DTU Library

Circular Economy in the Digital Age

Bressanelli, Gianmarco; Adrodegari, Federico; Pigosso, Daniela C. A.; Parida, Vinit

Published in:
Sustainability

Link to article, DOI:
10.3390/su14095565

Publication date:
2022

Document Version
Publisher's PDF, also known as Version of record

sustainability

Editorial

Circular Economy in the Digital Age

Gianmarco Bressanelli [1,*], Federico Adrodegari [1], Daniela C. A. Pigosso [2] and Vinit Parida [3,4]

1 RISE Laboratory, Department of Mechanical and Industrial Engineering, University of Brescia, 25123 Brescia, Italy; federico.adrodegari@unibs.it
2 Section of Engineering Design and Product Development, Department of Mechanical Engineering, Technical University of Denmark, 2800 Kongens Lyngby, Denmark; danpi@mek.dtu.dk
3 Department of Business Administration, Technology and Social Sciences, Lulea University of Technology, 97187 Lulea, Sweden; vinit.parida@ltu.se
4 Department of Business, History and Social Science, USN School of Business, University of South-Eastern Norway, 3679 Notodden, Norway
* Correspondence: gianmarco.bressanelli@unibs.it

The Circular Economy has been pointed out by scholars and policymakers as a promising approach to decouple economic growth from resource consumption and waste generation [1,2]. Companies fully embracing a Circular Economy can potentially advance sustainability without compromising the competitiveness of value chains. Unfortunately, several challenges arise in this transformation [3]. Nevertheless, the digital age we live in offers companies many opportunities for overcoming such challenges [4] since digital technologies can support the implementation of Circular Economy strategies into businesses by enabling the redesign of products, business models, consumption patterns, and value chains [5].

To advance the discussion on these aspects, the Special Issue 'Circular Economy in the Digital Age' called for a more critical discussion on the emerging Smart Circular Economy paradigm [6]. In response, eight articles were received and published, with original contributions to both theory and practice. These papers are briefly illustrated in this Editorial in a sequence that starts from the theoretical basis (e.g., literature reviews and conceptual development) to practical implementation aspects of the Smart Circular Economy paradigm (practices, drivers, and barriers).

The paper by De Felice and Petrillo [7] investigated how digital technologies can support a Circular Economy, identifying the current state of the art as well as defining new future research developments in this field. To pursue such an aim, the authors carried out a systematic literature review by integrating the PRISMA protocol—i.e., a systematic tool that guides the process of identification, screening, eligibility, and inclusion of articles—with the Analytic Hierarchy Process (AHP) technique—i.e., a multi-criteria decision-supporting procedure that allows experts to compare alternatives and define hierarchies, in this case among keywords to be used in the search for articles. The authors selected 104 documents and analyzed them under the lens of the RESOLVE framework, the EU Eco-Innovation Plan, digital technologies, business models, and the Sustainable Development Goals. They found that previous literature on digitalization and Circular Economy only analyzed a few digital technologies at a time and only focused on specific sectors and aspects, failing to approach the problem from a systemic point of view. From a practical point of view, they recognized the lack of interoperable solutions and communication protocols as the main factor hindering innovation adoption and the ecological transition. To overcome these challenges, an integrated approach combining technology, legislation, and cooperation of all the stakeholders on a global scale is required. They finally recognized the necessity to process and analyze data in only a few minutes to enable Circular Economy applications in industrial settings (such as predictive maintenance) as well as in urban environments (such as the development of smart cities to solve traffic-related pollution problems). Quantum computers—rather than traditional ones—seem to be promising for these scenarios.

Citation: Bressanelli, G.; Adrodegari, F.; Pigosso, D.C.A.; Parida, V. Circular Economy in the Digital Age. *Sustainability* **2022**, *14*, 5565. https://doi.org/10.3390/su14095565

Received: 29 April 2022
Accepted: 5 May 2022
Published: 5 May 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

The paper by Bressanelli, Adrodegari, Pigosso, and Parida [6] reviewed the literature to provide a definition of the Smart Circular Economy paradigm as an emergent phenomenon. The authors define the Smart Circular Economy paradigm as '*an industrial system that uses digital technologies along the product lifecycle phases to implement circular strategies, leading to an increased environmental, social, and economic performance for the value chain ecosystem*.' Following this definition, the authors propose a framework to consolidate the main concepts underlying the Smart Circular Economy paradigm. The framework suggests that digitalization, fueled by the application of a diverse range of digital technologies, enables a systemic redesign of products, business models, and value chains, impacting all the lifecycle phases of products to reduce material and energy consumption, and reuse, remanufacture, and recycle products, components, and materials. This, in turn, promotes the creation of value and the achievement of enhanced sustainability performance in terms of environmental, economic, and social benefits.

The paper by Preut, Kopka, and Clausen [8] presented the potential contributions of digital twins to the management of circular supply chains and the circularity of resources. Through a literature review and a process and stakeholder analysis, the authors derived and validated a working definition for the digital twin concept and identified the main information requirements for the stakeholders of a circular supply chain based on a digital twin. According to the proposed definition, digital twins can be defined based on eight key characteristics: a digital twin is (i) a virtual collection of information for (ii) a specific (planned or existing) product, (iii) which is described from an atomic to a macro level, (iv) following a distributed, decentralized structure for managing information (v) along the entire product lifecycle, (vi) based on a physical information link with the real product and on (vii) a (if possible) real-time data transmission system (viii) embedded in a suitable software and hardware environment. For each stakeholder involved in a circular supply chain, the authors also identified the information requirements and the potential information sources needed to develop the digital twin concept. For instance, repair service providers require information on the condition and disassembly details of the product to be able to carry out tests and repairs accordingly. The authors concluded that, although the use of digital twins in the context of the Circular Economy is still in its infancy, circular supply chains can benefit from digital twins, as they contribute to the better acquisition, consolidation, and provision of relevant information at the right points in the cycle. The authors highlighted that future research still needs to address issues related to data security, data protection, and the integration of various heterogeneous information systems from different stakeholders, especially by providing specific use-case implementation of the digital twin concept.

The paper by Izmirli, Ekren, Kumar, and Pongsakornrungsilp [9] studied different lateral inventory share policies on a digitalized omni-channel supply chain, in which each network shares real-time inventory data and demand information with each other, enabled by IoT. In fact, implementing a lateral inventory share policy allows inventory data to be shared between the same echelon locations in the supply chain, as physical and online channels are managed together, and online/offline stores are connected under an IoT environment. In doing so, the authors designed an (s, S) inventory control policy model (where s is the re-order point, and S is the order-up to level inventory) and simulated different share policies by using Arena software and the OptQuest tool. Simulation results were compared in terms of logistics costs, transportation frequency, and inventory. According to the results, lateral inventory share policies provided better total network costs than alternatives. Results showed how optimized inventory management contributes to the Circular Economy by simultaneously decreasing holding and transportation costs and by ensuring environmental sustainability through the reduction in transportation frequency and CO_2 emissions in the supply chain.

The paper by Andersen and Jæger [10] investigated how manufacturers of Electrical and Electronic Equipment (EEE) can build upon the Extended Producer Responsibility (EPR) to increase the circularity of products. In fact, the polluter-pays principle underlying the EPR requires producers to bear the costs of waste management, shifting the focus of manufacturers to taking explicit responsibility for the end of life of their products. The authors developed a model to conceptualize information flows during the lifecycle of a product. The model was based on edge data collection and distributed ledger technology. The authors demonstrated the conceptual model through a case study on lighting equipment. Based on their findings, the authors conceptualized three fundamental principles. The first principle—serialize product identifiers—stated that each product should have a unique identifier based on global identification standards. The second principle—data collection and storage at the edge—stated that each actor should act on data at the source (edge), following the edge computing paradigm, to have complete control over data and to only expose the information that they are willing to share. The last principle—employing public distributed ledger—stated that, to meet the challenge of having persistent information regarding products over time, public distributed ledger technologies based on a blockchain should be employed. Thanks to this model, different circular supply chain actors can write to the distributed ledger and find information on the product (such as disassembly procedures) using the product serialized identifier as a key. Nevertheless, more research should be carried out on the development of common standards and protocols, as well as on incentives to encourage supply chain actors to share information.

The paper by Çetin, De Wolf, and Bocken [11] investigated which digital technologies can potentially enable the Circular Economy in the built environment, exploring different methods and implementation paths. This is relevant because few studies have investigated how digitalization could enable the Circular Economy in the construction industry and because the built environment consists of several interconnected systems (buildings, infrastructures, and cities) and numerous actors. To pursue such an aim, the authors adopted an iterative method following four steps. First, they developed a framework to depict the role of digital technologies for the built environment across the building lifecycle stages and the Circular Economy resources principles of regenerating, narrowing, slowing, closing, and collaborating. Second, they carried out three expert workshops to deepen the usage of digital technologies to enable a circular built environment and to map them onto the framework. Third, the authors carried out a literature review to further fill the framework. Lastly, the authors synthesized the results of all the preceding steps into the framework. Accordingly, ten enabling digital technologies to support the transition of the construction industry towards the Circular Economy were identified and contextualized. The authors found that additive manufacturing is prominent for regeneration purposes, as it enables the use of bio-based materials in the construction industry, building information modeling is employed especially for the "design for reversibility" of buildings and to optimize the operational performance of buildings during usage, and digital marketplaces are seen as essential for the creation of a market for secondary building materials when they reach the end of life. Nevertheless, the authors recognized that most digital technologies interact with each other to perform specific tasks. Practitioners in the construction industry are invited to use the framework to create roadmaps for implementing the Circular Economy in the built environment, to highlight each possible strategy and the related enabling digital technologies.

The paper by Magrini, Nicolas, Berg, Bellini, Paolini, Vincenti, Campadello, and Bonoli [12] discussed the application of the IoT and distributed ledger technologies based on blockchain to enable different Circular Economy strategies for the professional electronic equipment industry. Electronic value chains are long, complex, and often go outside national boundaries; therefore, they represent a promising arena to test the potential of digitalization and information sharing. The authors investigated such a digital approach through a case study on five Italian companies in the electronics supply chain. Moreover, they tested the conceptualized IoT/blockchain system at the laboratory scale. Four business models were investigated. The first one prioritized repair and reuse strategies. The second business model also included recycling, while the third one added the involvement of final customers through a system of incentives based on smart contracts in the blockchain.

Finally, the fourth business model considered a product-as-a-service solution, where the manufacturer retained the ownership of the product and received a fixed monthly fee for the usage of the product by customers. The authors found that four types of data should be collected for the professional electronics supply chain: (i) data generated by each actor in the value chain; (ii) data collected in a centralized manner by the focal actor; (iii) IoT data that are autonomously generated by the product; and (iv) crowdsourcing data that are generated by customers. The authors concluded that the application of the IoT and blockchain helps manufacturers to control their electronics products across the entire lifecycle, going beyond traditional approaches only focused on manufacturing or waste management. Nevertheless, future research should assess the environmental consequences of circular business models enabled through energy-hungry digital technologies such as the IoT or blockchain, as rebound effects should be avoided.

Finally, the paper by Vacchi, Siligardi, Cedillo-Gonzalez, Ferrari, and Settembre-Blundo [13] developed and applied Ecodesign principles based on the integration of the IoT, Big Data, Life Cycle Assessment, and material microstructural analysis in the Italian ceramic tile manufacturing industry. In particular, the paper focused on the transformation of Big Data into Smart Data (i.e., Big Data able to generate value) for the redesign of the product and of the input sourcing system. To achieve this goal, the authors developed an Ecodesign model and validated it at the laboratory scale and in a pilot environment, where chemical analyses of different raw materials were performed. The authors also carried out a Life Cycle Assessment to understand the environmental impact of 1 m^2 of ceramic tiles in five different sourcing scenarios by changing the supply and sourcing of raw materials. Big Data were used to feed the Life Cycle Assessment and microstructural analyses of materials. The results showed that Ecodesign improves the environmental performance of the ceramic product. Overall, the study provided empirical validation of the enabling potential of digital technologies for a Circular Economy based on Ecodesign in the Italian ceramic tile manufacturing industry.

Although existing studies have provided relevant contributions to the literature [14–18], they fail to stress the whole range of research perspectives in the domain of the Smart Circular Economy paradigm. We believe that the eight published papers in this Special Issue will provide a significant contribution both to academia and the managerial community, stimulating the debate on the possible ways in which digital technologies can enable the Smart Circular Economy paradigm in the Digital Age in which we live. We thus hope that this Editorial will inspire future researchers in advancing theories on these topics and their interlinkages, as well as in enriching practical implications in future studies. Given the richness of the case studies and practical applications reported in this Special Issue, we are also confident that professionals and practitioners could gain inspiration and relevant insights from this Special Issue, to master the transformation process towards a Smart Circular Economy in their companies. Finally, we are aware that several research questions remain unanswered in the complex domain of the Smart Circular Economy paradigm. We, therefore, reinforce our call for new research on Circular Economy in the Digital Age, especially following the research directions drafted in [6] about the need to:

(i.) Develop research objectives and methodologies from exploratory to confirmatory purposes–e.g., by postulating hypotheses and constructs of the Smart Circular Economy theory and by statistically testing them–and from descriptive research to prescriptive frameworks to support decision-making activities, also relying on a variety of research objectives and methods.

(ii.) Move the focus from single organizations to the entire ecosystem of stakeholders, to shift away from the burdens of single organizations, thus extending the research scope to the entire network of actors, focusing on defining incentives (e.g., financial ones) and requirements (e.g., legislative ones) to encourage cooperation and information sharing in circular value chains, for both native Circular Economy companies and adopters, highlighting their differences and similarities.

(iii.) Combine different enabling digital technologies and study their interlinked effects on the Circular Economy, to provide a more comprehensive picture of the combined role of different digital technologies for the Smart Circular Economy paradigm, leveraging on their synergistic potential and addressing the practical lack of common interoperable solutions and communication protocols, or advancing the IoT and Big Data debate between edge and cloud computing.
(iv.) Assess the environmental impact of digital technologies involved with the Circular Economy through Life Cycle Assessment to show whether and in which conditions environmental gains offset their intrinsic environmental issues, as to consider potential trade-offs and rebound effects connected to the implementation of such technologies.

Author Contributions: Conceptualization, G.B., F.A., D.C.A.P. and V.P.; methodology, G.B., F.A., D.C.A.P. and V.P.; validation, G.B., F.A., D.C.A.P. and V.P.; formal analysis, G.B.; investigation, G.B.; data curation, G.B.; writing—original draft preparation, G.B.; writing—review and editing, G.B., F.A., D.C.A.P. and V.P.; visualization, G.B.; supervision, G.B., F.A., D.C.A.P. and V.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Lieder, M.; Rashid, A. Towards circular economy implementation: A comprehensive review in context of manufacturing industry. *J. Clean. Prod.* **2016**, *115*, 36–51. [CrossRef]
2. Ellen MacArthur Foundation. *Towards a Circular Economy-Economic and Business Rationale for an Accelerated Transition*; Ellen MacArthur Foundation: Cowes, UK, 2012.
3. Bressanelli, G.; Perona, M.; Saccani, N. Challenges in supply chain redesign for the Circular Economy: A literature review and a multiple case study. *Int. J. Prod. Res.* **2019**, *57*, 7395–7422. [CrossRef]
4. Cagno, E.; Neri, A.; Negri, M.; Bassani, C.A.; Lampertico, T. The Role of Digital Technologies in Operationalizing the Circular Economy Transition: A Systematic Literature Review. *Appl. Sci.* **2021**, *11*, 3328. [CrossRef]
5. Bressanelli, G.; Pigosso, D.C.A.; Saccani, N.; Perona, M. Enablers, levers and benefits of Circular Economy in the Electrical and Electronic Equipment supply chain: A literature review. *J. Clean. Prod.* **2021**, *298*, 126819. [CrossRef]
6. Bressanelli, G.; Adrodegari, F.; Pigosso, D.C.A.; Parida, V. Towards the Smart Circular Economy Paradigm: A Definition, Conceptualization, and Research Agenda. *Sustainability* **2022**, *14*, 4960. [CrossRef]
7. De Felice, F.; Petrillo, A. Green Transition: The Frontier of the Digicircular Economy Evidenced from a Systematic Literature Review. *Sustainability* **2021**, *13*, 11068. [CrossRef]
8. Preut, A.; Kopka, J.-P.; Clausen, U. Digital Twins for the Circular Economy. *Sustainability* **2021**, *13*, 10467. [CrossRef]
9. İzmirli, D.; Ekren, B.Y.; Kumar, V.; Pongsakornrungsilp, S. Omni-Chanel Network Design towards Circular Economy under Inventory Share Policies. *Sustainability* **2021**, *13*, 2875. [CrossRef]
10. Andersen, T.; Jæger, B. Circularity for Electric and Electronic Equipment (EEE), the Edge and Distributed Ledger (Edge & amp; DL) Model. *Sustainability* **2021**, *13*, 9924. [CrossRef]
11. Çetin, S.; De Wolf, C.; Bocken, N. Circular Digital Built Environment: An Emerging Framework. *Sustainability* **2021**, *13*, 6348. [CrossRef]
12. Magrini, C.; Nicolas, J.; Berg, H.; Bellini, A.; Paolini, E.; Vincenti, N.; Campadello, L.; Bonoli, A. Using Internet of Things and Distributed Ledger Technology for Digital Circular Economy Enablement: The Case of Electronic Equipment. *Sustainability* **2021**, *13*, 4982. [CrossRef]
13. Vacchi, M.; Siligardi, C.; Cedillo-González, E.I.; Ferrari, A.M.; Settembre-Blundo, D. Industry 4.0 and Smart Data as Enablers of the Circular Economy in Manufacturing: Product Re-Engineering with Circular Eco-Design. *Sustainability* **2021**, *13*, 10366. [CrossRef]
14. Ingemarsdotter, E.; Jamsin, E.; Kortuem, G.; Balkenende, R. Circular Strategies Enabled by the Internet of Things—A Framework and Analysis of Current Practice. *Sustainability* **2019**, *11*, 5689. [CrossRef]
15. Beltrami, M.; Orzes, G.; Sarkis, J.; Sartor, M. Industry 4.0 and sustainability: Towards conceptualization and theory. *J. Clean. Prod.* **2021**, *312*, 127733. [CrossRef]
16. Alcayaga, A.; Wiener, M.; Hansen, E.G. Towards a framework of smart-circular systems: An integrative literature review. *J. Clean. Prod.* **2019**, *221*, 622–634. [CrossRef]

17. Kristoffersen, E.; Blomsma, F.; Mikalef, P.; Li, J. The smart circular economy: A digital-enabled circular strategies framework for manufacturing companies. *J. Bus. Res.* **2020**, *120*, 241–261. [CrossRef]
18. Liu, Q.; Trevisan, A.H.; Yang, M.; Mascarenhas, J. A framework of digital technologies for the circular economy: Digital functions and mechanisms. *Bus. Strateg. Environ.* 2022; *in press*. [CrossRef]