**The Mediating Role of Circular Economy in the Relationship between Industry 4.0 and Sustainable Performance in the Manufacturing Industry**

**Abstract**

Strong social pressure coupled with a tightening of environmental policies is forcing manufacturing firms to implement improvements in their production processes to reduce industrial waste and their negative impacts on the environment. To achieve this goal, manufacturing firms are increasingly adopting and applying Industry 4.0 (I4.0) and circular economy (CE) practices. However, the literature indicates that the implementation of I4.0 and CE does not always lead to a substantial improvement in the sustainable performance (SP) of manufacturing firms. Hence, this research analyzes how the concurrent adoption of I4.0 and CE impacts the SP of manufacturing firms within the context of Mexico. A research model was developed and validated with a sample of 338 manufacturing companies and by using PLS-SEM for its analysis, and measured I4.0 with 8 items (e.g. Systems that integrate the physical world with virtual computational space; interconnecting of small computing devices embedded in products and objects to the internet, enabling the ability to receive and send data), CE with 8 items (e.g. There is an environmental commitment by senior management; there is support for environmental management by mid-level managers), and SP with 7 items (e.g. The company's activities enable the transition to a low-carbon economy; the company's activities protect and/or restore the environment by focusing on environmental quality aspects and improving resource efficiency) in a research model that proposes 4 hypotheses that relate the analyzed constructs. The findings reveal that the sustainable performance of manufacturing firms increases substantially with the implementation of both Industry 4.0 and circular economy. Additionally, the results show that the circular economy plays a mediating role in the relationship between Industry 4.0 and sustainable performance. This study theoretically contributes by providing further empirical evidence that demonstrates the connection between I4.0 and CE as well as the mediating effect that CE exerts on the relationship between I4.0 and sustainable performance in manufacturing firms. From a practical standpoint, this study contributes by providing manufacturing companies with a better understanding of these relationships, which will help them formulate more effective policies and strategies to support the improvement of their environmental sustainability performance.

**Keywords:** *Industry 4.0, circular economy, sustainable performance, manufacturing industry.*

1. **Introduction**

Even though the environmental performance of the manufacturing industry has improved over the last decade, manufacturing companies continue to generate large volumes of industrial waste (Viles et al., 2022), causing damage and pollution to the environment (Tanco et al., 2021). Therefore, in the literature, good sustainable knowledge management is considered necessary to reduce CO2 emissions and improve the environment (Ul-Durar et al., 2023), particularly because sustainable knowledge management is linked to eco-innovation and circular economy (CE) activities, and CE is considered as a continuity and extension of eco-innovation (Viles et al., 2022). In that sense, CE is understood as an essential concept to achieve sustainability (Betancourt-Morales & Zartha-Sossa, 2020), particularly in manufacturing companies (Acerbi & Taisch, 2020).

In this context, the essential objective of CE is to *“maintain values ​​and manage stocks of assets, from natural, cultural, human and manufactured to financial stocks”* (Stahel & MacArthur, 2019, p. 5), particularly if we consider that CE can be defined as “*an economic system based on the reuse, reduction, recycling and extraction of end-of-life materials to achieve long-term sustainable development goals”* (Kirchherr *et al.*, 2017, p. 222). In addition, the adoption of sustainable practices could be enhanced by the implementation of Industry 4.0 (I4.0) technologies (Viles *et al.*, 2022), in that respect I4.0 can be defined as *“a combination of different technologies such as additive manufacturing, simulation, robots and autonomous vehicles, augmented and virtual reality, IoT, cloud and cybersecurity”* (RüBmann *et al.*, 2015).

For this reason, the importance of integrating I4.0 and CE has been recognized by academics and researchers (Pham *et al.,* 2019; Dantas *et al.,* 2021), and it is increasingly becoming an essential need in the manufacturing industry (Rosa *et al.,* 2020; Bag *et al.,* 2021). Furthermore, recent studies suggest that the use of I4.0 and CE at the same time helps manufacturing firms to increase Sustainable Performance (SP) (Jabbour *et al.,* 2018a; Belhadi *et al.,* 2020). However, even though previous studies agree that different technologies of I4.0 facilitate the application of CE in organizations (Belhadi *et al.,* 2022), it has not been possible to clarify in the literature how I4.0 improves CE in manufacturing firms (Jabbour *et al*., 2018b; Kamble & Gunasekaran, 2023). To investigate the connection between I4.0 and CE in sustainable context is required (Rosa *et al.,* 2020; Dantas *et al.*, 2021; Cheng *et al*., 2021; Awan *et al.*, 2020).

Therefore, in a sustainability context, the objective of this study is the analysis and discussion of the connection between I4.0 and CE as well as the mediating effect that CE exerts on the relationship between I4.0 and SP in manufacturing firms. To accomplish this objective, an empirical study was conducted in the Mexican manufacturing sector, utilizing a sample of 338 observations. A research model that theorizes the relationship between I4.0 and CE and the mediating effect that CE exerts on the relationship between I4.0 and SP was developed and tested using Partial Least Squares Structural Equation Modeling (PLS-SEM) through SmartPLS 4.0 software (Ringle *et al.,* 2022). It is important to highlight the interest in the manufacturing industry, mainly because this industry in Mexico is currently incompatible with sustainability and the care of the environment (Scur *et al.,* 2019), and because this industry generates a higher level of pollution (Farkavcova *et al.,* 2018).

According to data from the National Institute of Statistics and Geography (INEGI), in 2022 Mexico had a total cost of depletion of environmental resources equivalent to 4.6% of GDP, the environmentally adjusted GDP represented 75.7% of the country's total GDP, and the manufacturing industry generated the greatest negative impact on the environment, representing 15% of the total environmentally adjusted GDP (INEGI, 2022). However, it is also relevant to highlight the importance of the manufacturing industry in Mexico's economy, particularly because in the last five years the industry added value grew up at the rate of 10% (INEGI, 2022). In this sense, the lack of enough research evidence justifies the need of academics to provide empirical findings of the main costs of the environmental impact generated by manufacturing companies in Mexico.

However, even though there are some studies recently published in the literature that have tried to provide empirical evidence of the adoption of CE practices, which mitigate the negative impact on the environment in Mexico generated by manufacturing companies (e.g. Mora-Contreras et al., 2023; Rodríguez-González et al., 2023; Maldonado-Guzmán & Garza-Reyes, 2023), they cannot be considered conclusive. More empirical studies should provide new evidence on this relationship (Dantas et al., 2021), particularly because it is very difficult to measure results in manufacturing companies (Daglis et al., 2023). Consequently, as highlighted in previous literature, sustainable strategies in manufacturing companies can potentially benefit the execution of CE solutions (Mishra et al., 2022).

Likewise, according to Millar *et al.* (2019), Sehnem *et al.* (2019), Rosa *et al.* (2020), and Belhadi *et al.* (2022), to promote the adoption and implementation of this model in the context of SP, there is an urgent need to develop a holistic analysis and evaluation approach to the integration of I4.0 and CE in manufacturing firms. Thus, from a theoretical point of view, this study contributes to enhancing the existing body of knowledge by addressing the challenges when connecting I4.0 and CE to improve the SP of manufacturing firms. Additionally, it will provide robust empirical evidence to resolve inconsistencies observed in prior studies within the sustainability literature. The paper also contributes to industrial practice by equipping manufacturing companies with a deeper comprehension of the relationships between I4.0, CE and SP, so they can devise more effective policies and strategies to enhance their environmental sustainability performance.

The paper is structured as follows: first, we consider the literature review and develop research hypotheses; the next section includes the methodology, with the detailed sample design and the description of the PLS-SEM analysis; then, we show results and discussion; finally, we include conclusions, implications and future research.

1. **Literature Review**

In this section, we provide a theoretical background of Dynamic Capabilities Theory (DCT) for sustainability, particularly I4.0 and CE practices in manufacturing firms, to gain an understanding of how these concepts are related and develop a research model to guide this study.

2.1. Dynamic Capabilities Theory

Over the past decade, the concept of DCT has evolved and matured, becoming today a framework that favors the sustainable growth of organizations (Kodama, 2023). DCT is considered an essential element for the growth, survival, and competitiveness of manufacturing companies (Rifqi *et al.*, 2024). Recently, several researchers and academics have discussed the importance of DCT in improving companies' abilities to create competitive advantages (e.g. Horng *et al.*, 2022; Posen *et al.*, 2023; Al-Khatib *et al.*, 2024), particularly in maximizing economic benefits and the appropriate use of resources (Van Eechoud & Ganzaroli, 2023). However, although DCT is essential for the development of strategic management studies in manufacturing companies, it has serious limitations in explaining how it relates to I4.0 and CE practices in a sustainability context (Rifqi *et al.*, 2024).

Despite the popularity of DCT in the literature, there are several empiric and conceptual gaps that need to be explained (Kim *et al.*, 2023). For example, in manufacturing companies, Chirumalla (2021) acknowledged the scarce research on DCT in the context of digitalization and process innovation, while Chari et al. (2022) showed that little attention has been paid to DCT with the concepts of I4.0, CE, and SP. Furthermore, Lin *et al.* (2020) identified scarce literature analyzing and discussing the relationship between DCT and smart manufacturing transformation (I4.0). In that sense, Cyfer *et al.* (2021) also found weak empirical links between the DCT development process and its impact on improving firm performance. Therefore, the importance of researchers and academics focusing their studies towards providing robust empirical evidence on the relationship between I4.0, CE and SP in a DCT context has been established in the literature (Rifqi *et al.*, 2024).

2.2. Industry 4.0 and Circular Economy in the framework of DCT

The advanced manufacturing systems of various companies around the world are commonly characterized by a high level of automation, which allows the exchange of data in real-time and its integration into a network of products and the production in processes (Lin *et al.,* 2018; Carvalho *et al.*, 2018). In this context, I4.0 implies valuable resources for the collection, storage, and analysis of data needed by manufacturing firms for the efficient integration of their products and production processes (Belhadi *et al.,* 2022). Some authors argue that to achieve SP, manufacturing companies need to reconfigure their dynamic capabilities (Mohaghegh *et al.,* 2023). In this vein, the concept of I4.0 can be established under DCT, defined by the capacities of organizations literature as *"a firm's capacity to deploy its resources, tangible or intangible, to perform a task or activity to improve performance”* (Teece *et al.,* 1997; Amit & Schoemaker, 1993). Thus, I4.0 is considered a dynamic capacity that *"provides the ability to integrate, build, and reconfigure internal and external competencies to address rapidly changing environments"* (Teece *et al.,* 1997).

Moreover, similar studies identified CE as an essential dynamic capability of organizations, whose objective is the rate reduction of depletion of natural resources, and the creation of an efficient environment in the resources used (Jakhar *et al.,* 2019; Kamble & Gunasekaran, 2023). For this reason, manufacturing firms must embrace new business models that enable the acquisition of fresh dynamic capabilities for the reconfiguration of existing ones (Barney, 1991), seamless integration with current capacities (Helfat & Peteraf, 2003), or even the substitution of current capabilities with novel ones (Sirmon et al., 2007). These adaptations are critical when manufacturers implement CE, which are often high-cost, uncertain, rigid, and unclear on the benefits of successful implementation (Lahti *et al.,* 2018; Kamble & Gunasekaran, 2023). Therefore, this study seeks to advance the DCT literature by proposing an evaluation framework to assess the extent of influence exerted by I4.0 and CE on the SP of manufacturing firms.

2.3. The Research Hypotheses

Despite the existence in the literature of extensive empirical evidence of the importance of DCT in strengthening I4.0 capabilities (e.g. Centobelli *et al.*, 2023; Chatterjee *et al.*, 2023; Lepore *et al.*, 2023; Vu *et al.*, 2023), there are few studies that have analyzed I4.0 and SP from a DCT context (Rifqi *et al.*, 2024), particularly because the literature showed that DCT facilitates the adoption of technology that improves the I4.0 capabilities of manufacturing companies (Chatterjee *et al.*, 2023). Therefore, DCT can improve the capacity of manufacturing companies to manage data and artificial intelligence systems, which will allow them to develop innovative capabilities (Lepore *et al.*, 2023) and a better level of SP (Dubey *et al.*, 2019).

Besides, I4.0 helps manufacturing firms to autonomously detect the security of their production systems, as well as helps in the continuous improvement of production processes (Osterrieder *et al.,* 2019), which generally increases SP and productivity (Alavian *et al.,* 2020). In addition, the main objective of I4.0 is the continuous improvement of the production systems performance, and decision-making of humans and machines (Mittal *et al.,* 2019), thereby generating a positive impact on SP (Bokrantz *et al.,* 2019). For this reason, the literature establishes that the adoption of l4.0 helps manufacturing firms to develop their dynamic capabilities (Garbellano & Da Veiga, 2019), for which organizations must focus on the parameters operational and associated costs (Dev *et al.,* 2019).

Additionally, Kyläheiko & Maijanen (2020) concluded that DCT helps firms to change production capabilities and resource utilization to improve their dynamic capabilities, particularly I4.0 capabilities. I4.0 enables firms to transform their capabilities, especially in improving SP, and adapt them to an increasingly dynamic global market (Sasmoko *et al.*, 2019). In this context, the adoption of I4.0 helps manufacturing firms improve their organizational capabilities by exploring new opportunities and fully exploiting their resources (Vu *et al.*, 2023), which allows them to improve their SP level (Bag & Christiaan, 2022). Thus, based on the information presented, the following research hypothesis is proposed.

*H1: The greater the implementation of Industry 4.0, the greater sustainable performance in a DCT context.*

I4.0 has attracted the attention of the scientific, academic and business communities around the world (Bag *et al.*, 2021), particularly because I4.0 is considered as a game-changing methodology (Rehman *et al.*, 2023), which is able to predict both the entry into new markets (Al-Khatib & Ramayah, 2023) and the generation of modeling methods capable of reducing strategic risks in manufacturing companies (Al-Khatib & Shuhaiber, 2022), generating more and better competitive advantages (Al-Khatib *et al.*, 2024). Therefore, I4.0 helps manufacturing companies improve SP (Al-Khatib & Shuhaiber, 2022) and CE (Belhadi *et al.*, 2022). Nevertheless, the connection between I4.0 and CE is still at an embryonic stage in the literature, and its application and benefits for manufacturing firms are still unclear (Abdul-Hamid *et al.*, 2022).

Finally, advances in I4.0 technologies – for example, artificial intelligence, virtual and augmented reality, big data analytics, 5G connectivity, additive manufacturing, and smart sensors (PWC, 2018; Machado et al., 2020) – can improve flexibility, productivity, and resource efficiency, which would increase both the level of SP (Chari et al., 2021) and CE practices (Alstete & Mayer, 2020). However, as pointed out by Rejikumar *et al.* (2019) and Del Giudice *et al.* (2020) the relatively new nature of the connection between I4.0 and CE requires further investigation and additional empirical evidence. In light of the information presented above, it is possible to propose the following research hypothesis.

*H2: The greater the implementation of Industry 4.0, the greater the circular economy in a DCT context*

There are studies in the literature that have theoretically confirmed the relevance of DCT in the sustainability of manufacturing companies (e.g. Amui *et al.*, 2017; Buzzao & Rizzi, 2021), however, there are few studies that have applied DCT in the context of CE (e.g. Prieto-Sandoval *et al.*, 2019; Khan *et al.*, 2020a), and even rarer are the investigations that have focused on the analysis of the relationship between CE and BS in a DCT context (Elf *et al.*, 2021). Possibly one of the main causes of this gap is that the adoption of CE requires significant changes in companies (Marrucci *et al.*, 2021). In that sense, DCT helps companies to be more dynamic, which facilitates the implementation of CE practices (Khan *et al.*, 2020a), generating an increase in their level of competitiveness and BP (Prieto-Sandoval *et al.*, 2018).

DCT has recently been explored in relation to CE and BS (Marrucci *et al.*, 2021). Khan *et al.* (2020b) demonstrated how DCT helped manufacturing companies to identify and leverage CE practices that improved their BP level, while Scarpellini *et al.* (2020) found an increase in the sustainability of companies when CE is analyzed from the DCT perspective. However, these contributions are not enough, since becomes essential to provide empirical evidence of the relationship between CE and BP in a DCT context. This necessity arises from escalating environmental degradation, loss of biodiversity, resource scarcity, reliance on fossil fuels for energy, and the proliferation of air, water, and soil pollution (Geissdoerfer *et al.*, 2017; Horodytska *et al.*, 2020).

Despite the recent studies that have focused on the implementation of CE and its relationship with SP, robust empirical evidence of the effects that CE has on SP in manufacturing firms is lacking (Prieto-Sandoval *et al.,* 2018; Saha *et al.,* 2021; Dey *et al.,* 2022; Mora-Contreras *et al.,* 2023). Furthermore, although research on the application of CE is crucial to determine if there are improvements in SP, the literature on this topic remains limited and fragmented (Khan *et al*., 2021a, 2021b; Kristoffersen *et al.,* 2021), representing a gap in existing research that calls for further investigation and is open to debate (Kristoffersen *et al.,* 2021; Mora-Contreras *et al.,* 2023). This is particularly important as new gaps emerge due to recently published studies reporting confusing and even contradictory results (Mora-Contreras *et al*., 2023). Considering the information presented in the preceding paragraphs, one can put forward the following research hypothesis.

*H3: The grater implementation of circular economy, the grater sustainable performance in a DCT context.*

Previous literature shows that DCT assists manufacturing firms in adopting the structural changes required to achieve business sustainability through the application of CE (Marrucci *et al.*, 2021), as well as I4.0 (Al-Khatib *et al.*, 2024). However, DCT is underrepresented in SP studies (Daddi *et al.*, 2018), and even more so in studies analyzing the relationship between I4.0, CE, and BP (Abdul-Hamid *et al.*, 2022), particularly when CE acts as a mediating variable between I4.0 and BP (Samadhiya *et al.*, 2023). However, although it has been established in the literature that CE plays an essential role in the application of I4.0, which improves the efficiency of resource use, and firms SP (Abdul-Hamid *et al.*, 2020; Rodríguez-Espíndola *et al.*, 2022), there is still no clarity as to what extent synergy between CE and I4.0 improves SP (Ratnasari *et al.*, 2022).

The adoption and implementation of CE entails several challenges for manufacturing companies such as high levels of uncertainty, production loss, excess inventories (Ritzén & Sandström, 2017), complex material and energy flows, data management and attitudes (Bag *et al.*, 2021). However, it has been suggested in the literature that DCT can help manufacturing firms respond quickly to these uncertainties through the adoption of CE and I4.0 (e.g. Scapellini *et al.*, 2018; Moon & Lee, 2021; Shayganmehr *et al.*, 2021; Chari *et al.*, 2021), particularly since CE drives I4.0 to improve not only the resource utilization and SP level of manufacturing firms (Tseng *et al.*, 2018; Rosa *et al.*, 2020) but also the production methods (Sassanelli *et al.*, 2019).

In this sense, Massaro *et al.* (2021) found that the literature establishes the ability of I4.0 to improve companies' sustainability outcomes, particularly when CE acts as a mediating variable (Samadhiya *et al.*, 2023). In a more recent study, Samadhiya *et al.* (2023) demonstrated that I4.0 substantially improves companies' SP when CE acts as a mediating variable. In this context, the implementation of CE in I4.0 has excellent potential to boost coordination between CE and I4.0, which increases the reliability of SP improvement in companies (Lim *et al.*, 2021). Furthermore, integrating CE into I4.0 has the potential to significantly enhance existing production systems and foster a more sustainable trajectory for future generations (Boeing *et al.*, 2022). Taking into account the insights shared in the preceding section, we develop the subsequent research hypothesis.

*H4: The circular economy acts as a mediating variable between Industry 4.0 and sustainable performance in a DCT context.*

Figure 1 below, illustrates the four hypotheses in the research model.

**Industry 4.0**

**Circular Economy**

**Sustainable Performance**

**H2**

**H3**

**H1**

**H4**

Figure 1. Research Model

1. **Methodology**

3.1. Sample Design and Data Collection

To address the hypotheses proposed in the research model, an empirical model was established in manufacturing firms in Mexico. The National Statistical Directory of Economic Units (DENUE) was utilized as the population reference framework, which recorded 37,883 companies in the manufacturing industry across all subsectors with over 10 employees in 2022 (INEGI, 2022b). In the first phase of the study, a *Business Panel* was held in which five entrepreneurs from the manufacturing industry participated, two representatives of government agencies related to financial support to companies, and three academics from ​​I4.0 and CE area were given the survey that would be applied. The results obtained in this first phase allowed the design of a survey to collect information, which was applied to a pilot sample of ten manufacturing firms, making minor adjustments to writing, appearance, and spelling. Pilot studies are essential to ensure validity when surveys are self-administered or contain self-developed scales (Bryman, 2016; Hair *et al*., 2016).

The criteria used for the selection of participants in the Business Panel were, with respect to entrepreneurs, that the companies had implemented at least one I4.0 and/or CE practice in the companies in the last two years; as for the representatives of government agencies, that they were responsible for the departments of granting credits to companies, and that in the last two years at least they have granted credit to a manufacturing company; and with regard to academics, who were members of the National System of Researchers of Mexico, who have carried out at least one research project funded by the National Council of Humanities, Sciences and Technology of Mexico in the last two years, and who have published in the last two years at least one article in a WOS Journal with impact factor related to I4.0 and/or CE practices in manufacturing companies.

In the second phase, employing simple random sampling with a maximum error of ±5% and a reliability level of 95% of 284 surveys. Surveys were distributed to 600 manufacturing firms, and only 338 surveys were collected, resulting in a response rate of 55%, which is considered representative of the target population. Data collection was conducted by a specialized firm through a personally administered survey targeted at managers of the selected industrial companies between February and May 2022, who identified individuals with the relevant expertise to respond to the various sets of questions included in the survey (Kuo & Chang, 2021). To reduce potential response bias (Podsakoff *et al.*, 2003), participants were assured of the confidentiality of their responses. They were informed that there were no definitive right or wrong answers and were encouraged to respond honestly. Any unfamiliar terms were clarified with examples and detailed explanations for the various midpoint scales. This protocol aimed to minimize responses influenced by social desirability, leniency, or the desire to meet perceived expectations.

3.2. Measurement Development

An exhaustive literature review was carried out to identify the most appropriate scales for measurement I4.0, CE, and SP. I4.0 was measured using 8 items based on Feldmann *et al.* (2010); Zhong *et al.* (2016); Tjahjono *et al.* (2017); Hofmann & Rüsh (2017); Farahani *et al.* (2017); and Saberi *et al.* (2019). To measure CE, we were based on the Ormazabal *et al.* (2018) scale which considered 8 items for their measurement. Finally, to measure SP, the scale of Kettunen and Ten-Brink (2015) and D'Amato *et al.* (2017) established 7 items for their measurement. All the items were measured through a 5-point Likert-type scale, with 1 = Totally disagree to 5 = Totally agree, as limits. These scales have already been used in recent studies in the Mexican manufacturing industry (e.g., Maldonado-Guzmán *et al.*, 2020; Rodríguez-Gonzáles *et al.*, 2022; Maldonado-Guzmán *et al.*, 2023; Rodríguez-Gonzáles *et al.*, 2023). Table 1 presents the factor loadings of the items used, and it is observed that all the values ​​are greater than 0.6, as recommended by Hair *et al*. (2019).

Table 1. Measurement Model Assessment

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| **Indicators** | **Constructs** | **Factor Loads (p-value)** |
| **Industry 4.0 (IND)**  Cronbach’s Alpha: 0.886; Dijkstra–Henseler’s rho: 0.891; CRI: 0.910; AVE: 0.558 | | |
| IND1 | Systems that integrate the physical world with virtual computational space. | 0.655 (0.000) |
| IND2 | Interconnecting of small computing devices embedded in products and objects to the internet, enabling the ability to receive and send data. | 0.725 (0.000) |
| IND3 | Automated technology can design, construct, and operate without human intervention during the process. | 0.769 (0.000) |
| IND4 | The official industry standard of utilizing 3D- printing to create components in production. | 0.785 (0.000) |
| IND5 | The Practice consists of a network of remote servers that enable the storage, process, and management of data compared to a local server. | 0.797 (0.000) |
| IND6 | Process of investigating large, varied data sets to discover useful information and patterns that may help the decision-making of organizations. | 0.719 (0.000) |
| IND7 | Process of manufacturing ever smaller electrical, optical, and mechanical devices. | 0.773 (0.000) |
| IND8 | A distributed digital technology that ensures transparency, traceability, and security. | 0.741 (0.000) |
| **Circular Economy (CEC)**  Cronbach’s Alpha: 0.926; Dijkstra–Henseler’s rho: 0.929; CRI: 0.940; AVE: 0.661 | | |
| CEC1 | There is an environmental commitment by senior management | 0.792 (0.000) |
| CEC2 | There is support for environmental management by mid-level managers. | 0.817 (0.000) |
| CEC3 | There is cooperation between the different departments or functional areas to improve the environmental practices of the organization. | 0.860 (0.000) |
| CEC4 | There is a training program for the organization's employees and workers on environmental issues. | 0.873 (0.000) |
| CEC5 | A total environmental quality management program is in place | 0.866 (0.000) |
| CEC6 | There are permanent audit programs of the organization's environment, such as ISO 14000. | 0.741 (0.000) |
| CEC7 | Eco-labels are used on most of the products generated by the organization. | 0.768 (0.000) |
| CEC8 | There is a program to prevent contamination of waste generated by the organization, such as clean production. | 0.777 (0.000) |
| **Sustainable Performance (SPE)**  Cronbach’s Alpha: 0.855; Dijkstra–Henseler’s rho: 0.861; CRI: 0.889; AVE: 0.533 | | |
| SPE1 | The company's activities enable the transition to a low-carbon economy. | 0.706 (0.000) |
| SPE2 | The company's activities protect and/or restore the environment by focusing on environmental quality aspects and improving resource efficiency. | 0.660 (0.000) |
| SPE3 | The company's activities help maintain, protect, transform, and/or strengthen the economy | 0.728 (0.000) |
| SPE4 | The company's activities help to protect, transform, strengthen, and/or develop society, human well-being, and/or employment | 0.747 (0.000) |
| SPE5 | During the last 3 years, the company has invested in the integration of environmentally friendly technology to improve business activities | 0.772 (0.000) |
| SPE6 | The integration of sustainable policies in the company's activities has achieved a reduction in operating and/or production costs. | 0.733 (0.000) |
| SPE7 | The integration of sustainable policies in the company's activities has had a positive effect on recorded profits. | 0.760 (0.000) |

3.3. Data Analysis

Data analysis was carried out using a PLS-SEM. This method allows for understanding causal-predictive power and accounts for the measurement error of variances (Fornell & Larcker, 1981). This technique has gained recognition among researchers, enabling more complex models across various disciplines (Tenenhaus *et al.*, 2005). Hair *et al.* (2021) identified four critical factors for selecting this method: characteristics of the information, characteristics of the model, model estimation, and evaluation. Additionally, by analyzing observed data, predictive analyses provide better explanations of latent variables in areas with emerging theories (Chin *et al.*, 2020; Hair *et al.*, 2021). Now, studies in strategic management would benefit from using the PLS-SEM technique due to exploratory characteristics, development of new theories, non-parametric data, and small sample sizes, among others (Hair *et al.*, 2019).

PLS-SEM is considered an approach based on compounds that linearly combine indicators to form composite variables (Lohmöller, 1987), which generally serve as proxies of the concepts being evaluated (Ringdon, 2016). In this study, the use of a composite model was considered pertinent, which is an essential reason for the use of PLS-SEM (Sarstedt *et al.*, 2016), and the SmartPLS 4.0 software (Ringle *et al.*, 2022). This is because composite indicators are considered in the literature as an operational definition of an emergent construct that mediates all model effects, and the composites measured through composite indicators do not have an error term (Hair *et al.,* 2021). For the estimation of path models, PLS-SEM generally uses a Model A or a Model B. Model A is related to correlation weights derived from bivariate correlations between each indicator and the construct, while Model B relates to weights of the regression (Sarstedt *et al.,* 2016). Model A is used in this study.

Additionally, the PLS-SEM method is suitable for this paper to test theoretical relationships primarily due to a) its compatibility with non-parametric data, b) its usefulness for exploratory modeling, and c) its ability to handle causal-predictive characteristics. Following Rigdon *et al.* (2017), researchers must use a technique consistent with the type of model they intend to estimate. In this sense, researchers with a model of composites should use a composite-based method like PLS-SEM. According to Sarstedt *et al. (*2016), if there is any doubt about the nature of constructs, it would be better to use PLS since it provides the least biased solutions. Composite indicators are the operational definition of the emergent construct that mediates all its effects in the model to be considered (Henseler, 2017).

Constructs measured with composite indicators do not have an error term, contrary to what happens with causal formative indicator models. So, composite indicators contribute to a construct instead of truly causing it (Bollen, 2011). Therefore, these indicators have to share the same consequences (Henseler, 2017), although they may not be unidimensional and might not share a conceptual unit. Thus, composite indicators may represent different aspects relating to the construct. As Sarstedt *et al.* (2016) explained, to estimate the paths, PLS-SEM uses Mode A and Mode B. Mode A links to correlation weights derived from bivariate correlations between each indicator and the construct, while Mode B has to do with regression weights. This study proposes a Mode A composite model with direct and mediating relationships to ensure the response to the questions posed.

To estimate structural equation models, the scientific and academic community generally uses two essential methods: Covariance-Based Structural Equation Modelling (CB-SEM) and Partial Least Square Structural Equation Modelling (PLS-SEM), which differ in terms of how they statistically approximate constructs and in their optimization routines (Cho *et al.*, 2022). Various studies published in the literature have evaluated the effectiveness and differences between CB-SEM and PLS-SEM, in an effort to pinpoint situations in which each method stands out, or falls short of expectations (e.g., Sarstedt *et al.*, 2016; Hair *et al.*, 2017; Cho *et al.*, 2023). The basic difference between CB-SEM and PLS-SEM is the approach for this estimation: CB-SEM use a Factor-Based Approach, and PLS-SEM use a Component-Based Approach (Rigdon *et al.*, 2017).

In factor-Based CB-SEM, the constructs are represented as common factors which indicates that the constructs are considered as an external reality independent of the observed variables, causing them to covary (Jöreskog, 1978). Therefore, the estimation of the parameters of CB-SEM is based on the common variance of the indicators, assuming that it can be fully explained as a function of the construct (common factor) plus its error variance (unique) (Hair *et al.*, 2017). In contrast, factor-based PLS-SEM relies on powered sums of observed variables to approximate the constructs (Tenehaus, 2008). Therefore, PLS-SEM estimation does not focus on the common variance but rather considers the total variance of the indicators as if it were a unidimensional identity (Sarstedt *et al.,* 2024). Thus, PLS-SEM has gained more popularity among researchers and academics with applications increasingly in business research (e.g., Wiesböck *et al.*, 2020; Suder *et al.*, 2022; Berndt *et al.*, 2023).

* 1. Measurement Model

The measurement model focuses on relationships between exogenous and endogenous variables, while the structural model examines the contribution of indicators to constructs (Martínez & Fierro, 2018). When assessing the measurement model and relationships between latent and observed variables, it is essential to ensure internal consistency, reliability, convergent validity, and discriminant validity (Hair *et al.*, 2021). To examine internal consistency, the lower bound was assessed using Cronbach's alpha and Composite Reliability Index (CRI), while the upper bound was assessed using rho A (Dijkstra & Henseler, 2015). Convergent validity considers the Average Variance Extracted (AVE), and discriminant validity accounts for the Fornell-Larcker criterion (Fornell & Larcker, 1981). Furthermore, Henseler *et al.* (2015) proposed the Heterotrait-Monotrait Ratio (HTMT) as a more effective criterion to ensure discriminant validity through bootstrapping.

Once the measurement model criteria are met (Hair *et al.*, 2021), the structural model is analyzed using bootstrapping to determine if the indirect effects are significant and to identify the type of mediation. The significance of a moderating variable lies in its ability to increase, decrease, or even redirect the influence between variables. The analysis of CE as a moderating variable is carried out using a two-step method, involving first the calculation of latent variable values. Subsequently, the obtained values of the exogenous and moderating variables are multiplied to ultimately derive the interaction effect (Hair *et al.*, 2021). The PLS-SEM statistical technique has been used in recent similar studies published in the literature (e.g.Viles *et al.*, 2022; Ali & Kaur, 2023; Maldonado-Guzmán *et al.*, 2023).

The loadings of the indicators were evaluated, ranging from 0.855 to 0.940 (Table 2). Optimal values were considered to be above 0.7, as they explain over 50% of the indicator variance (Hair *et al.*, 2021). When examining the model´s internal consistency favorable results were observed, with Cronbach's alpha exceeding 0.90. CRI figures ranged from 0.889 to 0.940 (Table 2), which falls within the recommended range by Hair *et al.* (2021). The rho A values were situated between the two previous indicators, representing the actual reliability of variables (Bagozzi & Yi, 1988; Hair *et al.*, 2021). Similarly, AVE and communality (Table 2) explained over half of the indicator variance, exceeding the 0.50 value (Fornell & Larcker, 1981; Hair *et al.*, 2021). Discriminant validity was validated using the Fornell-Larcker criterion, and HTMT ratio, with values ranging from 0.614 to 0.768, all falling below the 0.80 threshold (Henseler *et al.*, 2015).

Table 2. Measurement Model. Reliability, Validity, and Discriminant Validity

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **PANEL A. Reliability and Validity** | | | | | | | | | | |
| Variables | Cronbach's Alpha | | | Dijkstra-Henseler rho | | | CRI | | AVE | |
| Circular Economy | 0.926 | | | 0.929 | | | 0.940 | | 0.661 | |
| Industry 4.0 | 0.886 | | | 0.891 | | | 0.910 | | 0.558 | |
| Sustainable Performance | 0.855 | | | 0.861 | | | 0.889 | | 0.533 | |
| **PANEL B. Fornell-Larcker Criterion** | | | | | | **Heterotrait–Monotrait ratio (HTMT)** | | | | |
| Variables | | 1 | 2 | | 3 | 1 | | 2 | | 3 |
| 1. Circular Economy | | **0.813** |  | |  |  | |  | |  |
| 2. Industry 4.0 | | 0.646 | **0.747** | |  | 0.708 | |  | |  |
| 3. Sustainable Performance | | 0.557 | 0.683 | | **0.730** | 0.614 | | 0.768 | |  |

**Note:** **PANEL B:** Fornell-Larcker Criterion: Diagonal elements (bold) are the square root of the variance shared between the constructs and their measures (AVE). For discriminant validity, diagonal elements should be larger than off-diagonal elements.

1. **Results**

Using SmartPLS 4.0 software (Ringle *et al.,* 2022) through a structural equation model using partial least squares (PLS-SEM), the hypotheses raised in the research model were tested. Commonly, PLS-SEM is used in underdeveloped theories (Hair *et al.,* 2019), and in various disciplines of knowledge (Sarstedt *et al.,* 2014; do Valle & Assaker, 2015; Richter *et al.,* 2016). Moreover, employing PLS-SEM becomes crucial when the aim of applying the structural equation model is to predict and elucidate constructs within the research model (Rigdon, 2012). In addition, the use of compounds in PLS-SEM, as a weighted combination of its indicators, facilitates the explanation of the measurement error of the constructs, which allows this method to be more powerful than multiple regression (Hair *et al.,* 2019).

4.1. Structural Model Evaluation

The structural equation technique is basic to evaluate the structural models (Tenenhaus *et al.*, 2005). When analyzing the relationships between constructs, it is important to ensure non-collinearity using the Variance Inflation Factor (VIF), as well as to verify the significance and relevance of path coefficients effect sizes (f2) and determination coefficients (R2) (Martínez & Fierro, 2018). The observed VIF results (2.1 - 3.2) were below 5.0, and the R2 values were 0.421 for CE and 0.493 for SP (Table 3). The model fit (Table 3) was confirmed with an SRMR of 0.043 (Hu & Bentler, 1998), an Unweighted Least Squares Discrepancy (dULS) of 0.517, and the Geodesic Discrepancy (dG) of 0.191, all values below the HI99% (Dijkstra & Henseler, 2015).

Table 3. Structural Model

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Paths** | **Path (*t-value; p-value*)** | **95% Confidence Interval** | **f2** | **Support** |
| IND → SPE (H1) | 0.557 (10.506; 0.000) | [0.442 – 0.651] | 0.365 | Yes |
| IND → CEC (H2) | 0.649 (17.848; 0.000) | [0.563 – 0.708] | 0.742 | Yes |
| CEC → SPE (H3) | 0.198 (3.469; 0.001) | [0.086 – 0.310] | 0.050 | Yes |
| **Indirect Effects** | | | | |
| IND → CEC → SPE (H4) | 0.128 (3.400; 0.000) | [0.058 – 0.206] | 0.036 | Yes |
| **Endogenous Variable** | **Adjusted R2** | **Model Fit** | **Value** | **HI99** |
| SRMR | 0.043 | 0.050 |
| CEC | 0.421 | dULS | 0.517 | 0.698 |
| SPE | 0.493 | dG | 0.191 | 0.250 |

**Note:** IND: Industry 4.0; CEC: Circular Economy; SPE: Sustainable Performance. One-tailed t-values and p-values in parentheses; bootstrapping 95% confidence intervals (based on n=5,000 subsamples); SRMR: standardized root mean squared residual; dULS: unweighted least squares discrepancy; dG: geodesic discrepancy; HI99: bootstrap-based 99% percentiles.

Table 3 shows the results obtained, which indicate that the estimated data have acceptable statistical levels. The adjusted R2 value exceeds the minimum recommended threshold of 0.10 (Henseler *et al.,* 2014; Hair *et al.,* 2019). Additionally, SRMR, geodetic discrepancy (dG), and unweighted least squares discrepancy (dULS) all fall below the HI99 threshold according to Dijkstra and Henseler’s (2015) criterion. Likewise, estimated data verify that I4.0 has a positive impact on SP (0.557; p-value 0.000), and CE (0.649; p-value 0.000), providing evidence in support of hypotheses H1 and H2. Similarly, CE positively impacts on SP (0.198; p-value 0.001), further hypothesis H3. This suggests that CE leads to an improvement in the SP of manufacturing firms in Mexico.

Finally, results obtained also establish that CE can act as a mediating variable in the relationship between I4.0 and SP (0.198; p-value 0.000), suggesting evidence in support of hypothesis H4, indicating that a great part of the effects of I4.0 on the SP of manufacturing firms is transferred by CE. Therefore, it is possible to establish that CE not only significantly improves the SP of manufacturing firms but can also act as a vehicle that helps to improve the existing relationship between I4.0 and SP.

1. **Discussion**

The results obtained in this study support our argument about the positive impact of I4.0 on the SP of manufacturing firms, these results being consistent with the findings by Bag and Christiaan (2022), Ralston and Blackhurst (2020), and Alavian *et al.* (2020). The main reasons that could explain this positive effect are, first, the clarity that managers have of various benefits generated by applying I4.0 in manufacturing firms, not only in environmental terms but also in terms of social and economic sustainability. Second, the strong pressure that firms are increasingly facing from consumers and stakeholders to produce more environmentally friendly products, as well as the tightening of environmental standards by public administration so that companies adopt production systems that improve the environment and sustainability.

Likewise, the results support our argument that I4.0 has positive effects on CE. These findings align with those of Paul and Bussemaker (2020), Yadav *et al.* (2020), and Lardo *et al.* (2020). This effect could be explained by the increased use of digital technologies in the CE of manufacturing firms, which significantly reduces not only costs but also time in the production processes. Generating economic benefits and more attractive profit margins. On the other hand, this effect can be attributed to the reduction of risks related to non-compliance with various environmental regulations established by public administration. The benefits associated with CE are further amplified when manufacturing firms integrate it with the digital technologies of I4.0.

Also, the obtained results support the argument that CE has a positive effect on SP. These results are consistent with the research of Scarpellini *et al.* (2020), Dey *et al.* (2022), and Mora-Contreras *et al.* (2023). One significant explanation for this positive effect is the relatively minor costs associated with implementing CE in manufacturing firms compared to the substantial benefits it generates in terms of SP (including social, economic, and environmental benefits). Additionally, CE streamlines compliance with various environmental standards set by public administration, as it significantly reduces waste levels in production processes. This is achieved through the reuse and recycling of various components, which are then integrated into new products.

Additionally, the obtained results corroborate the assertion that CE may act as a mediating variable in the relationship between I4.0 and SP within manufacturing firms. These findings align with research conducted by Abdul-Hamid et al. (2021), Alnajem et al. (2021), and Ghobakhloo et al. (2021). A key underlying factor that could account for this outcome is that the integration of CE not only supports the enhancement of SP through the application of I4.0 in manufacturing but also enables firms to significantly reduce production costs. This is achieved by reusing and recycling components and materials, which can be seamlessly incorporated into the remanufacturing process of new products. Consequently, this leads to a greater economic and SP impact.

1. **Conclusions, Implications and Limitations for Future Research Directions**

*6.1. Conclusions*

The empirical findings from this study lead to several key conclusions. On one hand, it is possible to conclude that the research model exhibits high internal consistency, resulting in a positive correlation between I4.0, CE, and SP. This led to the acceptance of the hypotheses. Additionally, it provides a comprehensive overview of the primary digital technologies of I4.0, key CE practices, and the most pertinent indicators established in the literature on SP. Additionally, the literature that has analyzed these three concepts in the same empirical research model is scarce, since most published studies have been particularly oriented towards the analysis of two concepts at the same time, as well as bibliometric studies, which from our point of view they do not have a strong empirical contribution. Hence, this study furnishes substantial empirical evidence and novel insights affirming the relationship between I4.0, CE, and SP.

Additionally, it can be deduced that the adoption of I4.0 is widely recognized in the literature as a significant factor in enhancing the SP of manufacturing firms, especially when CE serves as a mediating variable between the two concepts. Within this context, our empirical study affirms that I4.0 advances the sustainability of manufacturing firms and CE. This is achieved through the integration of recycled materials into production processes, resulting in the creation of more environmentally friendly products. This, in turn, alleviates the substantial societal pressure on organizations to enhance sustainability and environmental efforts. Additionally, it is worth noting that our study contributes to the existing body of literature. There have been relatively few prior studies that have investigated CE as a mediating variable between I4.0 and SP in manufacturing firms within emerging economy countries.

*6.2. Implications*

*Theoretical Implications*

The study contributes to DCT, I4.0, CE, and SP literature in various ways. Firstly, expands the current debate on the importance of DCT and how manufacturing firms seek to achieve the highest use of their dynamic capabilities to improve I4.0 and CE in a sustainability context, for which this study provides a theoretical framework that considers the DCT as an essential background for the adoption of I4.0 and CE that improves SP. Second, it addresses concerns of limited investigations that examine DCT as a major determinant of I4.0 (Ellström et al., 2022; Lepore et al., 2023), and CE (Marrucci et al., 2021; Khan et al., 2021) in SP context. Furthermore, this paper also reduces a research gap identified by Chari et al. (2021), presenting robust empirical evidence on the relationship between I4.0 and CE in the context of business sustainability.

Third, the study provided empirical evidence that supports the importance of DCT in I4.0 and CE capabilities in supporting SP in the manufacturing sector, therefore the results obtained in this paper lead to a greater understanding of the needs of this sector regarding the strategic view of adopting I4.0 and CE capabilities and improving SP. Fourth, the literature indicates that I4.0 and CE capabilities are necessary for manufacturing firms SP, therefore, this study analyzed the mediating influence of CE in the relationship of I4.0 and SP. To address this gap, this research uncovers and confirms that CE offers a partial mediation effect on the association of I4.0 and SP. Furthermore, this paper also narrows a research gap identified by Samadhiya et al. (2023), presenting robust empirical evidence on the mediation that CE has in the link between I4.0 and SP in a DCT context.

*Practical Implications*

The data estimated in this empirical study holds diverse implications for managers, manufacturing firms, industry professionals, and public administration.

Firstly, the findings in our study indicate that the adoption and implementation of I4.0 and CE is not a constant practice in manufacturing companies in Mexico, as in the rest of the emerging economy countries, on the one hand, due to the high costs generated by the digitalization of production processes and, on the other hand, due to the resistance to change of both the personnel and the managers of the companies. Although the results of our study provide company managers with the benefits of acquiring digital technology, we consider the need for an intra- and inter-organizational analysis of other studies to empirically validate our results; such efforts could facilitate the adoption of I4.0 and CE practices.

Secondly, industry professionals would be recommended to strategically analyze the business environment in which manufacturing companies operate, mainly in emerging economy countries, from a sustainability context. Various manufacturing companies may need to analyze aspects of their organizational culture to assist in the adoption and application of I4.0 and CE practices, for example, employee characteristics, staff skills and commitment, as well as the motivation of managers in carrying out innovations in business activities. These efforts could help manufacturing companies establish an organizational structure that adds greater value to production processes by adopting I4.0 and CE.

Thirdly, the results obtained can serve as a basis for policymakers to design and implement policies and programs aimed at exponentially increasing the adoption of I4.0 and CE practices in all manufacturing companies in the supply chain so that sustainability is improved. Furthermore, these results could also help the public administration to design programs and fiscal incentives to support the acquisition of digital technology, particularly because sustainability should be part of the public administration's commitments to society in general. We believe that this collaboration would influence the application of I4.0 and CE practices both at the macro level (for example, establishing policies and fiscal incentives for technological development), and at the micro level (for example, establishing goals and objectives of improvement of environmental sustainability).

*6.3. Future Research Directions*

Even though the existing literature establishes the importance of the adoption and implementation of I4.0, CE and SP in a DCT context in manufacturing companies, particularly in emerging economy countries (Abdul-Hamid et al., 2022), our study identified specific knowledge gaps that indicate future research agendas. Firstly, future research should focus on expanding knowledge by providing robust empirical evidence on the link between I4.0, CE and SP in various application scenarios. For example, to better understand the interaction between I4.0 and CE, the scientific and academic community can focus its attention on the development and application of big data and the Internet of Things (IoT), specifically in an SP context. We urge researchers and academics to adopt a management perspective for future research and use existing theories to test the advantages and disadvantages of integrating CE practices into I4.0.

Secondly, the current literature has analyzed and discussed the various sustainable benefits that the adoption and implementation of I4.0 and CE practices generate in manufacturing companies (Dantas et al., 2021), but more studies are required that provide robust empirical evidence to have greater knowledge of how the adoption of I4.0 by manufacturing companies, particularly in emerging economy countries, can achieve better sustainable results by linking it with the CE than with the traditional linear economy, from a DCT perspective, for example, measuring the negative environmental impacts generated by companies that adopt a linear economy versus those companies that have adopted a CE. The literature review of our study highlights the need to delve deeper into providing theoretical and empirical evidence of the link between I4.0, CE, and SP in a DCT context in emerging economy countries.

Third, the findings found in our study emphasize that the process of adoption and implementation of I4.0 and CE practices faces enormous challenges, many of which revolve around the costs of their application and the quantification of the performance of the resources invested. Therefore, since the adoption of I4.0 and CE remains a persistent challenge for many manufacturing companies in emerging economy countries, we urge the scientific and academic community to guide their studies in analyzing the potential of the process. of technology assimilation to improve the management of organizations and facilitate the adoption of CE practices that improve the SP and the economic and financial performance of companies. Although our study identified some facilitating factors for the adoption and implementation of I4.0 and CE practices (benefits) and inhibitors (barriers), researchers and academics can explore other factors that potentially the application of I4.0 and CE.

Finally, future research related to the adoption of industry 4.0 technologies and AI by companies should consider the impact of quantum computing. In fact, quantum computing can have a significant effect during the digitalization process. Digitalization often involves optimizing processes, material resources, and systems. Quantum computing excels at solving complex optimization problems. For example, it can optimize supply chain logistics, financial portfolios, energy distribution, and various other aspects of digitalized systems. Quantum computing can accelerate the training processes of machine learning models developed by AI systems.

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