Circular Economy, Industry 4.0 and Supply Chain

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The vertical disintegration of companies has increased the complexity of management in terms of time and quality and increased uncertainty in the markets, making it impossible today for companies to compete effectively if they are isolated from their suppliers and other stakeholders. In this context, adopting the concept of supply chains (SCs) is increasingly essential for a company's performance. Moreover, two themes are being increasingly discussed in the context of SCs, the circular economy (CE) and Industry 4.0 (I4.0). The CE paradigm consists of a possible way to achieve environmental objectives and economic sustainability by developing systemic changes that go beyond the individual company and involve the other actors in the SC, contributing to adding value to a product and/or service

Keywords: circular economy ; industry 4.0 ; supply chain management ; interpretive structural modelling ; MICMAC approach

1. Introduction

The vertical disintegration of companies has increased the complexity of management in terms of time and quality and increased uncertainty in the markets, making it impossible today for companies to compete effectively if they are isolated from their suppliers and other stakeholders [1][2]. In this context, adopting the concept of supply chains (SCs) is increasingly essential for a company's performance. Moreover, two themes are being increasingly discussed in the context of SCs, the circular economy (CE) and Industry 4.0 (I4.0) [3]. The CE paradigm consists of a possible way to achieve environmental objectives and economic sustainability by developing systemic changes that go beyond the individual company and involve the other actors in the SC, contributing to adding value to a product and/or service [4][5]. On the other hand, I4.0 refers to an industrial revolution based on the deployment of automation technologies and information and communication technologies, which can be helpful to meet current SC needs, such as flexibility, increased productivity, reducing waste, resource optimisation, and more sustainable production processes [2]. Consequently, the CE can be used to minimise resource usage and decrease waste generation in a high-tech manufacturing environment, integrating sustainable resource management and transforming SCs in the I4.0 [6][7].

Previous research has assessed the relationship between these themes. For example, some researchers have linked the CE to I4.0 [7][8], while others have linked, separately, the implementation of I4.0 or the CE to SC performance [1][2][9][10][11]. However, a systematic analysis from the perspective of experts concerning the relationship between these three topics is still missing. Many articles do not provide insight into the realization of initiatives to introduce Sustainable Industry 4.0 in the supply chain context. Our paper uses combined Interpretive structural modelling (ISM) and the MICMAC approach was used as a systematic methodology to establish the interrelationships between these topics. However, there is still a lack of studies that analyse this relationship more deeply, to create a consensus between the relationships between the different strategies of I4.0 and CE in the supply chain [12][13]. To clarify our research gap, **Table 1** was developed to contrast the research gap with the studies already published.

The discussion on sustainable development and the CE has been highlighted worldwide since the 1980s, recognising that natural resources are limited and are suffering significant and irreversible damage from human activity [4]. This new perspective has created pressure from several stakeholders (consumers, investors, governments, etc.) for companies to reduce their negative impact on the environment [4]. Therefore, organisations have been working on improving their environmental performance to obtain competitive advantages (such as increased market share and product differentiation) capable of improving financial performance without significantly increasing (or even reducing) costs [13]. At the same time, I4.0 has been impacting the development of the global industry as it has been providing solutions for computerisation and digitalisation. In other words, the CE and I4.0 are seen as having the potential to increase the efficiency and competitiveness of organisations and, consequently, to offer performance improvements for SCs. Sustainable development depends on its relationship with technological development [14]. The I4.0, through technological

pillars, has the potential for transition to CE, by maximizing the use of available resources and minimizing waste and emission [2][15].

2. The Importance of the CE and I4.0 for SC Performance

Population growth linked to economic and technological development has led to changes in the types of production and consumption, making SCs increasingly dependent and unsustainable [4]. Growing market competitiveness, environmental changes, public pressure, and environmental legislation have generated the need for organizations to change their production systems' operations to ensure the coexistence of industrial development and environmental protection [16]. For these changes to occur, it is necessary to redefine the basic structure of SCs to include environmental issues [17]. As recommended by the CE literature [5], the first step of this change is to migrate from a linear SC to a closed-loop one. When SCs extend environmental concerns to their operations, they are characterized as a circular supply chain (CSC) [6]. According to Srivastava [18] (p. 54), circular supply chain management (CSCM) can be defined as "the integration of environmental thinking with supply chain management, including product design, material selection and supply, manufacturing processes, delivery of the final product to consumers and the management of the entire product life cycle, even after the end of its useful life".

The adoption of the CSCM requires a paradigm shift [13][18]. Specifically, organisations need to stop seeing environmental issues as external restrictions that impose limits, increase the costs of their operation, and reduce their competitiveness [19] and start instead to see them as an opportunity to generate economic and financial gains [18], thus improving their performance [13]. To achieve this, several practices need to be adopted, including: circular projects; designing products and operations in the SC taking into account environmental protection and health throughout the product's life cycle; reverse logistics (planning and controlling the flow of raw materials, inventories, and products from the point of consumption to the point of origin to recapture value or ensure proper disposal); recycling and remanufacturing operations; the recovery, reuse, and reforming of products and packaging; waste management and minimisation; and the substitution of hazardous materials or processes with less problematic ones [20].

The SC involves coordinating, planning, and controlling products and services through integrated activities between suppliers and customers. However, despite being connected, many of these activities are carried out independently by each member organisation of the chain [21]. Thus, the results obtained in the traditional SC structure are no longer sufficient and do not match current technological developments [21]. In this context, the concept of the integration and digitisation of the SC emerges to add value, strengthen the competitive potential of organisations, and improve the corporate performance of intra-organisational and inter-organisational processes [22].

A digitised SC is an intelligent system of networks, hardware, and software that requires a massive amount of data, as well as cooperation and communication, to support and synchronise interaction between organisations to provide higher value and more accessible services based on agility, consistency, and effectiveness [3]. Several technologies and innovative solutions are used for digitising and integrating of SCs, including I4.0 technologies [21][23], such as: flexible and digitally integrated production systems; inter-organisational information integration, synchronisation and communication systems; worker support technologies; the Internet of Things (IoT); cloud computing; big data; and data analytics. Further, as Vacchi et al. [7] (p. 1) stated, "Industry 4.0 pushes manufacturing industries to make their processes minimise waste: this transition to efficiency links Industry 4.0 with the goals of the circular economy". Therefore, there is an opportunity to investigate the relationship between these three themes.

3. The Literature Regarding the Relationship between the CE and I4.0 and Its Effect on SC Performance

The need to optimise SCs due to the competitive pressures of the market promotes and encourages the adoption of I4.0 technologies in parallel with CE approaches [15]. According to Rajput [24], the CE integration with I4.0 is a way to achieve sustainability, as it reduces barriers such as lack of information regarding the life cycle of products and uncertainty about the return on investments [25]. For example, as Tiwari [8] (p. 2) stated, "the advent and adoption of digital technologies based on the principles of Industry 4.0 may help to overcome the barriers to the adoption of CE". In other words, if organisations want to maintain and strengthen their competitive potential, they need to embrace technological and environmental changes together [12]. In this context, Jabbour et al. [15] proposed the relationship between the CE business actions and I4.0 technologies (**Table 1**).

Table 1. Relationship between the ReSOLVE framework and I4.0 technologies.

ReSOLVE Strategies	I4.0 Technologies
Regenerate	**Internet of Things (IoT)**
Share	**Cloud computing and IoT**
Optimise	**Cyber–Physical Systems (CPS) and IoT**
Loop	**CPS, IoT and Cloud computing**
Virtualise	**Cloud computing, IoT and Additive Manufacturing**
Exchange	**Additive Manufacturing**

Source: [14].

More recently, some studies have simultaneously addressed all these three themes Laskurain-Iturbe et al. [12] showed evidence of the potential impacts of additive manufacturing and robotics by integrating industry 4.0 and the CE. Rajput and Singh [24] used DEMATEL to identify enablers and barriers to the relationship between these topics. Dev et al. [26] simulated a reverse logistics model to propose a roadmap for the joint implementation of I4.0 principles using the ReSOLVE model. Further, Yadav et al. [27] developed a framework to overcome challenges in SCs through solutions based on I4.0 and the CE, subsequently validating it through a case study in the automotive industry. Various researchers have used other perspectives to examine this relationship [28][29]. Although the theme's relevance in the literature has been highlighted, no research was identified in the SLR assessing the relationship between the themes systematically from the perspective of experts.

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