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Integrating Smart Technologies into Circular Supply Chain Management: A Framework for Sustainable, Transparent, and Data-Driven Operations

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Abstract

The Circular Economy (CE) is gaining momentum as businesses and governments worldwide recognize the need to reduce waste, minimize environmental impacts, and unlock new economic opportunities. Supply chain management, which needs to change to meet circularity principles, is at the center of this shift. This study examines how smart technologies support Circular Supply Chain Management (CSCM), emphasizing how they can change conventional methods into more adaptable, efficient, and sustainable systems. The potential for improving efficiency, sustainability, and resilience has led to a great deal of interest in the integration of smart technologies in supply chain management. In the framework of CSCM, which attempts to reduce waste and maximize resource use throughout the product lifecycle, this article investigates the deployment of smart technology. This study identifies several smart technologies, including the Internet of Things (IoT), blockchain, Artificial Intelligence (AI), and big data analytics, and investigates their roles in supporting CSCM practices through a thorough analysis of the available literature. This paper also addresses the advantages, difficulties, and potential applications of smart technology adoption in CSCM. The results add to our understanding of how businesses might use smart technology to make it more sustainable.

Keywords: Smart technologies, Circular supply chain management, Internet of things, Blockchain, Artificial intelligence, Big data analytics, Sustainability.

1 | Introduction

The definition of Circular Supply Chain Management (CSCM) by [1] effectively captures the essence of the Circular Economy (CE): circular thinking, a crucial element in achieving sustainability. A new, complex

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decision-making domain for process managers arises when CE principles are integrated into supply chains, for example, in green procurement, product design, production, logistics, sales, product use, and information management [2]. This is, although doing so is suggested as an effective way to support sustainability. Finding trustworthy CE partners who can provide or consume materials and waste flows, and who can match quality and quantity to create a circular network, is a big problem for businesses. Since companies can now analyze the efficacy of potential CE linkages between organizations thanks to rapid data production, we are encouraged to investigate how information technologies can also support circular decision-making. Especially considering that these enabling ICTs are essential for promoting sustainable development [3], [4]. The main issue is that many of the circular supply chain initiatives of today depend on various industry players realizing the benefits of ecosystem convergence, which is the process of integrating the markets, expertise, and technologies of various industries to identify distinctive value propositions that necessitate a large number of supply chain participants, specifically, given the dearth of resources that allow various stakeholders to investigate circular business prospects inside supply chains. In recent years, the concept of CE has gained momentum as a sustainable alternative to traditional linear production and consumption models. Central to the CE paradigm is the concept of CSCM, which emphasizes the importance of reducing waste and maximizing resource efficiency throughout the product lifecycle. Achieving the goals of CSCM requires innovative approaches and technologies that enable the seamless flow of materials, products, and information across various stages of the supply chain [5].

The incorporation of smart technologies, which comprise a variety of digital advancements intended to enhance operational procedures and decision-making capacities, is one viable path toward the advancement of CSCM practices. Supply chain management could undergo a radical transformation thanks to smart technologies like big data analytics, blockchain, Artificial Intelligence (AI), and the Internet of Things (IoT). These technologies offer real-time visibility, improve traceability, optimize resource allocation, and allow predictive analysis. Although the use of smart technologies in conventional supply chains has been the subject of many studies, there is an increasing need to investigate how they can support CSCM activities. Organizations may improve the efficiency and sustainability of their supply chains, as well as open new avenues for value creation and competitive advantage, by leveraging smart technology [6], [7].

This paper aims to provide a comprehensive overview of current research on smart technologies for CSCM. Through a synthesis of existing literature, we identify key technologies, discuss their potential benefits and challenges, and outline future research directions in this emerging field. By shedding light on the transformative potential of smart technologies in CSCM, this study seeks to inform and inspire practitioners and researchers alike to embrace innovation and sustainability in supply chain management [8], [9].

2|Literature Review

2.1|Circular Supply Chain Management

The introduction of CE principles into supply chain management confronts firms with new considerations across product design, procurement, manufacturing, logistics, sales, product use, and information management. For example, a firm's product design may now be reviewed in terms of product lifetime (extension), product/component reuse guidelines, and other circular redesign strategies. Furthermore, a firm's material procurement in a CE requires it to track component properties and their inventories (e.g., material passports), which, in turn, necessitates organized data collection and exchange across the supply chain (e.g., defining the degree of transparency and accuracy of the data). The general practice for manufacturing is to make wastes available as substitutes of inputs, which may involve assessing: 1) processing techniques needed (waste treatment or waste processing), 2) the mismatch in both quantity and the quality of produced wastes since these are not produced upon demand, 3) the economic viability of the synergy, and 4) the contractual clauses. From a logistics perspective, this may require changes and additions to distribution networks (e.g., pipelines to facilitate heat exchange, recycling networks, or reverse logistics under extended producer responsibility). Sometimes, integrating CE principles may even affect sales and require a business model transformation [1], [2], [10], [11].

Furthermore, the consumption patterns of consumers may also be affected. Supply chain actors or governmental agencies responsible for minimizing impacts due to product use may coordinate awareness campaigns and sustainability education to influence consumer behavior. Finally, a firm's information management is affected, for example, by the need to manage the new logistics or by the need to keep track of the environmental impacts of product components [12], where there is often a duality between the benefit of information sharing and protecting a firm's competitive advantage [13], [14].

These circular developments in supply chains are often the result of firms' convergence activities, i.e., identifying new opportunities in which the unique value proposition is delivered through collaboration among multiple stakeholders, typically from different sectors (e.g., integrating products or creating shared knowledge). These convergent activities are increasingly intertwined with the software industry, partly because of the important role ICT plays in identifying problems that require a common strategy, as seen in the era of CSCM. However, there is still a lack of decision support for many problems in CSCM. A particular problem area exists at the first step of procurement: the firm's task of finding symbiotic partners relevant to waste exchanges, which is a prerequisite for implementing and sustaining a circular supply chain [4], [15].

2.2 | Industrial Symbiosis

The increasing procurement of waste material, energy, and services to create circular networks is also known as Industrial Symbiosis (IS). IS entails the identification and utilization of a company's secondary outputs, generally considered as waste, to substitute (part of) primary resources, possibly after pre-processing, in the production process of another company, usually representing a different industrial sector. This implies that the potential business partners are from traditionally disengaged sectors [16]. Among others, new IS opportunities are often identified during facilitated industry workshops, by using specific IS identification systems, and through the exploration of items in IS marketplaces [17], [18]. A typical example of opportunity identification is when a company states that it wants to find a sustainable, circular solution for the daily use of large amounts of a particular waste sludge, rather than discharging it into the environment (specific details are typically intentionally omitted). While the company currently disposes of the waste in landfills, it is interested in learning which IS opportunities can be discovered in the geographic proximity. Thus, it searches for companies that can be the potential (local) IS partners from different industry types to construct the symbiotic transfer of the waste sludge'. Once the IS-based business is implemented, then, the sludge is not considered waste anymore but a resource used sustainably and circularly. This reduces waste discharge costs for the waste producer and traditional input purchase costs for the waste user; thus, environmental achievements are accompanied by economic achievements. However, there are thousands of wastes with different technical characteristics, and this leads us to ask how one can identify that a certain waste type can offer IS opportunities.

Existing IS identification systems struggle to analyze data due to the high level of implicit knowledge in IS, which is a burden on the development of techniques to identify IS exchanges. This is also reflected in the tools that currently facilitate IS, of which many require the exchange of resource information as a prerequisite for revealing IS opportunities [19], [20].

2.3 | Recommender Systems

Recommenders, because of their capacity to increase item explorations and to reduce the search costs for identifying relevant IS opportunities can support areas experienced as a resource-intensive process. The purpose of the recommender system is to predict the preference of an item for a user. Thereby, recommenders facilitate the exploration of available options while also filtering a set of items in an attempt to decrease the users' information load. Traditionally, recommender system research has focused on different aspects, including (hybrid) algorithm design, evaluation mechanisms, recommender goals, data issues, context-awareness, solicitation techniques, and, more recently, also address concerns around transparency, explanations and user-system interactivity, interface design and security [21].

A branch of recommender systems, more recently, also aims to improve circular thinking, including works on recommenders for energy-saving, finding sustainable products, discovering sustainable waste exchanges, and achieving environmentally sustainable mobility. While in the field of information retrieval, various methods exist for visualizing large data, exploration support through visualization in recommender systems is a relatively new paradigm. The visualization techniques support the transparent explanation of the provenance of recommendations, while the interaction techniques increase user control over recommendations, overcome display limitations associated with large data volumes and high-dimensional data, and provide structure to reduce cognitive effort [22], [23]. Existing work suggests a relationship between a recommender agent's perceived value and the degree of algorithmic transparency. In addition, shows that systems in which users can select the list of recommendations that are perceived to be of interest improve the effectiveness and user experience of the recommender due to the increased control over the recommender and transparency provided. This transparency helps users understand why a recommendation is provided, which increases the consideration of accepting the recommendation [24], [25].

2.4 | Techniques for Visual Exploration of Set-Based Recommendations

One of the key advantages of visual browsing is the positive effect on item discovery (i.e., the novelty of item recommendations) provided by the quick-scan function that allows a quick scan of a large number of items. There exists literature that addresses the challenges concerning the visual exploration of set-based recommendations.

3 | Proposed Study

3.1 | Research Gap

While there is growing interest in the application of smart technologies in supply chain management, the literature remains unclear about their specific role in facilitating CSCM practices. Existing studies have primarily focused on the adoption of smart technologies in traditional linear supply chains, overlooking the unique challenges and opportunities associated with circularity. Furthermore, the integration of smart technologies in CSCM has not been comprehensively explored, leaving significant gaps in understanding how these technologies can be leveraged to achieve circularity goals such as waste reduction, resource efficiency, and closed-loop systems. Therefore, there is a need for research that examines the application, benefits, and challenges of smart technologies in the context of CSCM, as well as their potential to enable organizations to transition towards more sustainable and circular supply chain models [7], [8].

4 | Analysis

IoT in CSCM: The IoT has emerged as a powerful enabler of real-time visibility and connectivity in supply chains. IoT technologies have the potential to improve resource flow monitoring, facilitate circular product lifecycles, and improve traceability in the context of CSCM. IoT-enabled sensors, for example, can monitor the flow of goods and materials along the supply chain, enabling effective resource management and waste minimization [26], [27].

Blockchain technology for circular traceability: It is ideally suited to improve traceability and transparency in circular supply chains, as it provides decentralized, transparent data management capabilities. Blockchain enables stakeholders to verify the provenance and sustainability credentials of materials and goods by recording transactions and product data on immutable ledgers. This can assist in resolving trust concerns and encourage the use of circular processes like recycling and remanufacturing [9], [28].

AI for resource optimization: algorithms based on AI have the potential to improve resource allocation and decision-making in circular supply networks. AI can find chances for closed-loop systems, product remanufacturing, and waste reduction through sophisticated analytics and predictive modeling. Demand forecasting and inventory management systems powered by AI, for instance, can reduce overproduction and excess inventory, supporting resource efficiency and sustainability [29].

Big data analytics for sustainability performance monitoring: It enables businesses to gather, analyze, and make sense of vast amounts of information on consumer behavior, supply chain management, and environmental performance. Big data analytics can reveal opportunities for improvement and offer insights into how supply chain operations affect the environment in the context of CSCM. Key Performance Indicators (KPIs) such as material recovery rates, energy efficiency, and carbon footprint reduction can be monitored by enterprises using data analytics tools in relation to circularity goals [30].

5 | Finding

To address the challenges and opportunities presented by CSCM, organizations can adopt a comprehensive approach that harnesses the capabilities of smart technologies. The proposed solution involves integrating various smart technologies to optimize resource utilization, enhance transparency, and promote sustainability throughout the supply chain lifecycle [6], [7]. Below are the key components of the proposed solution:

IoT integration: throughout the supply chain, use IoT-enabled sensors and devices to collect data in real time on product usage, material flows, and environmental conditions. By tracking a product's journey from the extraction of raw materials to its disposal at the end of its useful life, these sensors enable companies to monitor resource consumption and identify opportunities for recycling and waste reduction [27], [31].

Blockchain-based traceability: By creating transparent, immutable records of product provenance, stakeholders can confirm the legitimacy and sustainability credentials of materials and products. Blockchain facilitates the implementation of circular processes, like remanufacturing and closed-loop recycling, by improving traceability and accountability through the recording of transactions and data exchanges on a distributed ledger [28], [32].

AI for decision support: utilize AI algorithms to examine vast amounts of data about the supply chain and produce insights that may be used to improve operational effectiveness and resource allocation. Predictive analytics powered by AI can estimate demand, spot potential bottlenecks, and optimize production schedules to reduce waste and maximize resource use. Recommendation engines driven by AI can also make recommendations for product recycling, refurbishment, or reuse based on past performance and market trends [29].

Big data analytics for performance monitoring: monitor KPIs related to sustainability and circularity objectives using big data analytics techniques. Organizations are able to monitor their environmental impact, gauge their progress toward circularity goals, and pinpoint areas for improvement through the collection and analysis of data from several sources, such as internal databases, blockchain transactions, and IoT sensors. Machine learning and other advanced analytics approaches can find patterns and correlations in the data, allowing for ongoing optimization of CSCM procedures [30].

Collaborative platforms and ecosystems: encourage cooperation and information exchange between supply chain participants by utilizing digital platforms and ecosystems. Organizations can exchange best practices, share resources, and co-innovate toward more sustainable and circular solutions by establishing interconnected networks of stakeholders. By facilitating the sharing of information, resources, and skills, collaborative platforms can help supply chain participants address complex sustainability issues and drive systemic change [33].

Continuous improvement and innovation: adopt a culture of innovation and constant improvement to keep up with changing consumer needs and technical breakthroughs. Promote experimenting with new smart technologies and business models, and provide incentives for staff members to suggest and carry out creative ways to improve sustainability and circularity. Organizations may remain ahead of the curve and establish themselves as pioneers in sustainable supply chain management by cultivating an innovative culture [34].

Organizations can enhance the sustainability, resilience, and circularity of their supply chains by implementing a comprehensive strategy that incorporates smart technologies. Smart technologies enable enterprises to maximize resource usage, avoid waste, and create value across the product lifecycle through improved visibility, transparency, and decision-making capabilities. In the end, the suggested approach helps businesses fulfill their circularity objectives while promoting a long-term financial environment. The proposed solution of leveraging smart technologies for CSCM holds significant promise in enhancing sustainability, efficiency, and transparency across supply chain operations [4], [8]. Through the integration of the IoT, blockchain, AI, and big data analytics, organizations can achieve several key outcomes:

I. Improved resource utilization: organizations can reduce waste and improve resource management by gaining real-time visibility into material flows and product lifecycles through the deployment of IoT-enabled sensors and devices. AI-driven analytics further improve production procedures and resource allocation, reducing waste and increasing resource efficiency [27], [29].

II. Enhanced traceability and transparency: blockchain technology enables transparent and immutable records of product provenance, fostering trust and accountability throughout the supply chain. Stakeholders can verify the sustainability credentials of materials and products, facilitating the adoption of circular practices such as remanufacturing and recycling [9], [28].

III. Data-driven decision-making: big data analytics provides actionable insights into supply chain performance and environmental impacts, enabling organizations to monitor progress toward circularity goals and identify areas for improvement. AI algorithms support decision-making by predicting demand, optimizing inventory levels, and recommending sustainable practices [30].

IV. Collaborative innovation: partners in the supply chain can share knowledge and engage in co-innovation through collaborative platforms and ecosystems that encourage collective efforts towards sustainability and circularity. Organizations may expand sustainable solutions throughout the supply chain, exchange resources, and work together on circular projects by utilizing digital platforms [35].

In general, companies can build more robust, flexible, and sustainable supply chains that adhere to the CE principles by implementing smart technology in CSCM [4], [36].

6 | Conclusion

In conclusion, smart technologies offer immense potential to transform supply chain management and advance circularity goals. Organizations may improve resource utilization, traceability, transparency, and collaboration throughout the supply chain lifecycle by utilizing IoT, blockchain, AI, and big data analytics. By combining these technologies, businesses can reduce waste, maximize productivity, and build lasting value, all while promoting social responsibility and environmental sustainability. However, it is essential to acknowledge that successfully implementing smart technologies in CSCM requires overcoming various challenges, including technological barriers, data privacy concerns, and organizational inertia. Moreover, maintaining an edge over changing market conditions and legal mandates requires constant innovation and adaptability. The implementation of smart technologies marks a paradigm shift in supply chain management, enabling businesses to move toward more circular, sustainable business models. Organizations can create a more resilient and equitable future for the global supply chain by embracing innovation and teamwork.

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Data Availability

All data are included in the text.

Conflicts of Interest

The authors declare no conflict of interest.

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