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Total Productive Maintenance and Industry 4.0 in a Sustainability Context: Exploring the Mediating Effect of Circular Economy

Abstract

Purpose: The purpose of this research is to establish a conceptual model to understand the impact of Total Productive Maintenance (TPM) and Industry 4.0 (I4.0) on the transition of a Circular Economy (CE). Also, the paper explores the combined impact of TPM, I4.0, and CE on the sustainability performance (SP) of manufacturing firms.

Methodology: The conceptual model is proposed using the dynamic capability view (DCV) and empirically validated by partial least squares-structural equation modelling (PLS-SEM) using 304 responses from Indian manufacturing firms.

Findings: The results suggest that I4.0 positively impacts TPM, CE, and SP, also showing TPM's positive impact on CE and SP. In addition, CE has a positive influence on the SP of manufacturing firms. Furthermore, CE partially mediates the relationship between I4.0 and SP with TPM and SP. The study also identifies TPM, I4.0, and CE as a new bundle of dynamic capabilities to deliver SP in manufacturing firms.

Originality: The present research adds to the knowledge and literature on DCV by identifying the importance of CE in the settings of I4.0 and TPM, especially in the context of sustainability. Also, the current study offers a new set of dynamic capabilities and provides some significant future recommendations for researchers and practitioners.

Keywords: Circular economy, Industry 4.0, Total productive maintenance, Sustainability performance.

1. Introduction

The notion of sustainability swiftly went worldwide after the World Commission on Environment and Development (WCED) first raised its concerns about the issue related to "our common future" in 1987 (Khodeir and Othman, 2018). Organisations are under pressure to evolve into social, economic, and environmentally (Triple bottom line (TBL)) sustainable corporations (Naseem and Yang, 2021). Ecological degradation from economic behaviour has become more and more of an issue worldwide in recent years (Laari *et al.,* 2017). Organisations at the present time face serious dangers from sustainability problems due to economic, environmental, and social implications (Dantas *et al.,* 2021).

Past research has claimed that, even with a greater focus on sustainability challenges, existing literature lacks a thorough approach to recognising and managing these concerns both through novel scholarly reasoning and at a company level in such a period of peak awareness and immediacy pertaining to sustainability challenges (Touboulic and Mccarthy, 2019). This has prompted a large number of industrial enterprises to investigate the feasibility of recycling materials or elements of goods in order to extend the useful life of their materials and energy investments for an extended span of time (Rajput and Singh, 2019). This will result in the transformation of the economies throughout the globe into ones that are more ecologically acceptable and sustainable.

In spite of the fact that the concept of sustainability has existed for some time, the Circular Economy (CE) approach has just lately began to occupy a more prominent place in the thoughts of decision-makers in an effort to find solutions to problems associated with environmental sustainability (Brennan *et al.,* 2015). The CE model is one of the key cornerstones that a number of nations and international organisations have included in their respective strategies for sustainable development (Laskurain-Iturbe *et al.,* 2021). Manufacturing firms are investing large sums of money into developing more sustainable goods and circular operations. In this regard, a variety of approaches, including reusing, reprocessing, and recycling, have been examined in earlier research (André *et al.,* 2019). In addition, certain commercial methods (Rosa *et al.,* 2019a) to enable the pragmatic deployment of CE and achieve genuine benefits from this have been assessed (Rosa *et al.,* 2019b).

Silvestre and Tirca (2019) suggest that sustainability performance will be impossible to accomplish without digital transformations. Massaro et al. (2021) indicate that a large majority of practitioner and academic publications trumpet the capacity of I4.0 technologies to improve sustainability outcomes, particularly in the circular economy (CE). CE has now been adopted by academia and practitioners (Zhang *et al.,* 2021), and is considered as a new sustainability perspective that might improve value development by reducing the consumption of environmental commodities and waste generation to preserve ecological integrity (Geissdoerfer *et al.,* 2017).

I4.0 technologies, such as IoT, have the potential to facilitate the move to CE practices (Zhang *et al.,* 2019). However, emerging closed-loop processes, which are entirely oriented toward harmonising economic, environmental, and societal consequences, are gradually attempting to replace previous industrial methods (Sassanelli *et al.,* 2021). CE is driven by I4.0 (Rosa *et al.,* 2020), which jointly offers a large capacity for achieving SP targets, including lower resource usage and gas discharge rates (Tseng *et al.,* 2018). Wang et al. (2018) argue that strengthening manufacturing activities is critical to promoting lifecycle-based CE.

However, although there is an assumption that I4.0 technologies will help businesses accomplish their CE goals (Lacy and Rutqvist, 2016), the converse may also be true (Di Maria *et al.,* 2022). Frank et al. (2019) stress that there is no consensus regarding the impact that I4.0 technologies have on circularity or the opportunity for transformation that they provide to businesses. In addition, earlier studies indicate that limited research has investigated the interconnections among the various I4.0 technologies and CE (Bag and Pretorius, 2020; Dalenogare *et al.,* 2018). Therefore, earlier research provides evidence for a dispute over the direction of the link between I4.0 and CE. This debate addresses a critical academic research gap, resulting in the formulation of the subsequent research question:

RQ1: What is the association between I4.0 and CE in the context of sustainability of manufacturing firms?

The Ellen Macarthur Foundation is a leader in CE research. It defines CE "as a systems solution framework that tackles global challenges like climate change, biodiversity loss, waste, and pollution" (Ellen MacArthur Foundation., 2021). CE principles may be used to explain the optimal functioning of the economy as a whole and they can also be used to pinpoint particular areas where economic value can be generated (Obrien *et al.,* 2014). Economic and comparative proposals (e.g. reuse versus reprocess versus recycling) might vary dramatically in every single supply chain region for various goods, parts and other kinds of resources. The ideas of circular value creation, however, can be easily grasped (Sobral and Ferreira, 2018). In addition, CE recommends that in order for organisations to be successful, they should maximise their utilisation of resources while minimising their waste to create progress that is both harmonic and sustainable (Ghisellini, 2016), since CE orientation is zero waste (Farooque *et al.,* 2019b).

A report from the Ellen MacArthur Foundation (2015) suggests that maintenance represents the most cost-effective, material and resource-efficient CE system solution, making it the most efficient and accessible alternative, as maintenance is primarily about keeping the same machinery, materials, and commodities in use. Maintenance is becoming an appealing approach to start CE and develop pace in a more sustainable path as raw materials and end-of-life treatment expenses rise (Allen, 2021). Total Productive Maintenance (TPM) places a focus on maintenance by treating it as an essential component of the company that must be carried out (Venkatesh, 2007). It enlists the engagement of a firm's entire workforce, boosts the efficiency of its machinery, cuts down on the number of breakdowns that occur, and encourages autonomous maintenance (Ahuja and Khamba, 2008). TPM looks to be the quickest and most effective way to achieve continual growth in maintenance while also having a positive influence on CE. Machinery performance can be continually improved through an ongoing operation that entails all company departments and employees in order to create an efficient framework of preventive maintenance for as long as the machinery is in service (Sobral and Ferreira, 2018).

TPM's various tools and pillars help firms reduce waste (Vukadinovic *et al.,* 2018), reduce toxicants and leakages (Chiarini, 2014), and offer better environmental performance (Garza-Reyes *et al.,* 2018). Also, TPM assists a firm to obtain a better monetary performance (Gu *et al.,* 2017) by improving its operational performance (Gupta and Vardhan, 2016). Therefore, TPM can be an enabler of company sustainability. Also, waste reduction and optimal resource consumption indicate the possibility that TPM can enable enhanced CE outcomes. Nevertheless, no academic study has been previously conducted to determine the direct connection in both TPM and CE, especially in the context of business sustainability. The dearth of research in this area leads to the formulation of the second research question:

RQ2: What is the association between TPM and CE in the context of sustainability of manufacturing firms?

The integration of I4.0 technologies into classical maintenance fosters the development of contemporary maintenance practices, which ultimately results in efficient data and mechanical operations (Silvestri *et al.,* 2020). I4.0 requires conventional machines to be transformed into self-cognizant and autodidactic machines to enhance comprehensive operation and maintenance management by environmental stimulus (Vaidya *et al.,* 2018). The findings of Raji et al. (2021) suggest that I4.0 positively influences the implementation of lean manufacturing. Thanki et al. (2016) suggest that TPM has proved itself to be the most effective and influential lean manufacturing shop-floor practice. I4.0 has a favourable impact on how manufacturing shop floors are governed and structured as well as on the business models, goods, and operation of enterprises (Tortorella *et al.,* 2019). A real-time machine monitoring system is made possible by I4.0 (Shafiq *et al.,* 2021). In addition to keeping track of the health of the equipment, the environment is also monitored. The findings of Tortorella et al. (2021) suggest that integrating I4.0 technology into TPM enhances decision-making and assists businesses in achieving better functional performance. Tortorella et al. (2022a) indicate that I4.0 has a positive influence on TPM philosophy. However, no research has empirically examined the relationship between I4.0 and TPM within a sustainability context. In order to fill this void, the present research has developed a third research question:

RQ3: What is the relationship between I4.0 and TPM in the context of sustainability of manufacturing firms?

CE is one of the most recent approaches to achieving environmental sustainability (Clarke Murray *et al.,* 2015). Industry choices to develop sustainable production strategies demand a rigorous and ongoing practice, notably in process safety and the environment (Toha *et al.,* 2022). Two reports, one from the Ellen MacArthur Foundation and the other from the academics and modelling experts at the McKinsey Centre for Business and Environment, imply that in a CE situation, the amount of materials that are used may be reduced by approximately 32% within 15 years and by over half (53%) by 2050 (Toha *et al.,* 2022). Furthermore, switching to a CE has the power to remove 100 million tonnes of material pollution worldwide over the next five years. This indicates the significant contribution of CE in leading a firm towards sustainability. Also, by incorporating CE concepts into scientific operations, establishing additional employments, and allowing a diversity of assets that may usually be regarded as waste into the financial loop, high energy effectiveness and energy reductions can be obtained (Toha *et al.,* 2022). Therefore, investigating the role of CE in the sustainability context is important; this leads to examining the CE contribution in the overall SP of manufacturing firms. Additionally, previous research has investigated the direct association between CE with I4.0 and TPM in a sustainability context. This motivated the present research to explore how CE may act as a mediator (not a moderator) between TPM and SP, and I4.0 and SP. As a result, the following constitutes the formulation of a fourth research question:

RQ4: What is the mediation effect of CE on the relationship of TPM and I4.0 with SP?

Dynamic capabilities help enterprises overcome problems by quickly evolving environments through fostering capabilities (Teece *et al.,* 1997). Dynamic capabilities are often identified to meet the complicated challenges associated with accomplishing organisations' sustainability goals (Beske *et al.,* 2014). Sustainability oriented past research has emphasised the requirement for further investigations in choosing appropriate dynamic capabilities that companies could use to boost their sustainability (Amui *et al.,* 2017). Therefore, the current study fills this gap in past research by presenting TPM, I4.0 and CE as dynamic capabilities to practise sustainability and empirically assess the impact of their relationships on the SP of a manufacturing firm.

Following a comprehensive analysis of the existing research, a conceptual framework is presented here. The framework is then validated by Partial Least Squares Structural Equation Modelling (PLS-SEM), using 304 responses from Indian manufacturing organisations for the analysis.

The paper is structured as follows: Section 2 presents the theory background and hypothesis development, followed by the proposed conceptual framework. Section 3 illustrates the methodology used for the research of this paper, followed by Section 4, which introduces the results and findings of the investigation. Section 5 offers the discussion and implications of the present research. Finally, Section 6 offers the conclusions, limitations, with the future research scope of the current study.

2. Theory Background and Hypothesis Formulation

2.1 Dynamic Capability View (DCV)

Changing consumer demands and increased supply chain competitiveness have driven organisations to employ technological innovations to enhance conventional into intelligent manufacturing operations (Kamble and Gunasekaran, 2021). I4.0 intends to improve business productivity and competitiveness by utilising digital technology to integrate businesses through their supply chains (Nounou *et al.,* 2022). I4.0 gives businesses tactical and functional leverage over their competitors (Müller *et al.,* 2018). Also, organisations using I4.0 aim to coordinate smart machines throughout the entire end-to-end operation, including vendors, production, and item delivery. I4.0 is considered as a combination of precious assets owned by businesses with a high natural ability for combining goods and manufacturing operations. I4.0 technologies have significantly integrated production activity structures with networking, data, and smart platforms (Wang *et al.,* 2017). I4.0 has the capability to deliver numerous benefits to businesses, including more lucrative business models, increased productivity and quality, and enhanced working environments (Hofmann and Rüsch, 2017). It is possible that I4.0 will be able to solve several environmental and social problems caused by conventional industrial practices and technologies, thereby leading to a path for a more sustainable society (Morrar and Arman, 2017). Many businesses have recognised the potential for sustainability to provide them with a competitive advantage (Cantele and Zardini, 2018). The findings of past research help in the establishmentt of the proposed investigation based on the Dynamic Capability View (DCV). Scholars have defined DCV as "*capabilities that enable businesses to develop novel goods and operations and adapt to shifting market trends"* (Helfat, 1997). Some other perspectives of DCV can be understood as *"The capability of organisations to effectively address their organisational challenges is fundamentally dependent on their abilities"* (Dosi *et al.,* 2000). DCV is an augmentation of the resource-based theory's fundamentally static vision. It investigates how resources are developed and renewed throughout time in response to shifting business contexts (Helfat and Peteraf, 2003).

The merits of CE practices include minimising environmental impact through waste reduction to redesign goods with more monetary benefits (Coghlan *et al.,* 2021). Therefore, CE practices can also be a strategic tool to offer competitiveness in an organisation (Diéguez-Santana, 2022). Also, CE practices have been highlighted as a possible sustainable development solution to fulfil the company's objectives (Ogunmakinde *et al.,* 2022). However, in implementing CE practices, organisations must replace their capabilities with new ones to maintain their competitive edge. (Sirmon *et al.,* 2007).

According to Lieder and Rashid (2016), information technology in manufacturing has advanced CE implementation. CE seeks to substitute the "end-of-life paradigm" by completing material loops and prolonging item lifespan (Batista *et al.,* 2019). However, one of the most difficult issues is eliminating waste in terms of time and resources spent on maintenance (Basten *et al.,* 2014). To overcome this issue, TPM can be used as a maintenance management strategy in manufacturing firms, leading to the elimination of numerous wastes (Chiarini, 2014). Additionally, TPM helps to deliver cleaner production in manufacturing companies (Amjad *et al.,* 2021). TPM practices have assisted in the optimal utilisation of available resources in a production line, enabling productivity improvements (Wudhikarn, 2012) and leading manufacturing firms towards increased competitiveness (Chen, 2013). Therefore, TPM has been considered in this study as an important operational tool to offer CE through waste reduction, efficient resource consumption, and greener production. The performance of TPM can also be improved from the incorporation of I4.0 technologies. I4.0 technologies enable real-time monitoring of machines to offer accurate results (Tortorella *et al.,* 2021a). Also, the nature of I4.0, CE, and TPM is to deliver the SP of a manufacturing firm. Nevertheless, no past research has examined the relationship between I4.0, TPM, and CE within the context of sustainability. Therefore, the purpose of the current investigation is to provide a contribution in the field of DCV by studying the impact of I4.0, TPM, and CE interactions on the SP of manufacturing firms.

2.2 Hypothesis Formulation

2.2.1 TPM and CE

As climate issues have risen, manufacturers have been forced to reconsider attaining operational excellence while also making their activities and operations more environmentally sustainable (Garza-Reyes *et al.,* 2018). CE practices suggest that organisations should optimise resource usage and eliminate waste to accomplish harmonious, sustainable development (Ghisellini *et al.,* 2016). Smith and Hawkins (2004) identified the most frequent factors in process industries that lead to waste. These include "equipment condition", "non-optimised operation", "equipment availability", and "project and technology". TPM is a maintenance management philosophy that overcomes the factors that cause waste. For instance, TPM helps to improve and restore the condition of equipment through its maintenance pillars (Tsarouhas, 2013). TPM offers optimised operations through preventive maintenance procedures (Sobral and Ferreira, 2018). TPM restores equipment's health, enabling adoption to new technologies (Sobral and Ferreira, 2018). Also, TPM prevents machine breakdowns to ensure the availability of equipment when needed (Ahuja and Khamba, 2008). In this way, TPM can lead a firm to deliver CE outcomes by eliminating waste and optimising resource consumption.

Ghisellini et al. (2016) suggest that some dimensions of CE are cleaner production, green consumption, and product recycling. TPM has been implemented in manufacturing firms as the most effective lean tool (Belekoukias *et al.,* 2014). TPM adoption in manufacturing enterprises aids in the reduction of pollutants such as fume emissions and oil leaks (Chiarini, 2014). Also, TPM implementation helps optimise energy usage in manufacturing processes. According to Amjad et al. (2021), TPM is extremely beneficial in building a more effective and greener production operation by reducing toxic gas emissions by 55%. Therefore, outcomes such as waste reduction, cleaner production, and better environmental performance of TPM implementation in manufacturing firms indicate that TPM could lead manufacturing companies to adopt and implement better CE practices. However, no previous studies have addressed this relationship. Thus, H1 has been formulated as follows:

H1: TPM positively influences CE practices in manufacturing firms.

2.2.2 I4.0 and TPM

TPM promotes operational consistency by maintaining manufacturing machinery efficiently, resulting in minimal failures and quality faults (Wickramasinghe and Perera, 2016). Furthermore, TPM incorporates various aspects of conventional maintenance, such as reactive, planned, proactive and predictive maintenance (Coleman *et al.,* 2017). The digitalisation of these maintenance practices complements each other and offers enhanced operational performance and unique potential (Nowakowski *et al.,* 2018). I4.0 could potentially improve maintenance operations by utilising embedded sensors and fast data computation, allowing for the creation of innovative methods and increasing machine performance and longevity (Klathae and Ruangchoengchum, 2019). Technology incorporation also boosts maintenance performance standards because it may aid in enhancing maintenance schedules, facilitating decision-making, and reducing human failures (Mourtzis *et al.,* 2020a, b). I4.0 technologies can aid in the optimisation of maintenance scheduling by spotting machine flaws early on (Felsberger *et al.,* 2020). Simultaneously, augmented reality may offer more precise instructions for detecting and checking machinery (Silvestri *et al.,* 2020). Therefore, this discussion suggests the positive influence of I4.0 on the performance of TPM practices. Nevertheless, past research has not yet empirically investigated the relationship between I4.0 and TPM. Thus, the following hypothesis has been formulated:

H2: I4.0 positively influences TPM practices in manufacturing firms.

2.2.3 I4.0 and CE

Industry 4.0 (Thoben *et al.,* 2017), a German governmental project, has gained interest from academics and professionals alike, opening the path for a whole new concept of value generation (Reinhard *et al.,* 2016). I4.0 has been outlined in detail by the German government and academic institutions, with the following overview:

"In the future, businesses will establish global networks that incorporate their machinery, warehousing systems and production facilities in the shape of Cyber-Physical Systems (CPS). In the manufacturing environment, these Cyber-Physical Systems comprise smart machines, storage systems and production facilities capable of autonomously exchanging information, triggering actions and controlling each other independently. This facilitates fundamental improvements to the industrial processes involved in manufacturing, engineering, material usage and supply chain and life cycle management. The smart factories that are already beginning to appear employ a completely new approach to production. Smart products are uniquely identifiable, may be located at all times and know their own history, current status, and alternative routes to achieving their target state" (Kagermann *et al.,* 2013).

A growing number of practitioners and academics are advocating the use of I4.0 technologies, notably within the framework of the CE, to obtain superior environmental outcomes (Massaro *et al.,* 2021). Implementing I4.0 technologies such as Internet of Things (IoT), cyber-physical system, big data analytics, and some innovative business frameworks are envisaged to support CE practices to develop a sustainable industrial ambience (Bressanelli *et al.,* 2018). The operation, functional status, and availability of smart products may be tracked in actual time after incorporating I4.0 technologies into traditional systems (Pagoropoulos *et al.,* 2017). Knowledge of intelligent devices may assist organisations in upgrading device firmware, decreasing expiration issues, increasing item longevity, and supporting CE (Pialot *et al.,* 2017). Radio Frequency Identification (RFID) and IoT have been found to perform a vital function in item and repair parts traceability (Franco, 2017), helping to achieve CE goals (Nobre and Tavares, 2017). The studies of Kamble and Gunasekaran (2021) and Lopes de Sousa Jabbour et al. (2018) indicate the positive influence of I4.0 technologies on CE practices. Some contradictory research is also available in past literature. For instance, Di Maria et al. (2022) suggest that due to inherent tensions between achieving economic results and doing what is best for the environment, certain I4.0-related technologies, such as robotics, 3D printing, and augmented reality, may make it more difficult to put environmental initiatives into action. In addition, there may be trade-offs in the link between digitization and CE. It is possible that digitalization may boost resource productivity; nevertheless, this may also promote energy consumption and waste generation (Chen *et al.,* 2020). It is still unclear how I4.0 technologies will improve the results of CE practices (Di Maria *et al.,* 2022). Therefore, previous research offers debatable findings. Very limited empirical research has been conducted to investigate this relationship, which creates the need of investigating this relationship empirically. Thus we hypothesise that:

H3: I4.0 positively influences CE practices in manufacturing firms.

2.2.4 TPM and SP

Dieste et al. (2021) indicate that the deployment of TPM practices in a manufacturing firm enhances its financial performance. Hofer et al. (2012) categorised TPM as an internal lean package, claiming that proper TPM execution contributes to improved economic performance. TPM is widely employed in lean approaches in manufacturing to offer monetary benefits within the manufacturing firm (Negrão *et al.,* 2016).

Chen et al. (2019) demonstrated that TPM enhances manufacturing firms' environmental performance. Garza-Reyes et al. (2018) indicate that TPM improves the environmental sustainability of a manufacturing firm's operations. Heravi et al. (2020) suggest that TPM adoption in a manufacturing firm lowers carbon footprints and encourages efficient energy use.

TPM execution aids in providing improved health and a safer working climate for manufacturing personnel (Vukadinovic *et al.,* 2018). Also, TPM fosters excellent interaction among its personnel (Agustiady and Cudney, 2018). A manufacturing company's social sustainability performance is measured by a healthier, safer work environment and outstanding personnel communication (Abid *et al.,* 2020). Therefore, previous research has suggested the positive impact of TPM on TBL sustainability. Nevertheless, no previous research has examined the relationship between TPM and the overall sustainability (as a single index) of a firm. The dearth of empirical evidence for the relationship between TPM and SP leads this research to examine the relationship. Thus, we hypothesise that:

H4: TPM has a positive impact on the SP of manufacturing firms.

2.2.5 I4.0 and SP

I4.0 supports reaching the sustainability goals of manufacturing companies (Kamble and Gunasekaran, 2021). I4.0 helps to improve operational agility and item quality (Ghaithan *et al.,* 2021). I4.0 digitalisation aspects lead to shorter production times, shorter lead times, and lower shipping and manufacturing costs, all of which result in better consumer satisfaction and, as a consequence, increased market position and profitability (Stock and Seliger, 2016). I4.0 enables actual-time data and information exchange among supply chain collaborators that aid in the efficient distribution of primary goods, water, power, and personnel time (De Sousa Jabbour *et al.,* 2018); this leads to eliminating resource scarcity, greenhouse gas releases, and wastage production (Wang *et al.,* 2016). Also, incorporating I4.0 technologies in enterprises enhances workplace surroundings, ensures safer operating situations for staff, and introduces new technologies to employees, all of which boost enthusiasm and satisfaction (Herrmann *et al.,* 2014). Therefore, evidence from past research indicates that TPM could offer enhanced SP for a manufacturing firm. Thus, the following hypothesis has been proposed:

H5: I4.0 has a positive effect on the SP of manufacturing firms.

2.2.6 CE, SP, and CE's mediation

CE is built on resource conservation, in which businesses can minimise commodity consumption by remanufacturing and recycling goods throughout production lines by employing green circular purchasing (Sakthivadivel *et al.,* 2020). CE was highlighted by Geissdoerfer et al. (2017) as one of the imperative factors for sustainability, requiring additional research into the connection between CE and sustainability. CE approaches boost manufacturing efficiency, resulting in better monetary results (Tang *et al.,* 2022). Furthermore, Tang et al. (2022) indicate that CE's ecological and financial gains are interconnected, and both can be obtained simultaneously. Increasingly, it's being recognised as having enormous potential to assist firms in making significant strides toward more sustainable operations (Farooque *et al.,* 2019a). CE practices have a favourable influence on the sustainability TBL dimensions, supporting the organisations' long-term viability and reducing asset cycles (Hobson *et al.,* 2018). Manufacturing companies are progressively implementing CE and sustainable manufacturing methods to reduce environmental concerns (Moktadir *et al.,* 2018). CE methods can help to mitigate the adverse consequences of industry on the ecosystem (Madueke *et al.,* 2020). CE is predicted to be a critical aspect of emerging supply chains to achieve sustainability-oriented outcomes (Manninen *et al.,* 2018). These insights from literature lead to the subsequent hypothesis:

H6: CE has a positive influence on the SP of manufacturing firms.

CE is among the most intriguing concepts for structuring upcoming financial operations in a sustainable manner (Del Giudice *et al.,* 2020), and as an approach to reverse the environmental deterioration that affects the world's ecosystem (Hazen *et al.,* 2020). Looking at the rapid adoption of CE for a manufacturing firm's sustainability and assessing CE as a pre-requisite of sustainability, CE could be an enabler for achieving sustainability outcomes. Therefore, CE can act as a mediator/moderator for I4.0 and TPM to offer better sustainability outcomes. The present research investigates the direct connection among I4.0, TPM, and CE in the sustainability framework. Thus, it is not possible that a moderating variable (in this case CE) can have a direct association with independent variables (in this case I4.0 and TPM). Either way, a third variable (moderating) can have a direct association with the independent variable or a third variable can moderate the association of independent variables (I4.0 and TPM) and dependent variables (in this case SP).

The direct interconnection among TPM, I4.0, and CE does not open the possibility of having a moderating effect of CE on the connection of TPM and I4.0 with SP. Also, no previous studies have investigated the mediating impact of CE on the association of I4.0 and TPM with the overall SP of the firm. Thus, the lack of research in this area necessitates further research on the mediation of CE. Therefore, we hypothesise that:

H7: CE has a significant mediation effect on the association of TPM and SP.

H8: CE has a significant mediation effect on the association of I4.0 and SP.

From the previous discussion and proposed hypotheses, a conceptual framework is developed as demonstrated in Figure 1. It indicates the proposed relationship between the different constructs considered in the present study.

"Insert Figure 1 here"

3. Research Methodology

The followed research methodology was adopted from Agyabeng-Mensah et al. (2020), and its research phases are illustrated in Figure 2.

3.1 Phase 2: PLS-SEM for Conceptual Framework

The method of path modelling known as partial least square structural equation modelling (PLS-SEM) was used to carry out the data analysis for the present investigation. PLS-SEM is a multivariate statistical method that has been developed recently and is effective in analysing the connection among latent variables and the indicators that represent them (Hair *et al.,* 2017a). Sample size has been one of the biggest prominent justifications for utilising PLS-SEM (Ringle *et al.,* 2012). However, other motivations also include prediction (Hair *et al.,* 2011), non-normal data, sophisticated models and advanced analysis (Hair *et al.,* 2018) as well as a desire to uncover previously undiscovered variability in a population (Hair *et al.,* 2016a).

PLS-SEM uses soft modelling to conduct SEM, which does not require data dispersion restrictions (Vinzi *et al.,* 2010). Therefore, PLS-SEM is a good replacement for covariance-based SEM (CB-SEM) if sample sizes are small, predictive accuracy is high, application awareness is limited, and accurate model specifications cannot be guaranteed (Tian *et al.,* 2020). Thus, it was considered the most suitable approach for the present study.

"Insert Figure 2 here"

3.1.1 Scale development

21 items were adopted from the literature review. TPM was measured through six items adopted from Wang (2006), Ahuja and Khamba (2008), and Wickramasinghe and Perera (2016). CE was assessed through five items considered from the study of Khan et al. (2020). I4.0 was evaluated through five items adopted from Bibby and Dehe (2018). Finally, SP was assessed by four items adopted from the studies of Abdul-Rashid et al. (2017), Chen et al. (2019), and Nath and Agrawal (2020). A total of five academics and four professionals carried out the initial assessment of the questionnaire. The five academics had extensive knowledge of I4.0, CE, and logistics operations, and they belonged to the sustainability and TPM groups. The four industry practitioners worked for reputable logistics organisations in India. They currently manage logistics supply chain operations and are working towards transitioning from traditional supply chain methods to I4.0. The experts provided their insightful feedback in the form of comments and suggestions about other metrics that may be included in the questionnaire. In addition, the revised questionnaire was subjected to a pilot test with around 12 industry professionals in the field of logistics; this was followed by a further consultation on LinkedIn. All of the suggested changes were implemented, which included making some small adjustments to the questionnaire architecture, scale, and the inclusion or deletion of measurements. The study employed a 5-point Likert scale (interpreted as "1= strongly disagree, 2= disagree, 3= neutral, 4= agree, and 5= strongly agree") to evaluate the 21 items of the questionnaire.

3.1.2 Measurement

The study used the CMIE (Centre for Monitoring Indian Economic) ProwessIQ database to obtain responses via email survey from Indian manufacturing companies. The research included Indian companies with a minimum yearly revenue of 100 crore Indian rupees. This parameter was set for the firms in the survey to ensure an adequate understanding of sustainable practices (Mani and Gunasekaran, 2018).

The responses were gathered between November 10th 2021 and March 15th 2022. Overall, 310 responses, individual responses from one firm, from 12 types of companies were received out of 733 emails distributed. The respondents were from different backgrounds such as senior managers, floor supervisors, TPM and CE consultants, and I4.0 practitioners with more than 15 years of experience. To obtain the responses, continuous reminder emails were sent to the respondents within a period of 2 months. Some responses had missing or incorrect data, which led to 304 useful responses (with a response rate of 41.47%) for the final empirical analysis. It was made clear to the participants that their responses would be kept confidential and that the data would be processed in accordance with best standards (Zhu *et al.,* 2013). Paticipants were requested to answer in favour of their organisation rather than themselves in order to avoid social desirability bias (Carter and Jennings, 2004). Non-response bias was checked by conducting t-tests on 100 early responders and 50 late respondents (Nath and Agrawal, 2020). According to the study outcomes, there was no statistically significant variation among the earlier and later responders ($p > 0.05$). The respondent's company background and their response rate are shown in Table 1.

"Insert Table 1 here"

Table 1 demonstrates the diversity of companies that participated in the present research. This diversity offered responses with less chance of bias. The study's sample size (304) is significant for this kind of research and adheres to minimum thumb rule (Hair *et al.,* 2019).

4. Results and Findings

4.1 Common method bias (CMB)

Questionnaire-based research is operationalised using a set of items that make up a pre-existing or freshly constructed scale. While surveys are one of the most widely used methodologies in social sciences, they also carry the risk of common method variance and bias, compromising the reliability and validity of empirical findings (Baumgartner and Steenkamp, 2001). The common method refers to a systematic error variance resulting from a common method used to evaluate the study's constructs (Podsakoff *et al.,* 2003).

The questionnaire was confidential and self-reported. It was made clear to the participants that their replies would not be used to identify them or their companies. CMB concerns were alleviated by changing the construct and measurement scales. Following Nederhof (1985), the present research used the manufacturing firm as a dummy subject at the construct level instead of the individual. Similarly, to avoid the influence of consistency in response trends, the current study employed distinct measuring scales in the survey. In aggregate, these variances enabled us to assess respondents' participation in the process and to screen out non-engaged responses.

Since all data for this study came from a single source via a self-report questionnaire, CMB may be a cause for concern (Guide and Ketokivi, 2015). Therefore, the research conducted two tests to determine the existence and degree of CMB. Harman's single factor test was deployed as a first test to examine the CMB of the investigation. According to Podsakoff et al. (2003), the single factor variance should be less than 50%. The current study used principal axis factoring as an extraction method while performing Harman's single factor test; this resulted in a 40.78% variance value for a single factor (less than the threshold of 50%). Therefore, the result suggested that CMB was low in the received responses. The variance inflation factor (VIF) was utilised as a second test in this work; this is a comprehensive collinearity test that has been frequently employed in past studies (using SmartPLS 3.0) to examine the CMB (Hair *et al.,* 2019). The findings of VIF (Table 2) were significant (VIF< 3) (Hair *et al.,* 2019), suggesting that a low CMB was present in the study.

"Insert Table 2 here"

4.2 PLS-SEM

In this investigation, the SmartPLS 3.0 software (Ringle *et al.,* 2015) was used for framework estimation and inside approximation. Furthermore, the assessment of PLS-SEM was based on the measurement and structural model.

4.1.1 Assessment of measurement model

Internal consistency (as evaluated by Cronbach Alpha), reliability (as assessed by outer loadings), and validity are used to evaluate the reflecting measurement model (Hair *et al.,* 2016b). Specific measurements include composite reliability (CR), convergent validity, and discriminant validity. Internal consistency implies an evaluation of the intercorrelations of indicators. The degree to which a scale corresponds to other measures of the same construct is referred to as its convergent validity. It is evaluated depending on the outer loadings of indicators and the average variance extracted (AVE). According to Hair et al. (2016), the threshold values of various relevant indicators should be as follows:

- "Outer loadings" > 0.6
- "Cronbach Alpha (CA)" (Threshold 0.7)
- "rho_A" (Threshold 0.7)
- "Composite reliability (CR)" (Threshold 0.7)
- "Average variance extracted (AVE)" (Threshold 0.5)

Table 3 shows the results of the PLS-SEM analysis of all important indicators for each construct item with the exceeded value of the threshold. These results indicate that the model was internally consistent, reliable and valid.

"Insert Table 3 here"

The next critical aspect of the analysis was discriminant validity, which assesses the different predictions of latent variables from dependent variables. Two criteria can measure discriminant validity i.e. "Fornell Larcker" and "heterotrait–monotrait (HTMT)". However, Henseler et al. (2015) indicate that HTMT is more reliable than Fornell Larcker criteria to measure discriminant validity. Therefore, the present research used the heterotrait–monotrait (HTMT) ratio to evaluate the discriminant validity of the measurement model. With this criteria, the threshold value should be less than 0.9. The results presented in Table 4 illustrate that all values were lower than 0.9. Therefore, the study met the criteria of discriminant validity.

"Insert Table 4 here"

4.1.2 Assessment of the structural model

Examining the model's findings can reveal the structural model's capacity to forecast one or more planned constructs. The investigation used non-parametric bootstrapping with 5000 sub-samples to test the error estimation. Model fitness was checked with the help of standardised root mean square (SRMR) values. This should be less than 0.08 (Cho *et al.,* 2020) for a population more than 100 (in this case, it is 304). For the present study, the value of SRMR was 0.05, see Table 8; this is lower than 0.08. Thus, the findings of the SRMR values indicated the goodness of fit of the model. The values of R^2 and Q^2 are presented in Table 5. The acceptable value of R^2 must be greater than 0.1 (Hair *et al.,* 2016b). Moreover, the Stone-Geisser (Q^2) test was evaluated through blindfolding. The values 0.245, 0.240, and 0.226 (see Table 5) were found to correspond to Q^2 for the present model. The fact that the value of Q^2 was more than zero was evidence that the path model had enough predictive significance (Nath and Agrawal, 2022; Hair *et al.,* 2017b).

"Insert Table 5 here"

In addition, the f^2 effect size for each of the independent factors was computed so that it could be determined whether or not the independent variables significantly contributed to the accuracy of the prediction of the dependent variable. The f^2 effect size for each independent variable is shown in Table 6. According to the standards established by Hair et al. (2017b), the magnitude of these falls somewhere in the range of small to medium.

"Insert Table 6 here"

To provide statistical significance of paths and hypothesis acceptability, the value of different standard coefficients, such as *β*, must be more than zero, and the *p*-value must be less than 0.05. The results shown in Table 7 and Figure 3 indicate that all of the hypotheses provided in this study were accepted.

"Insert Table 7 here"

"Insert Figure 3 here"

The outcomes of the PLS-SEM method and the bootstrap technique in SmartPLS comprised the direct effect, total indirect effect, particular indirect effect, and overall effect. These results, which have been accessible in the SmartPLS results reports, allowed the execution of a mediation assessment (Hair *et al.,* 2017b). The outcomes offered in Table 7 and Figure 3 suggest that the direct association between TPM, I4.0, and SP was significantly positive. Moreover, the indirect relationship between TPM, I4.0, and SP was positive, indicating a positive mediation of CE on their relationship. According to Nitzl et al. (2016), partial mediation occurs when both influences are substantial and direct impacts are negligible, but if the indirect impact is significant and positive, significant partial mediation occurs. The results shown in Table 7 and Figure 3 suggest that CE has a partial mediation effect on the interconnection between TPM and SP, and I4.0 and SP.

5. Discussion and Implications

The present research investigates how TPM, I4.0, and CE respond to each other within the context of sustainability of manufacturing firms from the perception of the DCV theory (RQ1-RQ3). Furthermore, the study explores the role of CE as a mediator in the association of TPM and I4.0 with SP (RQ4). The outcomes of the research identify TPM, I4.0, and CE as dynamic capabilities of manufacturing firms that can enhance their SP. Further, the testing of the hypotheses addresses the proposed research questions of the present study as discussed below.

Hypothesis 1 (H1) was accepted with the significant values of standard coefficients (β = 0.285 and $p < 0.000$); this indicates that TPM affects CE positively. No previous research that has investigated the association of TPM and CE exist. However, the results of this study corroborate some investigations that suggest the acceptance of H1, including Ellen MacArthur Foundation (2015), Allen (2021), Vukadinovic et al. (2018), and Amjad et al. (2021).

The second hypothesis (H2) was likewise supported by significant standard coefficient values ($\beta = 0.580$ and $p < 0.000$), showing that I4.0 technologies have a beneficial effect on TPM practices. The findings support the studies of Nowakowski et al. (2018), Klathae and Ruangchoengchum (2019), Felsberger et al. (2020), and Tortorella et al. (2022a). On the other hand, the substantial values of standard coefficients ($\beta = 0.399$ and $p < 0.000$) indicate the acceptance of H3; this indicates that I4.0 has a positive influence on CE practices. The acceptance of H3 is supported by the studies of Pialot et al. (2017), Lopes de Sousa Jabbour et al. (2018), and Kamble and Gunasekaran (2021).

The fourth hypothesis (H4), proposing a relationship between TPM and SP, was accepted with the standard coefficient value of $\beta = 0.225$ and $p < 0.000$. Past scholars have ignored the impact of TPM on the overall SP of manufacturing firms. Still, some scholars have examined the relationship of TPM with some of the individual dimensions (economic, social, or environmental) of TBL sustainability. Therefore, the findings support previous studies investigating the relationship of TPM with an individual dimension of TBL sustainability. These studies include those of Hofer et al. (2012), Vukadinovic et al. (2018), Agustiady and Cudney (2018), Garza-Reyes et al. (2018), Chen et al. (2019), Heravi et al. (2020), and Dieste et al. (2021).

The fifth hypothesis (H5), investigating the direct relationship between I4.0 and SP, was supported with significant standard coefficient values of $\beta = 0.204$ and $p < 0.002$. The results are in line with the studies of Herrmann et al. (2014), Stock and Seliger (2016), De Sousa Jabbour et al. (2018), and Kamble and Gunasekaran (2021). In the case of H6, it examined the last direct relationship, indicating the positive influence of CE on the SP of manufacturing firms. The results support H6 with significant standard coefficient values of $\beta = 0.263$ and $p < 0.000$. The findings support the past studies of Geissdoerfer et al. (2017), Hobson et al. (2018), Madueke *et al.,* 2020, and Tang et al. (2022).

The hypotheses H7 and H8 suggest a mediation effect of CE on the relationship of TPM and SP, and I4.0 and SP, respectively. The values of the standard coefficient for H7 ($\beta = 0.075$ and $p < 0.007$) and H8 ($\beta = 0.105$ and $p < 0.001$) indicate that CE mediates both relations. The analysis indicates that the 76.91% size provides evidence confirming the CE partial mediation effect on the connection between TPM and SP. In addition, a total of 33.96 % of the effect size indicates that CE does, in fact, partially mediate the association between I4.0 and SP. This suggests that Indian manufacturing practitioners believe that the successful adoption of CE practices can lead to SP success in an environment characterised by I4.0 technology and TPM procedures. Finally, the values of R^2 (more than 0.1) and Q^2 (greater than 0) for all latent variables suggest that the study is substantial and reliable.

5.1 Theoretical implications

The majority of the extant work on I4.0, TPM, and CE has been of an explorative nature, providing conceptual predictions about how they affect an organisation's sustainability objectives. This investigation analyses the influence of I4.0, TPM, and CE on SP, thus filling a research gap in academic literature. Two substantial theoretical contributions are made in this work to current literature. This research advances the theory of dynamic capability by conceptualizing I4.0, TPM, and CE as dynamic capabilities of manufacturing enterprises that enable them to achieve superior sustainable performance results. Thus, this investigation fills a major gap in literature by proposing a novel combination of dynamic skills in the form of

I4.0, TPM, and CE; this will empower an organisation's sustainability to become a competitive foundation.

Secondly, the literature indicates that CE is necessary for a manufacturing firm's SP. Therefore, the current investigation explores the mediating influence of CE on the association of I4.0 and SP, and TPM and SP. To address this gap, the present investigation uncovers and confirms that CE practices offer the partial mediation effect on the association of I4.0 and SP and the relationship between TPM and SP.

Additionally, the literature suggests that I4.0 could affect TPM (Felsberger *et al.,* 2020; Tortorella *et al.,* 2022a), I4.0 could affect CE (Lopes de Sousa Jabbour *et al.,* 2018; Kamble and Gunasekaran, 2021), and that TPM could affect CE (Ellen MacArthur Foundation, 2015). Therefore, this is the first study that examines these relationships and concludes that I4.0 technologies have a significant positive impact on TPM practices, I4.0 technologies have a significant positive impact on CE practices, and TPM practices have a significant positive impact on CE practices. This suggests that I4.0 technologies enable manufacturers to improve their CE practices. Additionally, in an I4.0 context, TPM implementation can improve results by minimizing the possibility of monitoring and scheduling problems. Finally, TPM procedures can contribute to a more favourable atmosphere for CE activities. When these three practices (I4.0, TPM, and CE) are used together, they can help a business achieve sustainability.

5.2 Practical implications

The current study has a number of important managerial implications. The findings show that the application of TPM procedures has a favourable effect on CE practices. Consequently, practitioners can apply TPM strategies in manufacturing firms and their supply chains to optimise and remove waste to achieve harmonious and sustainable outcomes (Ghisellini *et al.,* 2016). For instance, TPM practices offer the prevention of breakdowns and improved green outcomes (Amjad *et al.,* 2021), leading firms towards cleaner production and better environmental outcomes (Garza-Reyes *et al.,* 2018). Such outcomes can motivate managers to see TPM as a practice that offers green and cleaner logistics to achieve better environmental performance throughout the supply chains of their organisations.

Additionally, I4.0 technologies have a favourable impact on TPM procedures, allowing practitioners to more effectively regulate and monitor operating environments; this in turn reduces waste and allows for more proactive decisions (Zheng *et al.,* 2021). With the support of I4.0 technologies, for example, a machine's data may be accessed and monitored in real-time (Tortorella *et al.,* 2022b), resulting in better operational outcomes (e.g. fewer faults, faster deliveries, fewer breakdowns) and sustainable outcomes (e.g. waste reduction, safer working environment, and better environmental outcomes). Such results can inspire management to adopt I4.0 technologies in manufacturing logistics to explore the role of digital TPM outside of the shop floor. Furthermore, it can improve decision-making in manufacturing logistics and its entire supply chain to prevent breakdowns and achieve other TPM outcomes more accurately.

The impact of I4.0 technologies on CE practices has been positive. This may assist managers in the creation of a more environmentally friendly industrial atmosphere (Bressanelli *et al.,* 2018). For example, the incorporation of I4.0 technologies can transform a conventional into an intelligent system (Kamble and Gunasekaran, 2021). These smart systems perform an essential role in the traceability of goods and repair components (Franco, 2017), contributing to the accomplishment of CE goals (Nobre and Tavares, 2017). Moreover, traceability due to the adoption of I4.0 technologies in a manufacturing firm can help practitioners to promote a hassle-free reverse logistics supply chain with greener outcomes.

The partial mediation of CE indicates that TPM practices and I4.0 technologies implementation can help firms to deliver sustainability if both approaches (TPM and I4.0) focus on achieving CE targets. For instance, if firms that are implementing TPM practices focus more on waste elimination and cleaner production, they can achieve sustainable targets more efficiently. Therefore, they do not have to focus on achieving other aspects while implementing TPM. Similarly, the incorporation of I4.0 technologies can deliver SP by focusing on optimal resource consumption and waste minimisation (De Sousa Jabbour *et al.,* 2018). Such results can develop the required motivation in managers to focus on CE outcomes while adopting TPM and I4.0 technologies.

Finally, the results indicate that the combined implementation of I4.0, TPM, and CE can lead firms to a better SP which could assist managers to obtain a competitive edge (Cantele and Zardini, 2018). The findings imply that adopting and implementing I4.0 technologies allows real-time data and data interchange among supply chain stakeholders; this aids in resource efficiency and the reduction of waste and toxicants. For instance, I4.0 technologies can enable better decision-making of TPM (Tortorella *et al.,* 2022a) and help to trace items for CE objectives. Next, digital TPM can perform more precisely (Tortorella *et al.,* 2022b) to reduce emissions, breakdowns, accidents, and improve quality, machine and product life. Furthermore, digital TPM can promote and produce a greener and more sustainable ambience in terms of better working conditions, increased monetary benefits, and a better ecological environment.

5.3 Policy implications

The first and most important implication for policymakers is that they need to have a comprehensive insight into I4.0 technologies, TPM practices and CE, as well as how these factors contribute to the sustainability of various industries and their supply chains such as manufacturing, logistics, and automotive. This study focuses primarily on the impact of I4.0, TPM, and CE on manufacturing enterprise sustainability. Because of resource consumption restrictions posed by implementing I4.0 technologies at various stages of the supply chain and logistics, previous literature on this topic makes conflicting claims. For instance, Kiel et al. (2017) suggest that Industry 4.0 may facilitate process optimisation and favourably impact ecological sustainability by maximising resource use. In contrast, Ford and Despeisse (2016) indicate that incorporating I4.0 technologies may result in higher waste creation, such as electronic waste and a greater need for energy resources. However, governmental interventions may be able to relieve the impact of these barriers. More strict government rules are needed to keep up with the present supply chain's emphasis on minimising waste and extending the useful life of products and machinery. An increase in productivity is expected as a result of this. For instance, Japan's early embrace of CE ideas is largely responsible for the country's impressive achievements in resource productivity (Schröder, 2017). With the rise of reverse logistics and manufacturing industries, the need for a well-functioning supply chain has never been greater. It is recommended that businesses experiencing a digital transition give these TPM practices high priority since they stand to gain most from adopting the technologies of I4.0 (Tortorella *et al.,* 2022b). Regulatory bodies (e.g. regional, national, and global) tend to be established by governments to outline the justification for the digital transformation of supply chains and thus provide a strategic roadmap for its execution (Saha *et al.,* 2022). It is essential to understand that the only way to achieve sustainable development is for social and ecological sustainability to push towards economic sustainability, and vice versa (Velenturf and Purnell, 2021). The appropriate blend of I4.0, TPM, and CE to address alleviation of sustainability of manufacturing, logistics, and automobile industry with their relevant supply chain and stakeholders should be considered by policymakers as an area that they have to encourage.

6. Conclusion, Limitations, and Future Research Scope

This investigation draws on the experiences of professional experts from Indian manufacturing enterprises that have developed or integrated TPM, I4.0, and CE into their operations. The conclusions obtained from the study can act as a guide for organisations considering using TPM, I4.0, and CE to obtain SP oriented improvements. The results also shed light on how CE practices may be included within I4.0 and TPM implementation plans. The data demonstrates the significant advantage of TPM and I4.0 in improving CE practices and SP, hence suggesting to manufacturing companies to use both technologies concurrently.

The present investigation offers a comprehensive overview of the role of TPM, I4.0, and CE on the SP of manufacturing firms. Still, there are limitations and future propositions of the present study to be considered:

- The current research used I4.0 and TPM as a whole term to investigate their impact on CE and SP. However, I4.0 and TPM practices have their own tools, acting differently from overall I4.0 or TPM. Therefore, investigating the effect of individual tools/ technologies of I4.0 and TPM practices on CE and SP is needed.
- The present research investigates the impact of TPM, I4.0, and CE on the overall SP of manufacturing companies. Nevertheless, it is quite possible that all three practices/ technologies (TPM, I4.0, and CE) do not offer all the sustainable outcomes for a manufacturing firm. Therefore, future researchers can identify the actual factors of the individual sustainability dimensions that are affected by I4.0, TPM, and CE.
- The current study does not offer the prioritisation of I4.0, TPM, and CE in the context of sustainability. Hence, in future, some ranking methods can be considered to provide a hierarchical structure of various technologies/practices (internally and externally) based on their impact on the SP of manufacturing firms.
- The present investigation examines the mediation effect of CE on the relationship between I4.0 and SP with TPM and SP. Therefore, there is a possibility of exploring the moderation effect of CE on both associations. Also, there is a possibility of examining CE's mediating and moderating effect on the association of I4.0 and TPM.
- These results would not apply to different nations since the researchers only included experts representing Indian manufacturing companies in this study. However, researchers believe that the consequences might be compared to industrial enterprises

functioning in developing countries. Upcoming research should take into account a wider range of sectors and nations.

Disclosure statement

The authors did not disclose any possible conflicts of interest.

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Tables

Table 1
Respondent industry and their response rate summary

S. No.	Types of companies	Number of responses received	Percentage of individual types of company response to overall responses
1.	Cement	17	5.59%
2.	Textile	38	12.5%
3.	Steel	18	5.92%
4.	Automobile	23	7.56%
5.	Metal	19	6.25%
6.	Agricultural products	32	10.52%
7.	Packaging machinery	11	3.62%
8.	Medical equipment	14	4.60%
9.	Cotton fabrics processed	47	15.46%
10.	Aluminium bars, rods & profiles	36	11.84%
11.	Diesel engines	18	5.92%
12.	Ferro alloys	31	10.22%
Total		304	100%

Table 2
Collinearity statistics (VIF) summary

	CE	SP	TPM
CE		1.595	
I4.0	1.507	1.762	1.000
TPM	1.507	1.637	

Table 3
PLS-SEM results summary

Constructs	Item code	Item statements	Outer loadings	CA	rho_A	CR	AVE
Circular economy (CE)	CE 1	In our company, products are designed to be readily repaired or replaced.	0.817	0.873	0.873	0.908	0.663
	CE 2	Products are designed to be easily recyclable or biodegradable in our company.	0.814				
	CE 3	The company use biodegradable or	0.810				

		recyclable packaging for the products.					
	CE 4	The company recycle its own production waste.	0.822				
	CE 5	The company offers repairs or refurbished services to consumers.	0.807				
Industry 4.0 (I4.0)	I4.0 1	The company is deploying advanced connectivity technology among products, employees and machinery.	0.811	0.865	0.867	0.902	0.649
	I4.0 2	The company is capable to offer live manufacturing systems and react instantly to any changes that may occur.	0.823				
	I4.0 3	The company is investing in Industry 4.0 infrastructure.	0.799				
	I4.0 4	The company is exploring collaboration with external organisations to maintain Industry 4.0.	0.785				
	I4.0 5	The company does not use any paper in its data control, display, or transportation processes.	0.809				
Sustainability performances (SPs)	SP 1	At our company, pollution emission reduction programmes are effectively running.	0.883	0.882	0.890	0.919	0.739

	SP 2	The work environment is improving in our company.	0.799				
	SP 3	At our company, energy consumption reduction programmes are effectively running.	0.886				
	SP 4	At our company, product quality is increasing.	0.868				
Total Productive Maintenance (TPM)	TPM 1	Management is committed to improving maintenance in the company.	0.798	0.905	0.907	0.927	0.678
	TPM 2	There are safety safeguards in place to guarantee the wellbeing of the staff in the company.	0.827				
	TPM 3	"The company used to raise the awareness of leadership, teamwork, and quality."	0.812				
	TPM 4	In the workplace, operators are responsible for ensuring that their machines are running properly.	0.806				
	TPM 5	In terms of upkeep and dependability, the business makes use of cutting-edge technologies.	0.851				
	TPM 6	Emergency exits, signage, manuals, and other means of safety are all readily available at the business.	0.847				

Table 4
Discriminant validity through HTMT (heterotrait–monotrait ratio)

	CE	**I4.0**	**SP**
I4.0	0.649		
SP	0.560	0.547	
TPM	0.580	0.654	0.532

Table 5
Saturated model result summary

Constructs	R^2	R^2 **Adjusted**	Q^2	**SRMR**
CE	0.373	0.369	0.245	0.050
SP	0.336	0.329	0.240	
TPM	0.337	0.334	0.226	

Table 6
The value of f^2 effect size

	CE	SP	TPM
CE		0.065	
I4.0	0.169	0.036	0.507
TPM	0.086	0.046	

Table 7
Hypothesis result summary

Path	β	**T Statistics**	***p*-Value**	**Hypothesis**	**Accept/ Reject**
Direct Relations					
TPM→CE	0.285	4.066	0.000	H1	Accept
I4.0→TPM	0.580	9.932	0.000	H2	Accept
I4.0→CE	0.399	5.085	0.000	H3	Accept
TPM→SP	0.225	4.127	0.000	H4	Accept
I4.0→SP	0.204	3.133	0.002	H5	Accept
CE→SP	0.263	4.123	0.000	H6	Accept
Indirect or mediation effects					
TPM→CE→SP	0.075	2.699	0.007	H7	Accept
I4.0→CE→SP	0.105	3.231	0.001	H8	Accept

Figures

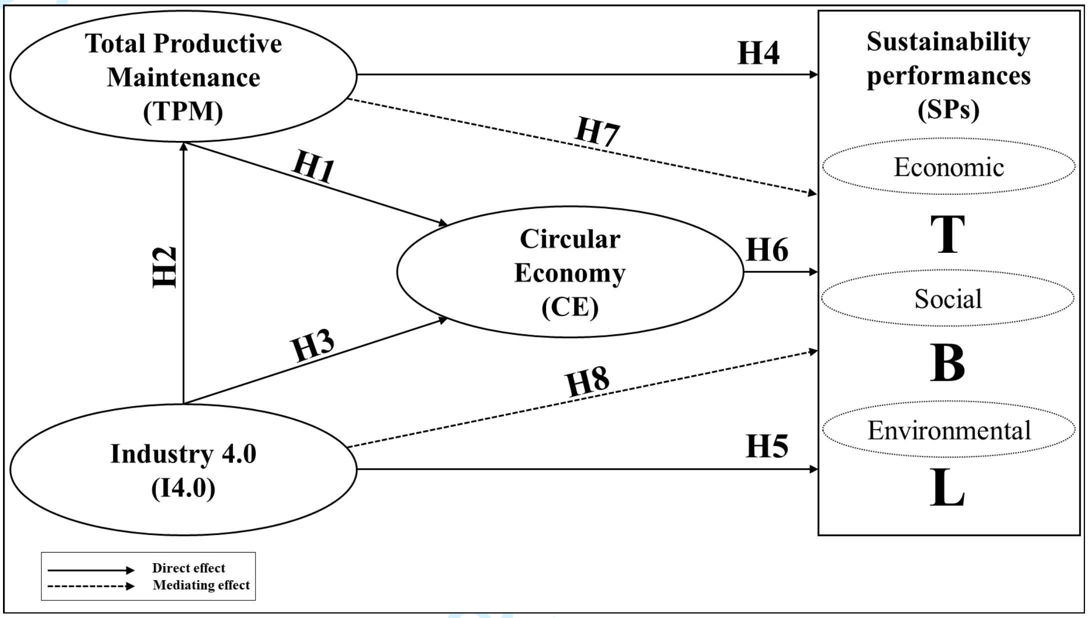

Figure 1

Conceptual framework

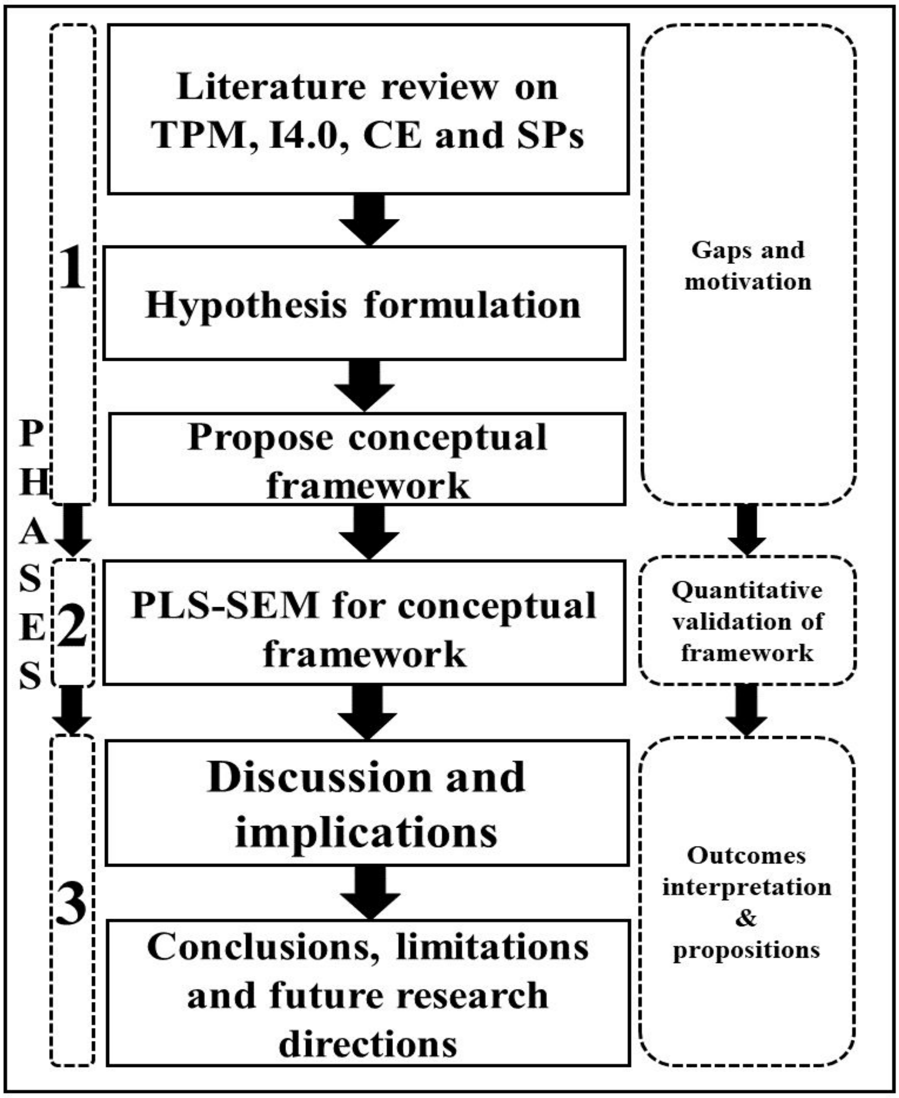

Figure 2

Research methodology

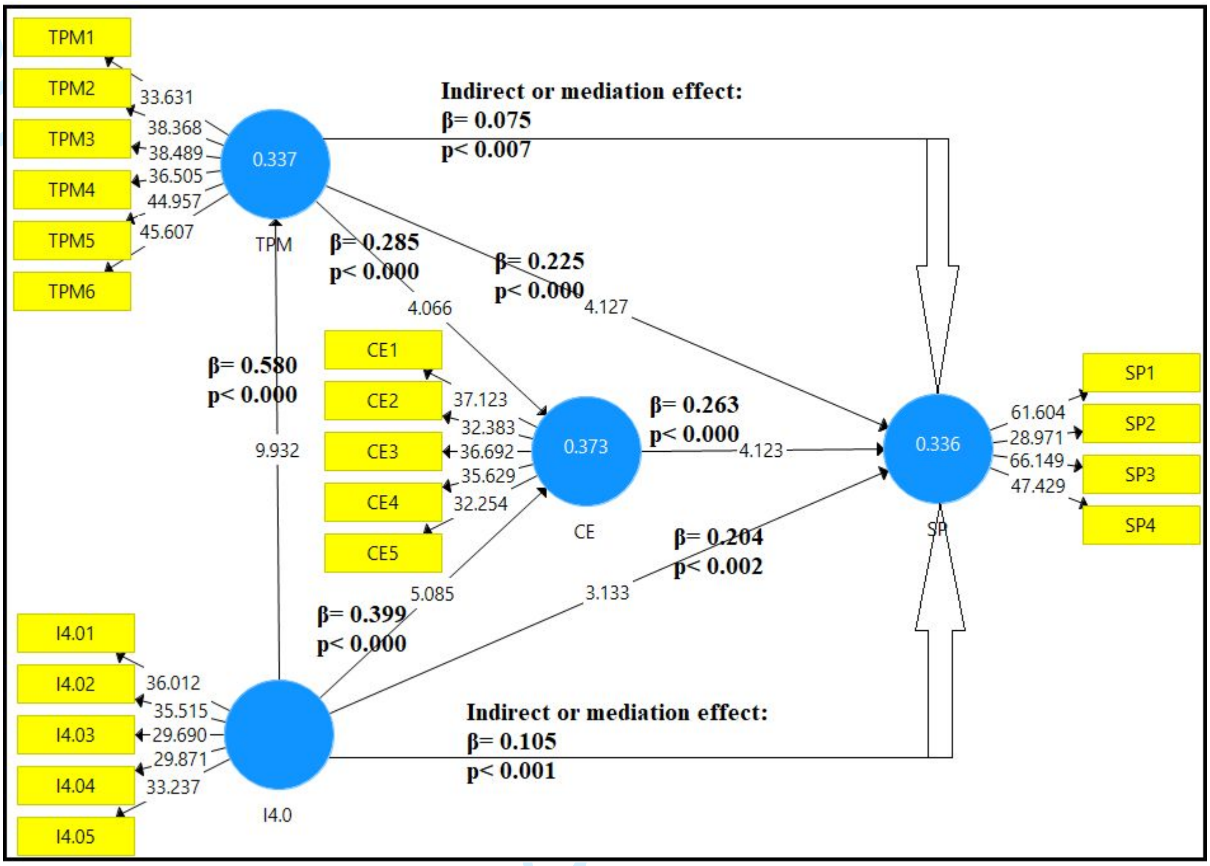

Figure 3

Empirically tested and validated framework