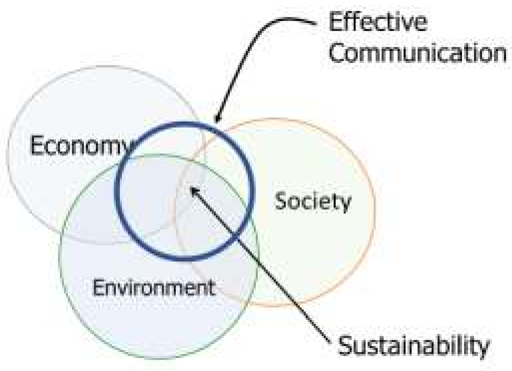

Figure 3: Sustainability adapted from [53].

Sustainability is an umbrella term that addresses a wide range of scenarios and issues and is far more complex than simply focusing on conservation, eco-friendly options, and renewable energy. To obtain sustainability, a shift in mindsets is essential. Effective communication is imperative for increasing awareness of the need for sustainability. Figure 3 depicts effective communication as a circle covering all dimensions of the Triple Bottom Line.

Many businesses have made the decision to transit to a circular and more sustainable approach. The main social concerns related to the Circular Economy are employment, health and safety. Child labor employed in textile recycling facilities in India are reported[9]. As businesses move toward a more Circular Economy, it is inevitable that there will be impacts on both the economy and the employment levels. Labor demand will have negative

[9] https://www.business-humanrights.org/en/latest-news/india-new-report-released-on-prevalence-of-child-labour-and-labour-rights-violations-in-the-textile-recycling-industry-in-panipat/

impacts on the extraction and disposal phases of consumption, and positive impacts on activities related to recycling.

4 Emerging Technologies enabling the transition to CE

The European Commission's Circular Economy Action Plan[10] explicitly states that "*digital technologies, such as the Internet of things, big data, blockchain, and artificial intelligence will... accelerate circularity*". Similarly, numerous businesses worldwide have built on digital technologies to further circularity. However, the progress toward CE implementation in the industry has been slow paced [38]. Diverse emerging technologies, such as Internet of Things (IoT), Cyber-Physical Systems (CPS), blockchain, Artificial Intelligence (AI), and cloud computing are enablers for the transition to a CE. They are also often used in combination. Moreover, small-scale chemical transformation processes enable shifts in the production-consumption and socio-economic systems [5]. Examples of recycling solutions include "*micro-recycling*" (selective synthesis of materials from electronic waste) [46]; "*peer-to-peer circularity*" (features of the sharing/platform economy regarding access over ownership) [2]; and 3D printing-enabled production and consumption [49; 16].

4.1 Industry 4.0 and Industry 5.0

The fourth industrial revolution (Industry 4.0) aims at transforming traditional industries into intelligent ones by incorporating innovative, intelligent, and smart technologies. CPS, IoT, and digital twins are some of the contemporary technologies that are used in the context of Industry 4.0 to instill intelligence into the industrial sector by changing traditional manufacturing to smart manufacturing [1; 41; 27].

Industry 4.0 enables physical assets to be integrated into intertwined digital and physical processes creating, thus, smart factories and intelligent manufacturing environments [30]. Industry 4.0 can be described as the convergence of several emerging concepts and new technologies, including radio-frequency identification (RFID), smart sensors, robotics, additive manufacturing, big data, cloud computing, AI, machine learning (ML), and IoT [6]. The main goal of Industry 4.0 is to enhance and transform traditional industries into "intelligent" ones by using new technologies and the improved computation power and hardware of modern systems and by creating a network of interconnected machines, devices, processes, and systems that can interact with each other in real time [26]. Manufacturing industries that adhere to Industry 4.0 technologies are expecting transformational and promising solutions [11].

Industry 4.0 and the CE are two major areas in the current manufacturing industry and they are both still in the nascent stage of development. It is generally expected that Industry 4.0 technologies will contribute to the CE. Despite the differences in aims, the technologies and approaches used in the context of Industry 4.0 can also be used for achieving a CE; hence, Industry 4.0 and CE are complementary. However, it is rather unclear how Industry 4.0 technologies might contribute to CE. Industry 4.0 has been recognized as a dynamic enabler of circular approaches which, in turn, can lead toward sustainable Industry 5.0 solutions [32].

Smart manufacturing provides autonomous decision making and simulated environments and optimizes the entire operation procedure (by digitalizing the production process as well as by transmitting, collecting, and analyzing data) [47], thus, it effectively influences the whole manufacturing process by increasing productivity and reducing costs [27]. Enterprises, which capitalize on smart manufacturing, utilize data analytics and information and communication technologies (ICT) so as to change from knowledge-based manufacturing to data-driven intelligent manufacturing [26].

Industry 5.0 leverages collaboration between creative human experts and powerful, smart, and accurate machinery. It is anticipated that Industry 5.0 will merge this machinery with cognitive thinking humans, thus creating versatility between humans and machines, improving human-machine interaction, and enabling real-time monitoring. Reddy et al. [42] argued that the quality of the production will increase by assigning repetitive and monotonous tasks to processes, robots, and machines and tasks which need critical thinking to humans. They also asserted that another important contribution of Industry 5.0 is mass personalization according to customer needs and preferences.

[10] https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en

Di Maria et al. [1] quoted that smart manufacturing technologies have a greater impact on CE outcomes than data processing technologies. Industry 4.0 can also be linked to the aims of the CE to disentangle environmental pressure from economic enhancement and bring the environment, economy, and society in harmony [18]. CE seeks cleaner production arrangements, adoption of renewable technologies and know-how, and development of appropriate policies and tools. Interweaving the issues of Industry 4.0 into the systems development life cycle (SDLC) from the perspectives of sustainability and CE will bring combined effects and important meaning to the world. Industry 4.0 is transforming operations management in industrial automation and manufacturing, supply chain management, lean production, and total quality management [6]. Rahanu et al. [41] proposed that Industry 4.0 designers and developers need to be conscious of the duty they have to incorporate ethics into the system specification and design at every stage of the SDLC. This also true for CE designers and developers as ethics and social responsibility are key aspects of CE.

Mumbarik et al. [34] suggested that policymakers and managers should promote Industry 4.0 technologies, such as blockchain technology because they (i) enhance the integration across the streams of the supply chain (ii) improve the demand and supply planning, eliminating, thus, redundant production and enabling just-in-time production, and (iii) promote green supply chain practices by eliminating unnecessary operations. However, a major shortcoming limiting the widespread application of blockchain technology is the huge amount of power required in validating transactions.

4.2 Cyber-physical systems (CPS)

CPS include engineered interacting networks of effectively integrated cyber and physical processes and components enabled by a network, contemporary computing, and sensor technologies [28]. They can be considered as complex multidimensional systems or systems of systems with real-time requirements. They can exert influence on both the digital and physical worlds. These interconnected and interdependent systems can work autonomously both collaboratively and independently due to the dynamic integration of control, computing, and communication. They can also interact with the physical environment by safely and robustly manipulating, emulating, controlling, and monitoring real processes, entities, and objects in real time. Such systems play an important role in enabling innovative services, solutions, and applications, impacting various aspects in everyday life and increasing the global market competition. Hence, they can be considered as critical infrastructure. The demand for their integration and utilization in various domains is continuously rising. Examples of their application domains are smart cities, intelligent manufacturing, e-health, e-commerce, agriculture, robotics, transportation, environmental quality, and energy.

4.3 Smart Additive Manufacturing (SAM)

A cost-effective manufacturing industry approach that supports execution of development plans, pollution reduction and resource utilization throughout the development life cycle is sustainable or additive manufacturing [42]. It is a process of creating an object by building it one layer at a time, opposed to subtractive manufacturing, in which an object is created by cutting away at a solid block of material until the final product is complete. Smart additive manufacturing (SAM) applies AI algorithms for accuracy and better graphical representation (e.g., 3D printing product design). Sustainability, profitability, and productivity are the main advantages of smart manufacturing industry. Additive manufacturing in Industry 4.0 facilitates transparency, interoperability, automation, and practicable insights [19].

The creation of digital twins of objects, machines, systems, processes, and assets are no longer just physical copies but virtual models [27]. Industry 4.0 capitalizes on this fact in order to perform real-time monitoring and optimization through simulation-based decision support tools utilizing digital copies of physical systems.

SAM enables material reduction and adequate resource consumption leading to contamination free environmental production. To obtain the utmost benefits of Industry 5.0, SAM is merged with integrated automation capability to streamline the processes involved in supply chain management and reduce the delivery time of the products.

4.4 Blockchain Technology

Blockchain technology is becoming popular in several domains (e.g., supply chain, retail, healthcare, insurance, travel, and energy) as well as in the context of Industry 4.0 due to its ability to decentralize data and processes whilst also warranting security [28]. Particularly, Blockchain is an open-source, peer-to-peer, distributed ledger including multiple transactions and related data stored within a chain of interconnected blocks in decentralized, peer-to-peer, open-access network [28; 54]. These blocks can be validated by the network using cryptographic means [36]. It is used for sharing and updating information by linking ledgers or databases in a decentralized open-access network and as a result, it improves collaboration and interaction between organizations and individuals within the network. It has the potential to create cleaner economic transactional processes and help achieve balance and harmony in the environment, economy, and society [18]. The underlying foundation of the CE is sustainability, ethical cleaner production, and social responsibility. This applies for both service and manufacturing industries. Furthermore, blockchain is characterized mainly by anonymity, transparency, auditability, permanence, persistency, and decentralization which in turn lead to improved performance, efficiency, and reduced costs [28; 55]. During the transaction processes, the blockchain technology uses public and private keys, which although traceable, are not disclosed [40]. Blockchain technology as a powerful distributed ledger tool of secure interconnectivity has the ability to facilitate cleaner production of goods and services, address the ethical agenda of business development, and support the creation of a CE.

Böhmecke-Schwafert et al. [4] presented a theoretical model which included the relationships among (i) drivers and barriers of the transition to a Circular Economy; (ii) blockchain innovation for the Circular Economy; (iii) technical challenges of blockchain; and (iv) Circular Economy. Additionally, studies have shown that the blockchain technology can contribute to the Circular Economy by reducing transaction costs, enhancing performance and communication along the supply chain, ensuring human rights protection, enhancing healthcare patient confidentiality and welfare, and reducing carbon footprint [50]. On the other hand, the environmental effects of blockchain technologies are also expected to bear pressure on the environment. Running a blockchain requires a significant amount of electricity, particularly when mining cryptocurrencies. However, blockchain integration in renewable energy sources could be the key to realizing energy sustainability by acting as an enabler for the creation of a decentralized and democratized energy system.

4.5 Artificial Intelligence (AI) and Machine Learning (ML)

AI is an important enabler for CE. It is central to realizing the transition from a linear to a Circular Economy. It can support the design, creation and maintenance of circular products and the creation of circular business models [45]. AI can be used for designing robust and sustainable products, facilitating new circular business models, and supporting the broader infrastructure needed to scale circularity [45]. Researchers [e.g., 22] have worked toward attaining SDGs by using AI and ML.

ML capitalizes on the increasing amount of data, the advancements in processing and computational power as well as the use of algorithms and statistical models. It imitates the human way of learning through examples by drawing conclusions from patterns in data without following explicit instructions [28]. By employing ML, human-like decision-making systems can be established which enhance the overall efficiency of a specific process or task without requiring any human intervention.

The use of AI and ML aims to develop an efficient mechanism to facilitate CE by taking the needs of the present generation into consideration without disconcerting the capability of future generations. AI encompasses a set of technologies that include ML and natural language processing (NLP), which enable machines to feel, understand, act, and learn [25]. AI aims at creating machines, systems, and applications that simulate human intelligence and imitate human actions to achieve increased rationality, learning, and reasoning capabilities [28]. As AI-based systems can observe their surrounding environment and autonomously carry out tasks, they have the potential to self-learn, adapt, and transform [26]. Used in conjunction with other novel technologies (e.g., ML, big data analytics, etc.), AI can assist in the creation of intelligent, autonomous, rational, and sophisticated decision-making systems [13]. When integrating AI into organizations, their overall efficiency, performance, and gains can be improved. Although there are several open issues and challenges related to privacy, security, fairness, and interoperability of AI systems, the use of AI to achieve a CE is vital as they can support the realization of CE in several domains including [31]:

- *Design of circular products, components and materials*. AI can accelerate and enhance the development of new products, components, and materials that fit the Circular Economy through iterative ML assisted design processes that allow for rapid prototyping and testing.
- *Operation of circular business models*. AI can increase the competitive strength of Circular Economy business models, such as product-as-a-service and leasing. By combining real-time and historical data from products and users, AI can help increase product circulation and asset utilization. This will have an influence on pricing, demand prediction, predictive maintenance, and smart inventory management.

- *Optimization of circular infrastructure.* AI can help build and improve the reverse logistics infrastructure required for improving the processes of sorting and disassembling products, remanufacturing components, and recycling materials.

4.6 Internet of Things (IoT)

IoT can semantically be defined as a dynamic, addressable, self-configuring, and world-wide network infrastructure of interconnected "*things*" that is based on standard and interoperable communication protocols [30]. Within this infrastructure, "*things*" possess sensing, communicating and naming processes. They are interconnected and seamlessly integrated into the information network that connects resources and collects data about the physical and virtual worlds.

IoT pervades our everyday and its objects, linking the physical to the digital world and allowing people and "*things*" to be connected anytime, anywhere, with anything, and anyone, ideally using any network and service [29].

For some time now, the manufacturing sector has been using sensors and devices as part of IoT projects to improve efficiency, detect and prevent issues before they occur, and maintain products remotely. Remote monitoring is becoming the norm, with manufacturers now seeking to extend this to improve customer experience (CX) and build brand loyalty. Industrial Internet of Things (IIoT) is a complex system of diverse systems and devices that function more efficiently than the sum of its parts and focuses on intelligent manufacturing and modern industries by implementing secure, autonomous, and robust connection and data exchange among "things".

IoT enables enterprises to gain a competitive advantage by providing more effective scheduling, planning, and controlling of operations and systems, ubiquitous connectivity as well as efficient decision-making systems and decentralized data analytic tools that develop insight, enable real-time responses and reactions and improve the capability of monitoring and controlling enterprise processes and assets [27]. To enhance productivity, intelligence, and efficiency, IoT combines several emerging technologies and utilizes networks of embedded sensing devices that communicate and share intelligence. For IoT to be fully integrated and its full potentials to be realized within the context of Industry 4.0, several security challenges need to be addressed.

The evolving capabilities of IoT opportunities in the CE have given rise to the creation of new technological architectures, such as IoT circular strategies and designs and enhanced systems of reusing, remanufacturing, and recycling enabled by IoT technologies [51]. Industry 4.0 and Industry 5.0 promote new perspectives in production and consumption by incorporating circularity principles. Additionally, the combination of Industry 4.0 and Industry 5.0 with CE is a key enabler for reduced costs, increased efficiency in monitoring resources, and high-quality throughout the life cycle of products and services. From a technological perspective, IoT technologies apply process algorithms developed for analysis of generated circular data and provide optimized decision-making actions for circularity [43].

5 The 4R Sustainability Framework

Dufourmont et al. [14] identified aspects that often remain blind spots in the literature and practice of the circular economy. These areas of ignorance involve: legal systems, culture, education, quality of life, values, behavioral norms as well as governance and political considerations. Therefore, this study advocates the proposal of a fourth R, RETHINK, which can be appended to the 3R Principles (Reduce, Reuse and Recycle)[11], presented above, related to CE.

The new, proposed 4R Sustainable Framework, shown in Figure 4 embeds in the very core of the 3R Sustainability Model a need for changing mindsets and taking action that demands the areas of ignorance be consciously considered. Whatever the initial aim, it is proposed that RETHINKing involves evaluation and quantification of the results.

[11] https://uncrd.un.org/content/3r-initiative

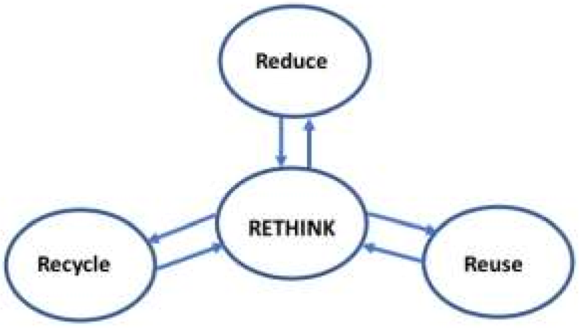

Figure 4: The 4R Sustainability Framework

For example, if the aim is to achieve reduction of using resources (physical, economic, human) by planning and following actions toward achieving reduction, the RETHINK module/stage will quantify the outputs and outcomes from different perspectives. The impact of actions (or inactions) will be manifold. This study argues that RETHINK can be considered and deployed via the use of two analyses: 1) Ethical/Legal and 2) Sociocultural, Technological, Economic, Environmental, Political, Legal, Ethical, and Demographic (STEEPLED).

5.1 Ethical / Legal Analysis (ELA)

According to Rahanu et al. [41], RETHINK includes an Ethical and Legal Analysis to extend the Sustainability Model shown in Figure 4. Kallman and Grillo [20] advocated a framework for conducting an ethical/legal analysis comprising a set of logically related steps. These steps are:

- Step 1: List the effects/challenges/impact of the issue (4Rs) under consideration;
- Step 2: Identify the stakeholders (those affected by the issues raised in Step 1);
- Step 3: Identify stakeholder obligation/duty to do or not to do something;
- Step 4: Apply normative ethical/legal principles for the purposes of substantiation.

In conducting ethical and legal analyses, stakeholders should be consciously aware of the moral and legal duties and obligations they have, and of the rights of others, in the context of the sustainability framework. Thus, ethical themes such of Life, Use of Power, Risks and Reliability, Property Rights, Privacy, and Equity and Access permeate the decisions made concerning Reduce, Reuse, and Recycle.

5.2 STEEPLED Analysis

RETHINK includes a STEEPLED Analysis [17; 41] to extend the Sustainability Model shown in Figure 4. A STEEPLED analysis urges decision-makers to consider how each factor will impact society, and how the results of Reduce, Reuse and Recycle will fit into future CE scenarios. The influence, negative or positive, of each macro-environmental factor can be determined and understood and thus, formulated strategies and respective remedial actions should be taken in terms of the 4Rs. The centrality of the RETHINK node in the 4R Sustainability Framework emphasizes the need to always take stock, analyze, measure, and improve.

5 Conclusions and Future Work

The aim of this study was to describe the Circular Economy and the emerging technologies used to enable a transition from today's linear economy to a Circular Economy. The Software Process Improvement (SPI) Manifesto[12] under the People Value the principles (i) "*Know the culture and focus on needs", (ii)* "*Motivate all people involved",* and (iii) "*Base improvement on experience and measurements"* attain a deeper meaning that can be adapted to the transition from a linear to a Circular Economy. Circular Economy focuses on better use of

[12] https://conference.eurospi.net/index.php/en/manifesto

natural resources. For developing a viable re-modelling approach of deep-rooted practices, a change in mindset is required; hence, the transition should be linked to society and culture through policy debates and frameworks. Individual consumers' cultural behaviors are the key factors in this transformational change. Individual actions need to be aligned with a wider social and cultural shift. The global challenges need to trigger and foster local changes at an individual level. The key benefits of transformational change include increased engagement, improved performance, and higher levels of creativity and innovation. The use of emerging technologies is a significant tool to achieve a CE and sustainable development which, in turn, will lead to a social and cultural shift.

Future work will concentrate on the changes needed to achieve a social and cultural shift toward a Circular Economy to reduce resource input and waste, minimize material and energy circles, and optimize renewable energy resources production, dissemination, and consumption. In order to validate the 4R Sustainability Framework, case studies within enterprises and industries will be carried out.

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