Blockchain Technology and Circular Economy in the Environment of Total Productive Maintenance: A Natural Resource-Based View Perspective

Abstract

Purpose - Total Productive Maintenance (TPM) could act as a practical approach to offer sustainability deliverables in manufacturing firms aligning with the natural resource-based view (NRBV) theory's strategic capabilities: pollution prevention, product stewardship, and sustainable development. Also, the emergence of Blockchain Technology (BCT) and Circular Economy (CE) are proven to deliver sustainable outcomes in the past literature. Therefore, the present research examines the relationship between BCT and CE and TPM's direct and mediation effect through the lens of NRBV theory.

Design/ methodology - The current study proposes a conceptual framework to examine the relationship between BCT, CE, and TPM and validates the framework through the Partial Least Squares Structural Equation Modeling. Responses from 316 Indian manufacturing firms were collected to conduct the analysis.

Findings - The investigation outcomes indicate that BCT positively influences CE and TPM and that TPM has a significant positive impact on CE under the premises of NRBV theory. The results also suggest that TPM partially mediates the relationship between BCT and CE.

Originality - This research fills a gap in the literature by investigating the effect of BCT and TPM on CE within the framework of the NRBV theory. It explores the link between BCT, TPM, and CE under the NRBV theory's strategic capabilities and TPM mediation.

Implications - The positive influence of TPM and BCT on CE could initiate the amalgamation of BCT-TPM, improving the longevity of production equipment and products and speeding up the implementation of CE practices.

Keywords: Natural Resource-Based View, Blockchain Technology, Total Productive Maintenance, Circular Economy

1. Introduction

Production equipment is expanding further into the realm of new digital and intelligent progress due to the improvement of present machinery systems and research and development (Chen *et al.*, 2020). In natural industrial environments, modern equipment is frequently used to accomplish crucial jobs; when an accident occurs, the repercussions can be rather severe (Chen *et al.*, 2020). Maintenance can potentially reduce the amount of time spent on non-value-adding activities in production by as much as 40%. (Ahuja and Khamba, 2008). Therefore, preventative machine maintenance is crucial for productive manufacturing processes (Wang *et al.*, 2021). For more than fifty years, manufacturers have relied on the maintenance management strategy known as total productive maintenance (TPM) to cut down on machine breakdowns and other unplanned halts in production (Ahuja and Khamba, 2008).

Modern machinery is often tasked with a more demanding manufacturing duty. Great possibilities for advancing maintenance to a new level have arisen due to the rise of Industry 4.0 and the fast evolution of Cyber-Physical Systems (Albano *et al.*, 2019). So, it's essential to make the most of today's technical tools for implementing smart maintenance of complicated equipment to keep it running well and accomplish its job (Chen *et al.*, 2020). However, owing to the rapid progress and use of the internet and digital technology after 1995, product maintenance focused on the entire lifespan emerged (Si *et al.*, 2020). A critical component of machine effectiveness is identifying problems and flaws in real time and sharing that data with other machines. Providing real-time monitoring and data sharing is a critical area in which blockchain technology (BCT) has excelled (Kumar *et al.*, 2020). Stakeholders with a common goal can use BCT to get insight into the production process, which in turn will lead to better quality control and risk mitigation (Lohmer and Lasch, 2020). BCT may be defined as "an online, open-source distributed ledger where transactions between different stakeholders can be recorded and updated simultaneously and in real-time" (Lakhani and Iansiti, 2017). Manufacturers in a wide variety of fields may put blockchain to use in several ways. Among them is the use of smart contracts for the exchange of machine data, the authentication of items, and the tracking of production and upkeep (Chang *et al.*, 2019).

The unique features of the blockchain make it essential for data transparency, sharing, and security in the system's data flow, which is why it is essential to use (Javaid *et al.*, 2021). BCT is used to build a life-cycle information management framework for advanced machinery (Chen *et al.*, 2020). BCT helps to map physical equipment and virtual digital simulations and then carry out state monitoring, fault detection, and life prediction of complex equipment, which allows for more brilliant operation and maintenance of the machinery (Chen *et al.*, 2020). Therefore, implementing BCT (especially at the shop floor level) may enhance the outcomes of maintenance management approaches, such as TPM practices. Still, no empirical evidence is available in the literature confirming the relationship between BCT and TPM. To address this gap and contribute to the fields of TPM and BCT, the present study addresses the following research question:

RQ1: What is the relationship between BCT and TPM in the context of manufacturing firms?

Simultaneously, the hazards to human survival posed by climate change, biodiversity loss, and the exhaustion of scarce resources are growing in severity (Köhler *et al.*, 2019). In recent years, the circular economy (CE) has emerged as a practical solution for mitigating the risks associated with these concerns (Prieto-Sandoval *et al.*, 2018). The end goal of CE is to move away from the linear economic model that is prevalent today and toward a closed-loop economy that uses resource regeneration and ecological restoration as its primary pillars of support (Murray *et al.*, 2017). In light of this, there has been a rise in the amount of interest in blockchain technology among both academics and industry professionals as a potential accelerant for the transition to an economy based on CE (Böhmecke-Schwafert *et al.*, 2022). There is a plethora of information to be gleaned from products in use, particularly those that are both durable and capital-intensive (Kärkkäinen *et al.,* 2003a). The use of blockchain in environmental sustainability has been investigated in recent research using a variety of perspectives, including supply chain sustainability, product-service systems, product deletion, and ecological sustainability in general (Agrawal *et al.*, 2021). According to more current study findings, the three CE principles of reducing, reusing, and recycling have recently been supported by BCT (Venkatesh *et al.*, 2020). By delivering correct information, blockchain-based supply chain management solutions may improve traceability in complicated supply chains and encourage consumers to make more responsible purchasing decisions. Using intelligent contracts, blockchain can assist in waste management by facilitating its trade and recycling initiatives (Khadke *et al.*, 2021). In addition to energy trading platforms and source verification systems, BCT may aid in utilising renewable energies by facilitating peer-to-peer transactions in energy (Yildizbasi, 2021). It is possible to use blockchain to create and manage new CE chains (Narayan and Tidström, 2020). Therefore, it is possible that the implementation of BCT in the supply chain of manufacturing firms could lead to CE practices. Also, recent literature published by Samadhiya *et al.* (2022) emphasises investigating the role of BCT in CE. Still, empirical evidence related to this relationship is lacking in the literature, which leads to the formulation of a second research question to address this gap:

RQ2: What is the relationship between BCT and CE in the context of manufacturing firms?

To achieve harmonious and sustainable growth, CE proposes that organisations optimise resource consumption and minimise waste to achieve success (Ghisellini *et al.*, 2016). As the cost of raw materials and end-of-life treatment rises, maintenance is becoming a more enticing way to start CE and move on a more sustainable route (Allen, 2021). Implementing TPM in a manufacturing firm delivers production-related commitments by preventing machine breakdowns (Ahuja and Khamba, 2008). However, to offer operational excellence, TPM reduces wastes and toxicants through its implementation (Vukadinovic *et al.*, 2018), as it is the most crucial concept of lean manufacturing (Thanki *et al.*, 2016). The philosophy of TPM practices is based on the optimum consumption of resources to deliver ecological-oriented outcomes (Wudhikarn, 2012). Past studies indicate that TPM leads to greener production and better environmental performance (Amjad *et al.*, 2021). Green and cleaner production are the indicators of CE practices (Ghisellini *et al.*, 2016). Therefore, for these two indicators (green and cleaner production), TPM is a feasible approach to leading CE outcomes. Also, TPM helps improve equipment's longer life span through preventive maintenance (Farrukh et al., 2019), which is also one of the CE outcomes. Nevertheless, no previous studies have focused on empirically exploring the relationship between TPM and CE. This led to the third research question of this study as follows:

RQ3: What is the relationship between TPM and CE in the context of manufacturing firms?

The previous discussion indicates that the implementation of BCT, TPM, and CE in a firm can address the issues related to pollution prevention, product stewardship, and sustainable development. The most suitable theory to underpin the present study is the natural resource-based view (NRBV) theory, which suggests that companies that are too devoted to a single set of resources may have trouble acquiring new resources or competencies (Hart, 1995).

Therefore, the present research identifies BCT, TPM, and CE as natural resources for the company to address the NRBV strategic capabilities of the firm. Although some past studies have used the NRBV theory as a lens for their investigations (Shahzad *et al.*, 2020; Huang *et al.*, 2021), no studies have investigated the relationship between BCT, TPM, and CE through the lens of the NRBV theory. Therefore, the present study has used NRBV theory as a theoretical foundation to investigate the relationship between BCT, TPM, and CE in manufacturing firms.

Further, to address the research questions (stated above), the current research develops a theoretical framework that hypothesises the relationship between BCT, TPM, and CE. The framework is then validated through an empirical study using Partial Least Squares Structural Equation Modeling (PLS-SEM) as an empirical tool.

2. Theoretical background, hypothesis formulation, and conceptual framework

2.1 NRBV theory

The NRBV is a well-known theory in academic circles, having particular importance in sustainable operations (Marshall *et al.*, 2015). NRBV examines a variety of new approaches to problem-solving that businesses and other organisations might use to address environmental concerns (Alt *et al.*, 2015). The three critical strategic capabilities that define the NRBV theory are pollution prevention, product stewardship, and sustainable development (Hart, 1995). Pollution prevention aims to cut down on the amount of waste generated throughout the production process, both operationally and environmentally. In addition to reducing the consumption of toxic substances and resources, product stewardship aims to include ecologically friendly design features in goods and operations (Hart *et al.*, 2010). The focus of sustainable development is on resource efficiency from the viewpoint of long-term ecological and economic sustainability, as well as personnel and ecological wellness and protection (Baumgartner and Raute, 2010).

Global supply networks are becoming more sustainable with the application of BCT (Saberi *et al.*, 2019). Also, a company's environmental sustainability may be impacted by BCT in various ways (Gong and Zhao, 2020). Blockchain advocates consider that its appropriate application may help reduce carbon emissions, particularly at the corporate level (Kouhizadeh and Sarkis, 2018). Sabri *et al.* (2018) believe that BCT will lead to new methods of producing environmentally friendly goods. Also, real-time environmental data may be monitored and stored via blockchain to allow for rapid choices on carbon footprints (Sabri *et al.*, 2018). Therefore, BCT could be recognised as a new organisational resource to address the strategic capabilities of NRBV theory.

To fit in the lens of NRBV, it is common to practice in CE to recycle materials periodically and at a high rate of return (Ellen MacArthur Foundation, 2012). CE incorporates economic, environmental, and social considerations into a company's operations to turn society into a more sustainable one (Dey *et al.*, 2020). CE offers an economical system that represents a paradigm change in how humanity relates to the environment to reduce resource scarcity, break materials and energy cycles, and promote sustainable development (Geissdoerfer *et al.*, 2017). Mishra *et al.* (2019) suggest CE as a firm resource to address the strategic capabilities of NRBV perception. Therefore, CE could be an organisational asset that can handle the NRBV's strategic capabilities.

TPM has also been a practical maintenance management approach adapted by manufacturing firms to reduce waste while preventing machine breakdowns and offering smooth operations (Chiarini, 2014). Farrukh *et al.* (2022) indicate TPM as a green lean six sigma practice, which can address the three strategic capabilities of NRBV theory. Also, TPM is a constructive lean philosophy to overcome issues such as spending colossal resources on maintenance for implementing CE effectively (Basten and Houtum, 2014) to offer the longevity of the materials and prevent the end of the product life cycle (Batista *et al.*, 2019). TPM has been an effective strategy for improving economic performance (Hooi and Leong, 2017), environmental performance (Garza-Reyes *et al.*, 2018), and social performance (Piercy and Rich, 2015) in manufacturing firms. Therefore, TPM can also be considered a practical natural resource for a firm to address the NRBV's strategic capabilities.

This way, TPM, CE, and BCT have the potential to become firm assets under the premises of NRBV theory. Nevertheless, minimal research has been conducted in this domain, or the conducted research has taken an individual dimension with NRBV theory.

2.2 Hypothesis formulation and conceptual research framework

2.2.1 BCT and TPM

In this era of mechanisation, maintenance is an essential tool to offer production-related commitments. TPM is a frequently implemented machine maintenance strategy in the manufacturing sector to minimise losses in production operations, extend machinery lifespan, and ensure machinery's efficient exploitation (Nallusamy and Majumdar, 2017). Predictive and preventive maintenance procedures may be orchestrated using blockchain as part of a more considerable Industrial Internet of Things (IIoT) plan (Stackpole, 2019). BCT is based on a decentralised control network. More advanced manufacturing service needs may be handled by gateways that process higher-level types of manufacturing service demands with a more excellent processing capability when using a decentralised control framework (Leng *et al.*, 2020a). BCT enables the digitalisation of systems for monitoring and tracing by providing real-time data.

The aspect of maintenance has been entirely reimagined (Karki *et al.*, 2022) as a result of recent developments in data and analytics technology and the introduction of IIOT (Paschou *et al.*, 2020). The digitalisation of maintenance today has the power to leverage information and intricate analytics to forecast, detect, diagnose, and rectify equipment issues, and be a durable and essential component to achieving numerous company goals, including the revenue (Karki and Porras, 2021). Digitalisation also has other advantages such as a better understanding of the data and the ability to foresee and fix problems as well as optimise the system and modernise it (Karki and Porras, 2021). Revamping maintenance via digitalisation is one of the most significant ways to do so, allowing for developing new, cutting-edge solutions that make businesses more efficient, productive, and durable in maintenance (Karki *et al.*, 2022). BCT offers real-time data, and maintenance companies can compete better, reduce unnecessary downtime, and optimise equipment availability and production schedules using real-time data. Real-time data may be used to enhance maintenance operations irrespective of the sector (Smith, n.d.). Failover data from several sources may be collected in real-time when equipment fails, automatic repair solutions are available and operators may be notified if they are needed (O'Brien, n.d.). With the help of real-time monitoring, as operational circumstances begin to deviate from the manufacturer's specifications, sensors begin reporting back, allowing manufacturers to forecast failure precisely (O'Brien, n.d.). Therefore, the implementation of BCT can improve the performance of maintenance management practices, such as TPM by offering real-time data, which will help to maintain the longevity of production equipment. In this manner, machine longevity and real-time monitoring of TPM practices will reduce waste and promote better sustainable growth. The results of this relationship (BCT and TPM) will be aligned with the objectives of the NRBV theory. However, no past studies have examined the relationship between BCT and TPM in the context of the NRBV theory. Thus, we hypothesise that,

H1: BCT has a significant favourable influence on TPM from the perception of the NRBV theory.

2.2.2 BCT and CE

CE's growing significance has identified optimal commodity use within the bounds of monetary development and environmental conservation as a priority (Morseletto, 2020).

Although blockchain has been hailed as a facilitator of CE via its use in the three primary domains of reuse, reduce, and recycle (3Rs), existing studies are primarily theoretical (Upadhyay *et al.*, 2021a). Upadhyay *et al.* (2021b) suggested that BCT may lower processing expenses and carbon emissions and enhance the CE's operational efficiency and connectivity. Moreover, material and item movements may be tracked accurately using blockchain-based supply chains while waste management tools can facilitate effective recycling and repurposing of materials (Böhmecke-Schwafert *et al.*, 2022). In order to facilitate the sharing of information about products individuals across their entire existence, the idea of "product-centric information management" was created (Kärkkäinen *et al.*, 2003b; Tang & Qian, 2008; Meyer *et al.*, 2009).

Circular supply chain (CSC) operations, commodities, natural resources, goods, and activities are highly impacted by the features of blockchain such as transparency, traceability, security, dependability, actual-time information, and smart contracts (Khan *et al.*, 2021). Through blockchain, the data is continually available to CSC stakeholders, improving their ability to collaborate both inside the company and with outside parties since a CE demands the creation of workable loops at multiple points along the supply chain (Nandi *et al.*, 2021). Additionally, because of the blockchain's high level of traceability, fewer items and resources are thrown out during CSC operations (Kayikci *et al.*, 2022). The previous discussion indicates that the implementation of BCT will enhance the performance of CE in terms of offering pollution prevention (through achieving 3Rs), a better environment (through optimal use of resources), and sustainable development (offering sustainable-oriented outcomes). The outcomes of the impact of BCT on CE are aligned with the three strategic capabilities of NRBV theory. Still, no research has been conducted in this context. This leads us to the following hypothesis-

H2: BCT has a significant positive influence on CE from the perception of the NRBV theory.

2.2.3 TPM and CE

The Ellen MacArthur Foundation, a significant stakeholder in the circular revolution, has defined CE as a fresh approach to developing, manufacturing, and consuming products within ecological limits (Jain, 2021). Instead of providing a general framework for economic activity, CE identifies particular areas where new value may be created and how that value might be captured (European Union Publication, 2013). In a CE, waste and pollution are eliminated, goods and resources are recycled, and nature is regenerated.

The butterfly diagram offered by the Ellen MacArthur Foundation (n.d.), also known as the CE system diagram, depicts the continual movement of commodities in the economy. The butterfly diagram shows the importance of maintenance operations by emphasising that these activities minimise systematic leakages and negative externalities (Ellen MacArthur Foundation, n. d.). When it comes to implementing CE and the pursuit of strategically focused goals, maintenance plays a significant role (Valkokari *et al.*, 2017). The TPM approach systematically analyses production systems to integrate regularly planned maintenance into conventional business operations (Encapera *et al.*, 2019). TPM can cut down other wastes or components that do not add value due to its efficient use of its resources and the preventative maintenance procedures it employs (Heravi *et al.*, 2019). TPM techniques may help generate production that is both more efficient and less harmful to the environment (Amjad *et al.*, 2021). TPM is a powerful maintenance technique that may help cut power usage and eliminate leaks and wastes by avoiding process breakdowns (Chiarini, 2014). Therefore, the maintenance deliverables in the butterfly diagram and other past studies discussed in this section lead to the possibility of a positive influence of TPM on CE implementation in a firm. The positive impact of TPM on CE could lead to environmental outcomes and sustainable development (through minimising waste and reducing ecological burden), aligning with the NRBV theory's objectives. The discussion develops a need to investigate the relationship between TPM and CE in the context of the NRBV theory. Thus, we hypothesise that,

H3: TPM has a significant favourable influence on CE from the perception of the NRBV theory.

TPM can reduce the amount of energy used and the amount of carbon dioxide emitted in the production system because of its efficient resource management and preventative maintenance practises, which in turn helps the firm improve its environmental performance (Chiarini, 2014). Maintenance data loses its value without an effective tracking mechanism for all parts, resulting in less precise estimates of key metrics like reliability (Mohril *et al.*, 2022). A technique that can reliably guarantee traceability is necessary for complete maintenance management (Mohril *et al.*, 2022). With the assistance of BCT, improvements in the maintenance system's ability to foresee breaks, losses, and wastes might be made (Smith, n.d.). In addition to this, it will lengthen the machine's lifespan and contribute to the delivery of improved environmental results. The many stages of a product's life cycle—from conception to retirement—are all made more streamlined by using BCT (Leng *et al.,* 2020b). Furthermore, with all these efforts, supply chains of manufacturing firms could be more aligned towards circular rather than linear. Therefore, it is possible to state, in a straightforward manner, that the incorporation of BCT into TPM has the potential to enhance the performance of CE. The argument leads to the possible mediation effect of TPM on the relationship between BCT and CE. However, no previous research has investigated the effect of TPM in this particular manner. Thus, we hypothesise that,

H4: TPM has a significant mediating influence on the relationship between BCT and CE.

2.2.4 Conceptual research framework

Figure 1 presents the theoretical research framework which illustrates the proposed relationship between BCT and CE and the direct and mediation effect of TPM from the NRBV theory perspective. Also, it constitutes the foundation for the present empirical study.

"Insert Figure 1 here"

3. Research methodology

In the present research, a research framework (Figure 1) is proposed and validated by the quantitative tool (Partial Least Squares Structural Equation Modeling (PLS-SEM) analysis). The methodology of reporting the PLS-SEM has been adopted by the recent studies of Jahed *et al.* (2022) and Wang *et al.* (2022).

3.1 Questionnaire development

The majority of the measures for the BCT, TPM, and CE constructs were adopted from previously published research and modified to meet the study's criteria. The structure and content of the questionnaire instrument were refined using a three-step process (Ramkumar and Jenamani, 2015). The survey's language and clarity were first reviewed by ten academics from India's top business schools. Together, they had more than a decade's worth of experience in the field. The survey data was then reviewed by a panel of ten industrial manufacturing experts to confirm the results' accuracy. The indicators' content was subsequently refined and validated using pilot surveys with 20 managers from a range of manufacturing firms. For measurement, a five-point Likert scale was used, which was interpreted as follows by the respondents:

- 1= strongly disagree, 2= disagree, 3= neutral, 4= agree, and 5= strongly agree

Table 1 illustrates the items adopted from the literature to define the constructs for the present study.

"Insert Table 1 here"

3.2 Data collection

The manufacturing sector of India was the focus of the research. The Centre for Monitoring Indian Economy (CMIE) ProwessIQ database was searched for a list of licenced businesses that could be contacted for participation in the research. Between December 2021 and June 2022, 783 manufacturing companies were contacted. The COVID-19 pandemic made it more challenging to collect data, especially during on-site assessments. As a result, a number of different channels of electronic communication with businesses were set up. In the end, 316 people answered the survey after multiple follow-up emails. The demographic information of the respondents and their companies is shown in Table 2 and Table 3.

"Insert Table 2 here"

"Insert Table 3 here"

3.3 Analytical approach

The data was analysed using the Partial Least Squares and Structural Equation Modelling (PLS-SEM) technique. Based on the SEM approach, the CB-SEM and the PLS-SEM both make it possible to examine the structural links between the latent variables (Cao *et al.*, 2021). However, both methods of SEM use different computing processes, make different predictions, and evaluate the structural model's fit in different ways (Hair Jr *et al.*, 2014). With a smaller sample size, PLS-SEM may compute complicated models with several constructs linked to numerous variables (Hair *et al.*, 2016). Although population heterogeneity resulted from data collection from different sectors, this was handled by employing a situationally based equality assumption (Rigdon, 2016), which allowed for a reduced sample size to be used while still achieving a statistically significant result (Hair *et al.*, 2018). Taking into account the needs of the complicated model and the lack of heterogeneity, we used Peng and Lai (2012) "10-times" rule of thumb for determining sample size. There were enough completed surveys (316) to meet the required minimum sample size.

4. Results

In the process of this research, the SmartPLS 3.0 software (Ringle *et al.*, 2015) was used for both the assessment of the framework and the approximation of the interior. In addition to this, the measurement and structural model were used to evaluate the PLS-SEM.

4.1 Evaluation of measurement model

The current research used the criteria proposed by Hair *et al.* (2016) to assess the measurement models' validity and reliability. First, the study computed the values of the Composite reliability (CR) and Chronbach alpha (CA) to determine how reliable the constructs were, and then their validity was evaluated. According to Hair *et al.* (2016), a value of 0.70 for CA and CR is the cutoff point for determining whether or not a construct has high levels of internal consistency. According to the findings presented in Table 4, all of the constructs had values higher than 0.70 in this category. In addition, the investigation looked at the values of factor loading to determine whether they were sufficient to ensure dependability. According to the present research findings, each item has a factor loading greater than 0.70, demonstrating strong indicator reliability.

"Insert Table 4 here"

In order to determine whether or not the constructs were reliable, the study followed the recommendations of Black and Babin (2019) and hence used a two-fold method. It investigates both the discriminant and the convergent validity of the hypotheses. The value of a construct's Average variance extracted (AVE) must be greater than 0.50 for the construct to be considered convergent valid (Hair *et al.*, 2016). The findings of the AVE are shown in Table 4, which shows that the values of every construct were greater than 0.50. As a result, each construct was considered to have convergent validity. The present research used the heterotrait-monotrait ratio of correlations (HTMT) criterion to test discriminant validity. The findings are presented in Table 5. Henseler *et al.* (2015) suggest that the HTMT criteria' cut-off value should be less than 0.9. The results from Table 5 indicate that the research also fulfilled the requirements for discriminant validity.

"Insert Table 5 here"

4.2 Common method bias (CMB)

The responses to the survey were completely anonymous and kept strictly confidential. Everyone who participated was made aware that their responses would be anonymous. However, in surveys based on questionnaires, there is always the possibility of common method variation and bias, which may hinder the reliability and validity of the empirical results (Baumgartner and Steenkamp, 2001).

Harmen's one-factor test was utilised to undertake a post-hoc analysis of the study's findings. Principal axis factoring was used to extract the data, and the results showed that 40.176% of the variation could be explained. According to Podsakoff *et al.* (2003), the cut-off value should be less than 50%. Therefore, CMB was not likely to be a problem in this research. Still, the present study conducted one more test to cross-check the possibility of CMB. The study used the variance inflation factor (VIF) as a collinearity test to examine the possibility of CMB in this case. The findings of Hair *et al.* (2019) suggest that the threshold value of VIF should be less than 3 for lower CMB. The results of VIF are shown in Table 6, which indicates the lower variance (CMB) of this research.

"Insert Table 6 here"

4.3 Evaluation of structural model

After analysing the model's results, it is possible to get insight into the structural model's ability to make predictions for one or even more proposed constructs. The research used a method known as nonparametric bootstrapping, using 5000 subsamples to assess the estimate's accuracy. Standardised root mean square (SRMR) values were used to evaluate the model's fitness. These values must be below 0.08 (Cho *et al.*, 2020) for a population of more than one hundred in a study (Cho *et al.*, 2020) (Here, it is 316). Table 6 shows that the SRMR value for the current research was 0.053, which is smaller than 0.08. Consequently, the results of the SRMR values suggested that the model was well-fit. In addition to this, the values of R^2 and Q^2 are shown in Table 7. The cutoff value for R^2 should be greater than 0.1 (Hair *et al.*, 2016). Additionally, the values of Q^2 have to be more than zero (Falk and Miller, 1992). According to the findings included in Table 7, the model had reached a level of predictive relevance.

"Insert Table 7 here"

In order to establish the statistical significance of pathways and acceptance of the hypotheses, the value of various standard coefficients, such as β, must be greater than zero, and the p-value must be less than 0.05. All of the assumptions presented in this research were shown to be valid based on the findings presented in Table 8 and Figure 2.

"Insert Table 8 here"

"Insert Figure 2 here"

Table 8 indicates that all the hypotheses have been accepted. In order to get a clear understanding of the direct influence that the study design had on the various components, a mediation impact assessment was carried out (Ramkumar and Jenamani, 2015). The assessment was contingent on the fulfilment of the following prerequisites, i.e. (1) the direct connection without mediation influence should be statistically significant; (2) the indirect influence after mediation ought to be statistically meaningful; and (3) if the variance accounted for (VAF) exceeds 80%, it symbolises a complete mediation effect; 20% < VAF < 80% means partial mediation, and less than 20% VAF value indicates that there is no mediation effect.

The mediation effect analysis revealed the existence of major and statistically significant mediating channels. In this case, there was a statistically significant relationship between the presence of partial mediation and the existence of mediation effects, which are represented by the routes BCT→TPM→CE ($\beta = 0.140$, T= 3.579, and VAF = 27.13%).

5. Discussion and implications

5.1 Discussion of findings

This study investigates how TPM, BCT, and CE are related within the premises of the three strategic capabilities of the NRBV theory. PLS-SEM was used to verify the conceptual research framework (see Figure 2 and Table 8). The findings suggest a high positive correlation between BCT to TPM and CE and TPM and CE. Table 8 and Figure 2 also show that TPM partially mediates the link between BCT and CE.

Concerning the first hypothesis (H1), the standard coefficient values ($\beta = 0.508$, T= 8.225, and $p < 0.00$) indicate that BCT has a substantial beneficial impact on TPM. The results are consistent with earlier research (Karki *et al.*, 2022; O'Brien, n.d.; Smith, n.d.). According to H1, adopting BCT may increase TPM performance by monitoring real-time data, resulting in greater waste reduction and optimal resource usage. Furthermore, the optimality of input and output resources at the shop floor level will lead to pro-environmental behaviours. Under the NRBV theory premises, H1 suggests that BCT has a substantial positive association with TPM.

The values of standard coefficients ($\beta = 0.376$, T= 5.175, and $p < 0.00$) support the second hypothesis (H2), which states that BCT has a substantial positive effect on CE. Prior investigations, such as those of Böhmecke-Schwafert *et al.* (2022), Upadhyay *et al.* (2021a), Upadhyay *et al.* (2021b), and Nandi *et al.* (2021), have shown similar results. But this research empirically validates the prior analysis as most offered theoretical foundations. The results also show that adopting BCT aids in the tracking of non-value-added resources throughout the CSC. Traceability also aids in the achievement of the CE's 3Rs aim. As a result, the application of BCT in the supply chain promotes CE practices under the NRBV paradigm.

The results of the standard coefficients ($\beta = 0.276$, $T = 4.068$, and $p < 0.00$) support the third hypothesis (H3), indicating that TPM has a considerable beneficial impact on CE practises. Some previous investigations, such as those conducted by the Ellen MacArthur Foundation (n.d.), Amjad *et al.* (2021), and Heravi *et al.* (2019), align with H3's findings. Although previous research does not immediately correlate with H3, it suggests that H3 is possible. The results have now been empirically validated, providing a solid basis for this approach. TPM's preventative maintenance method helps to decrease a variety of wastes. It also aids in the reduction of several hazardous pollutants and the extension of production equipment life. As a result, the impact of TPM on CE could offer outcomes within the premises of NRBV conception.

The PLS-SEM analysis shows that 27.13% of the overall effect size supports the partial mediation of TPM on the BCT and CE relationship. The data show that BCT has a positive causal connection with CE (Böhmecke-Schwafert *et al.*, 2022; Upadhyay *et al.*, 2021a; Upadhyay *et al.*, 2021b) and is partly mediated by TPM. Finally, the values of R^2 (greater than 0.1) and Q^2 (greater than 0) for all the constructs demonstrate that the study is strong and robust.

5.2 Theoretical implications

The primary objective of the present research was to address the research question: *"How are BCT, TPM, and CE connected within the premises of the NRBV theory, particularly in the context of three strategic capabilities supplied by NRBV theory as described by Hart (1995)?"*. Past studies have examined or indicated the possible correlations between BCT and TPM

(Karki *et al.*, 2022; O'Brien, n.d.; Smith, n.d.), BCT and CE (Böhmecke-Schwafert *et al.*, 2022; Upadhyay *et al.*, 2021a; Upadhyay *et al.*, 2021b; Nandi *et al.*, 2021), TPM and CE (Ellen MacArthur Foundation (n.d.), Amjad *et al.*, 2021; Heravi *et al.*, 2019). However, all these relationships are examined or proposed individually and in some general context, i.e., without any theoretical foundation. Therefore, this is the first study that examines the relationship between BCT, TPM, and CE as a combined effort through the lens of NRBV theory.

The second contribution this study makes to the existing body of the NRBV theory is developing a strong causal link between established (TPM) and establishing (BCT and CE) operations management philosophies. This finding is included in the literature on NRBV theory. The interpretation might be understood to mean that these three philosophies (BCT, TPM, and CE) have the potential to provide the vision of a manufacturing business if the firm is subject to the impact of the NRBV theory.

Third, in terms of the approach, the high sample size (n=316) allows for statistical extrapolation of the findings (Chand et al., 2022). Specifically, the results give a numerical assessment of the link, revealing the intensity with which the interaction influence was present. The paper makes a theoretical addition to the discussion of how manufacturing organisations might employ the BCT, TPM, and CE to understand their interaction behaviour to produce outcomes with an emphasis on NRBV. In manufacturing companies, our findings provide light on the interplay between BCT, TPM, and CE. Additionally, the research results provide a basis for theoretical validation in future studies that are equivalent to the present one, and they do so in the context of a separate industry.

Hart (1995) devised the NRBV paradigm, emphasising how firms may differentiate themselves via contributions to sustainable development. Based on the findings of this study, it appears that manufacturing companies can gain a competitive edge by implementing BCT, TPM, and

CE due to the positive and causal solid interrelation between these three factors, which in turn encourages the development of sustainability-related aspects within the manufacturing firm, particularly in the areas of pollution prevention, product stewardship, and sustainable growth. This study not only has theoretical ramifications but also implies that these skills might form the foundation for manufacturing organisations' capacity to provide a competitive edge.

5.3 Managerial implications

The results of this research have important implications for management's comprehension of BCT and TPM's impact on CE within the framework of NRBV theory. By using BCT as an integrated strategy in TPM, practitioners, managers, and shop floor supervisors may produce more environmentally friendly results, including less pollution, improved accessibility to resources, and minimised waste across manufacturing processes. Further, the insight that BCT has provided into each aspect of maintenance is excellent. This includes allowing product information, linking products to suppliers, commencing yearly maintenance, implementing service queries, storing service history, and producing invoices (A. R., 2020).

From what we can see, TPM practises have been widely adopted by industrial organisations for decades, and this trend shows no signs of slowing down. However, the study's empirical research suggests that, in the future, industrial organisations all over the globe, not only in India, will increasingly use TPM technologies in tandem with BCT. Practitioners see TPM and BCT as key motivators for obtaining CE in their relevant field of knowledge within the premises of the NRBV's three dimensions, as shown by the beneficial direct influence TPM and BCT have on CE. Equipment maintenance is crucial to a healthy CE since it helps keep machines running for longer, cuts down on waste, and increases productivity (Infraspeak, 2022). For instance, Caterpillar's Cat Reman programme refurbishes decommissioned machinery to provide clients not only substantial savings in the short term but also to assist prolong product lifetimes and make better use of raw resources (Caterpillar, n.d.). Since TPM has a positive impact on CE, its role in manufacturing companies may shift from a maintenance practice or an activity on the shop floor to that of a facilitator of CE practices. This is because of the positive effect that TPM has on CE. CE is already regarded as a necessity for sustainability (Geissdoerfer *et al.*, 2017), and the development of TPM on CE will provide TPM with a different persona as a facilitator of sustainable growth of manufacturing enterprises owing to the influence of TPM on CE.

Furthermore, the positive influence of blockchain on CE can be recognised in its practical ramifications, as blockchain also aids the end-user in determining the most efficient means of maintenance or disposal for the product and/or associated parts (Murphy, 2022). Because of the level of detail in the collected data, all stakeholders in an item's value chain can take on a fair share of accountability for the product's material movements, making the circular economy a reality (Murphy, 2022). For instance, under the "EU's Circular Foam" initiative, Electrolux and polymer manufacturer Covestro are collaborating to identify new solutions to recycle firm PU foam from refrigerators. The manufacturer can now save information on the most efficient ways to disassemble the refrigerator at the end of its useful life by employing blockchain, simplifying the currently difficult physical operation (Murphy, 2022).

Managers in manufacturing businesses would do well to recognise the importance of TPM and BCT as facilitators of CE due to the favourable effects they have on CE. In the long run, this would lead to lower emissions, better product care, and the continued success of the manufacturing company. Managers should realise that TPM and BCT are the motivation and basis for CE projects within the premises of NRBV theory.

6. Conclusions, limitations, and future scope

This study draws on the insights of working professionals at Indian manufacturing companies implementing TPM, BCT, and/or CE. Experts in the manufacturing sector are specifically interviewed for this research. The study's findings, if taken in light of the study's conclusions, could be used as a point of reference for manufacturing organisations considering the application of BCT and TPM to obtain CE-driven benefits within the framework of NRBV theory. Insight into how the NRBV theory might be incorporated into the BCT, TPM, and CE action plans were also gained from analysing the 316 responses received from manufacturing firms. The results show that both BCT and TPM have significant benefits for improving CE processes; hence, it is suggested that manufacturing companies adopt both technologies together.

The current research provides a comprehensive analysis of how TPM and BCT impact the CE of manufacturing organisations. However, here are some of the caveats of the existing study and some ideas for where to go next:

- In order to examine the impact of BCT and TPM on CE, we separated these concepts in the present study. When compared side by side, BCT and TPM approaches use different tools differently. But as TPM acts as a mediator in the relationship between BCT and CE, studying the impact of BCT-TPM integration on CE is essential.
- The current research, grounded in NRBV theory, investigates the impact of BCT and TPM on the CE practices of manufacturing organisations. Nonetheless, it's still possible that none of these three approaches will give the same association in a different context. Future studies will be able to explore the connection among BCT, TPM, and CE in many unrestricted settings.
- Present study does not indicate a priority order for BCT, TPM, and CE within the context of the NRBV theory. Future studies may therefore examine alternative ranking approaches to arrange the respondents' reports on a variety of technologies and

activities into a hierarchical framework consistent with the scope constraints of the NRBV theory.

- The current research investigates the mediating effect of TPM on the association between BCT and CE. That means we can look into how TPM moderates those similar associations. Another possible avenue of inquiry into the relationship between BCT and TPM is the potential mediating or moderating role played by CE. This study's conclusions are limited to India because all of the researchers were employed by Indian industrial companies. Researchers believe the findings are comparable to the results achieved by industrial businesses in developing countries. When doing the follow-up study, researchers should broaden their scope to include more sectors and nations.

References

Agrawal, T. K., Kumar, V., Pal, R., Wang, L. and Chen, Y. (2021), "Blockchain-based framework for supply chain traceability: A case example of textile and clothing industry", *Computers and Industrial Engineering*, Vol. 154, pp. 107130.

Ahuja, I. and Khamba, J. (2008), "Justification of total productive maintenance initiatives in Indian manufacturing industry for achieving core competitiveness", *Journal of Manufacturing Technology Management*, Vol. 19 No. 5, pp. 645-669.

Albano, M., Sharma, P., Campos, J. and Jantunen, E. (2019), "Energy saving by Blockchaining maintenance", *Journal of Industrial Engineering and Management Science*, Vol. 2018 No. 1, pp. 63-88.

Allen, K. (2021), "The link between maintenance and a more sustainable world", available at: https://www.fiixsoftware.com/blog/maintenance-and-sustainability-framework/ (accessed 15 May 2022)

Alt, E., Díez-de-Castro, E.P. and Lloréns-Montes, F.J. (2015), "Linking employee stakeholders to environmental performance: the role of proactive environmental strategies and shared vision", Journal of Business Ethics, Vol. 128 No. 1, pp. 167-181.

Amjad, M. S., Rafique, M. Z. and Khan, M. A. (2021), "Leveraging optimised and cleaner production through industry 4.0", *Sustainable Production and Consumption*, Vol. 26, pp. 859–871.

A. R., M. (2020, April 16), "How can blockchain add value in enterprise maintenance services?", available at: https://www.expresscomputer.in/guest-blogs/how-can-blockchain-add-value-in-enterprise-maintenance-services/53196/ (accessed 28 October 2022)

Astrachan, C. B., Patel, V. K. and Wanzenried, G. (2014), "A comparative study of CB-SEM and PLS-SEM for theory development in family firm research", *Journal of Family Business Strategy*, Vol. 5 No. 1, pp. 116-128.

Basten, R. and Van Houtum, G. (2014), "System-oriented inventory models for spare parts", *Surveys in Operations Research and Management Science*, Vol. 19 No. 1, pp. 34-55.

Batista, L., Gong, Y., Pereira, S., Jia, F. and Bittar, A. (2019), "Circular supply chains in emerging economies – a comparative study of packaging recovery ecosystems in China and Brazil", *International Journal of Production Research*, Vol. 57 No. 23, pp. 7248-7268. [CrossRef]

Baumgartner, H. and Steenkamp, J. E. (2001), "Response styles in marketing research: A cross-national investigation", *Journal of Marketing Research*, Vol. 38 No. 2, pp. 143-156.

Baumgartner, R.J. and Rauter, R. (2017), "Strategic perspectives of corporate sustainability management to develop a sustainable organization", *Journal of Cleaner Production*, Vol. 140, pp. 81-92

Black, W. and Babin, B. J. (2019), "Multivariate data analysis: Its approach, evolution, and impact", *The Great Facilitator*, pp. 121-130.

Böhmecke-Schwafert, M., Wehinger, M. and Teigland, R. (2022), "Blockchain for the circular economy: Theorising blockchain's role in the transition to a circular economy through an empirical investigation", *Business Strategy and the Environment.*

Cao, D., Meadows, M., Wong, D. and Xia, S. (2021), "Understanding consumers' social media engagement behaviour: An examination of the moderation effect of social media context", *Journal of Business Research*, Vol. 122, pp. 835-846.

Caterpillar. (n.d.), "Circular economy", available at: https://www.caterpillar.com/en/company/sustainability/remanufacturing.html. (accessed 28 October 2022)

Chand, P., Kumar, A., Thakkar, J. and Ghosh, K. K. (2022), "Direct and mediation effect of supply chain complexity drivers on supply chain performance: An empirical evidence of organizational complexity theory", *International Journal of Operations and Production Management*, Vol. 42 No. 6, pp. 797-825.

Chang, Y., Iakovou, E. and Shi, W. (2019), "Blockchain in global supply chains and cross border trade: A critical synthesis of the state-of-the-art, challenges and opportunities", *International Journal of Production Research*, Vol. 58 No. 7, pp. 2082-2099.

Chiarini, A. (2014), "Sustainable manufacturing-greening processes using specific lean production tools: An empirical observation from European motorcycle component manufacturers", *Journal of Cleaner Production*, Vol. 85, pp. 226–233.

Cottrill, K. (2018), "The benefits of blockchain: Fact or wishful thinking", *Supply Chain Management Review*, Vol. 22, pp. 20–25.

Chen, Q., Zhu, Z., Si, S. and Cai, Z. (2020), "Intelligent Maintenance of Complex Equipment Based on Blockchain and Digital Twin Technologies", *2020 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*, pp. 908-912

Chen, P., Fortuny-Santos, J., Lujan, I., and Ruiz-de-Arbulo-López, P. (2019), "Sustainable manufacturing: Exploring antecedents and influence of total productive maintenance and lean manufacturing", *Advances in Mechanical Engineering*, Vol. 11 No. 11, pp. 168781401988973.

Cho, G., Hwang, H., Sarstedt, M., and Ringle, C. M. (2020), "Cutoff criteria for overall model fit indexes in generalised structured component analysis", *Journal of marketing analytics*, pp. 1-14. [CrossRef]

Dey, P. K., Malesios, C., De, D., Budhwar, P., Chowdhury, S. and Cheffi, W. (2020), "Circular economy to enhance sustainability of small and medium-sized enterprises", *Business Strategy and the Environment*, Vol. 29 No. 6, pp. 2145-2169.

Edwin Cheng, T. C., Kamble, S. S., Belhadi, A., Ndubisi, N. O., Lai, K., & Kharat, M. G. (2021), "Linkages between big data analytics, circular economy, sustainable supply chain flexibility, and sustainable performance in manufacturing firms", International Journal of Production Research, pp. 1-15. https://doi.org/10.1080/00207543.2021.1906971.

Ellen MacArthur Foundation (2012), "What is a Circular Economy?", available at: www.ellenmacarthurfoundation.org/circular-economy (accessed 15 May 2022).

Ellen MacArthur Foundation. (n.d.), "The butterfly diagram: visualising the circular economy", available at: https://ellenmacarthurfoundation.org/circular-economy-diagram (accessed 15 May 2022).

Encapera, A., Gosavi, A. and Murray, S. L. (2019), "Total productive maintenance of make-to-stock production-inventory systems via artificial-intelligence-based iSMART", *International Journal of Systems Science: Operations and Logistics*, Vol. 8 No. 2, pp. 154-166.

European Union Publication (2013), "Eco-innovation and competitiveness, Enabling the transition to resource-efficient circular economy", Annual Report 2013, Luxembourg, available at: https://doi.org/10.2779/58269 (accessed 18 May 2022)

Falk, R. F. and Miller, N. B. (1992), "A primer for soft modelling", University of Akron Press. [CrossRef]

Garza-Reyes, J. A., Kumar, V., Chaikittisilp, S. and Tan, K. H. (2018), "The effect of lean methods and tools on the environmental performance of manufacturing organisations", *International Journal of Production Economics*, Vol. 200, pp. 170–180 [CrossRef]

Geissdoerfer, M., Savaget, P., Bocken, N. and Hultink, E. J. (2017), "The circular economy—A new sustainability paradigm?", *Journal of Cleaner Production*, Vol. 143, pp. 757–768.

Ghisellini, P., Cialani, C. and Ulgiati, S. (2016), "A Review on Circular Economy: The Expected Transition to a Balanced Interplay of Environmental and Economic Systems", *Journal of Cleaner Production*, Vol. 114, pp. 11–32.

Gong, J. and Zhao, L. (2020), "Blockchain application in healthcare service mode based on Health Data Bank", *Frontiers of Engineering Management*, Vol. 7 No. 4, pp. 605–614.

Hair, J. F., Risher, J. J., Sarstedt, M. and Ringle, C. M. (2019), “When to use and how to report the results of PLS-SEM”, *European Business Review*, Vol. 31 No. 1, pp. 2–24.

Hair, J.F., Sarstedt, M., Ringle, C.M. and Gudergan, S.P. (2018), “Advanced Issues in Partial Least Squares Structural Equation Modeling (PLS-SEM)”, Sage, Thousand Oaks, CA.

Hair, J. F., JR, Hult, G.T.M., Ringle, C. and Sarstedt, M. (2016), “A Primer on Partial Least Squares Structural Equation Modeling (PLS-SEM)”, Sage Publications. [CrossRef]

Hair Jr, J. F., Sarstedt, M., Hopkins, L. and Kuppelwieser, V. G. (2014), “Partial least squares structural equation modeling (PLS-SEM)”, *European Business Review*, Vol. 26 No. 2, pp. 106-121.

Hart, S.L. (1995), “A natural-resource-based view of the firm”, *Academy of Management Review*, Vol. 20 No. 4, pp. 986-1014.

Hart, S.L., Barney, J.B., Ketchen, D.J., Wright, M., and Dowell, G. (2010), “Invited editorial: a natural resource-based view of the firm”, *Journal of Management*, Vol. 37 No. 5, pp. 1464-1479.

Henseler, J., Ringle, C. M. and Sarstedt, M. (2015), “A new criterion for assessing discriminant validity in variance-based structural equation modelling”, *Journal of the Academy of Marketing Science*, Vol. 43 No. 1, pp. 115–135.

Heravi, G., Kebria, M. F. and Rostami, M. (2019), “Integrating the production and the erection processes of pre-fabricated steel frames in building projects using phased lean management”, *Engineering, Construction and Architectural Management*, Vol. 28 No. 1, pp. 174–195.

Hooi, L. W. and Leong, T. Y. (2017), “Total productive maintenance and manufacturing performance improvement”, *Journal of Quality in Maintenance Engineering*, Vol. 23 No. 1, pp. 2-21.

Huang, Y. C., Borazon, E.Q. and Liu, J.-M. (2021), “Antecedents and consequences of green supply chain management in Taiwan's electric and electronic industry”, *Journal of Manufacturing Technology Management*, Vol. 32 No. 5, pp. 1066-1093.

Infraspeak. (2022), “Maintenance, reliability, and the circular economy”, available at: https://blog.infraspeak.com/maintenance-reliability-and-the-circular-economy/ (accessed 28 October 2022).

Jahed, M. A., Quaddus, M., Suresh, N. C., Salam, M. A. and Khan, E. A. (2022), “Direct and indirect influences of supply chain management practices on competitive advantage in fast fashion manufacturing industry”, *Journal of Manufacturing Technology Management*, Vol. 33 No. 3, pp. 598-617.

Jain, A. (2021, November 15). Service is at the heart of the circular economy. Field Service Digital. available at: https://fsd.servicemax.com/2021/11/16/service-is-at-the-heart-of-the-circular-economy/ (accessed 11 May 2022).

Javaid, M., Haleem, A., Pratap Singh, R., Khan, S. and Suman, R. (2021), “Blockchain technology applications for industry 4.0: A literature-based review”, *Blockchain: Research and Applications*, Vol. 2 No. 4, pp. 100027.

Karki, B. R., Basnet, S., Xiang, J., Montoya, J., and Porras, J. (2022), “Digital maintenance and the functional blocks for sustainable asset maintenance service – A case study”, *Digital Business*, Vol. 2 No. 2, pp. 100025.

Karki, B. R., & Porras, J. (2021), “Digitalization for sustainable maintenance services: A systematic literature review”, *Digital Business*, Vol. 1 No. 2, pp. 100011.

Kayikci, Y., Subramanian, N., Dora, M. and Bhatia, M. S. (2022), “Food supply chain in the era of industry 4.0: Blockchain technology implementation opportunities and impediments from the perspective of people, process, performance, and technology”, *Production Planning and Control*, Vol. 33 No. (2–3), pp. 301–321.

Khadke, S., Gupta, P., Rachakunta, S., Mahata, C., Dawn, S., Sharma, M., Verma, D., Pradhan, A., Krishna, A. M. S., Ramakrishna, S., Chakrabortty, S., Saianand, G., Sonar, P., Biring, S., Dash, J. K. and Dalapati, G. K. (2021), “Efficient plastic recycling and remolding circular economy using the technology of trust–blockchain”, *Sustainability*, Vol. 13 No. 16, pp. 9142.

Khan, S. A. R., Razzaq, A., Yu, Z. and Miller, S. (2021), “Industry 4.0 and circular economy practices: A new era business strategies for environmental sustainability”, *Business Strategy and the Environment*, Vol. 30 No. 8, pp. 4001–4014.

Köhler, J., Geels, F. W., Kern, F., Markard, J., Onsongo, E., Wieczorek, A. and Boons, F. (2019), “An agenda for sustainability transitions research: State of the art and future directions”, *Environmental Innovation and Societal Transitions*, Vol. 31, pp. 1–32.

Kouhizadeh, M. and Sarkis, J. (2018), “Blockchain practices, potentials, and perspectives in greening supply chains”, *Sustainability*, Vol. 10 No. 10, pp. 3652.

Kumar, A., Liu, R. and Shan, Z. (2020), “Is blockchain a silver bullet for supply chain management? Technical challenges and research opportunities”, *Decision Sciences*, Vol. 51 No. 1, pp. 8-37.

Lakhani, K. R. and Iansiti, M. (2017), “The truth about blockchain”, *Harvard Business Review*, Vol. 95 No. 1, pp. 119-127.

Leng, J., Yan, D., Liu, Q., Xu, K., Zhao, J. L., Shi, R., Wei, L., Zhang, D. and Chen, X. (2020a), “ManuChain: Combining Permissioned blockchain with a holistic optimisation model as Bi-level intelligence for smart manufacturing”, *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, Vol. 50 No. 1, pp. 182-192.

Leng, J., Ruan, G., Jiang, P., Xu, K., Liu, Q., Zhou, X., & Liu, C. (2020b), “Blockchain-empowered sustainable manufacturing and product lifecycle management in industry 4.0: A survey”, *Renewable and Sustainable Energy Reviews,* Vol. 132, pp. 110112.

Lohmer, J. and Lasch, R. (2020), “Blockchain in operations management and manufacturing: Potential and barriers”, *Computers and Industrial Engineering*, Vol. 149, pp. 106789.

Marshall, D., L. McCarthy, C. Heavy, and P. McGrath. (2015), “Environmental and Social Supply Chain Management Sustainability Practices: construct Development and Measurement.” *Production, Planning and Control*, Vol. 26 No. 8, pp. 673–690.

Mishra, J. L., Chiwenga, K. D., and Ali, K. (2019), “Collaboration as an enabler for circular economy: A case study of a developing country, Management Decision, Vol. 59 No.8, pp. 1784-1800.

Mohril, R. S., Solanki, B. S., Lad, B. K., & Kulkarni, M. S. (2022), “Blockchain enabled maintenance management framework for military equipment, IEEE Transactions on Engineering Management, pp. 1-14.

Morseletto, P. (2020), “Targets for a circular economy’, *Resources, Conservation and Recycling*, Vol. 153, pp. 104553.

Murphy, C. (2022), “How blockchain can facilitate the transition to a circular economy”, Ellen MacArthur Foundation., available at: https://ellenmacarthurfoundation.org/tech-enablers-series/part-2#:~:text=Blockchain%20can%20facilitate%20the%20transition,greater%20level%20of%20collaborative%20work (accessed 29 October 2022).

Murray, A., Skene, K. and Haynes, K. (2017), “The circular economy: An interdisciplinary exploration of the concept and application in a global context”, *Journal of Business Ethics*, Vol. 140 No. 3, pp. 369–380.

Nallusamy, S. and Majumdar, G. (2017), “Enhancement of Overall Equipment Effectiveness using Total Productive Maintenance in a Manufacturing Industry”, *International Journal of Performability Engineering*, Vol. 13 No. 2, pp. 173-188.

Nandi, S., Hervani, A. A., Helms, M. M., and Sarkis, J. (2021), “Conceptualising circular economy performance with non-traditional valuation methods: Lessons for a post-pandemic recovery”, *International Journal of Logistics Research and Applications*, pp. 1–21.

Narayan, R., and Tidström, A. (2020), “Tokenizing coopetition in a blockchain for a transition to circular economy”, *Journal of Cleaner Production*, Vol. 263, pp. 121437.

O'Brien, J. (n.d.), “Improve maintenance with the Internet of things”, available at: https://www.reliableplant.com/Read/29962/internet-of-things (accessed 15 July 2022).

Paschou, T., Rapaccini, M., Adrodegari, F., and Saccani, N. (2020), “Digital servitization in manufacturing: A systematic literature review and research agenda”, *Industrial Marketing Management*, Vol. 89, pp. 278-292.

Peng, D.X., and Lai, F. (2012), “Using partial least squares in operations management research: a practical guideline and summary of past research”, *Journal of Operations Management*, Vol. 30 No. 6, pp. 467-480.

Piercy, N. and Rich, N. (2015), “The relationship between lean operations and sustainable operations”, *International Journal of Operations and Production Management*, Vol. 35 No. 2, pp. 282-315.

Podsakoff, P. M., MacKenzie, S. B., Lee, J.-Y., and Podsakoff, N. P. (2003), “Common method biases in behavioral research: A critical review of the literature and recommended remedies”, *Journal of Applied Psychology*, Vol. 88 No. 5, pp. 879.

Prieto-Sandoval, V., Jaca, C. and Ormazabal, M. (2018), "Towards a consensus on the circular economy", *Journal of Cleaner Production*, Vol. 179, pp. 605–615.

Ramkumar, M. and Jenamani, M. (2015), "Organizational buyers' acceptance of electronic procurement services—an empirical investigation in Indian firms", *Service Science*, Vol. 7 No. 4, pp. 272-293. [CrossRef]

Ringle, C.M., Wende, S. and Becker, J.M. (2015), "SmartPLS 3", SmartPLS GmbH, Boenningstedt. http://www.smartpls.com

Saberi, S., Kouhizadeh, M. and Sarkis, J. (2018), "Blockchain technology: A panacea or pariah for resources conservation and recycling?", *Resources, Conservation and Recycling*, Vol. 130, pp. 80–81.

Saberi, S., Kouhizadeh, M., Sarkis, J. and Shen, L. (2019), "Blockchain technology and its relationships to sustainable supply chain management", *International Journal of Production Research*, Vol. 57 No. 7, pp. 2117-2135.

Samadhiya, A., Kumar, A., Agrawal, R., Kazancoglu, Y., and Agrawal, R. (2022), "Reinventing reverse logistics through blockchain technology: A comprehensive review and future research propositions", *Supply Chain Forum: An International Journal*, pp. 1-22.

Shahzad, M., Qu, Y., Zafar, A.U., Rehman, S.U. and Islam, T. (2020), "Exploring the influence of knowledge management process on corporate sustainable performance through green innovation", *Journal of Knowledge Management*, Vol. 24 No. 9, pp. 2079-2106.

Si, S., Zhao, J., Cai, Z., and Dui, H. (2020), "Recent advances in system reliability optimisation driven by importance measures", *Frontiers of Engineering Management*, Vol. 7 No. 3, pp. 335-358.

Smith, K. (n.d.), "The importance of real-time data in maintenance", VIZIYA. available at: https://www.viziya.com/resource/importance-real-time-maintenance/#:~:text=Real%2Dtime%20data%20allows%20maintenance,data%20to%20improve%20their%20processes (accessed 15 July 2022).

Stackpole, B. (2019)., "Blockchain's role in factory automation", Automation World. available at: https://www.automationworld.com/home/article/13319698/blockchains-role-in-factory-automation (accessed 11 May 2022).

Thanki, S., Govindan, K., and Thakkar, J. (2016), "An investigation on lean-green implementation practices in Indian SMEs using Analytical Hierarchy Process (AHP) approach", *Journal of Cleaner Production*, Vol. 135, pp. 284–298.

Upadhyay, A., Mukhuty, S., Kumar, V., and Kazancoglu, Y. (2021a), "Blockchain technology and the circular economy: Implications for sustainability and social responsibility", *Journal of Cleaner Production*, Vol. 293, pp. 126130.

Upadhyay, A., Laing, T., Kumar, V., and Dora, M. (2021b), "Exploring barriers and drivers to the implementation of circular economy practices in the mining industry", *Resources Policy*, Vol. 72, pp. 102037.

Valkokari, P., Hanski, J., and Ahonen, T. (2017), "Impact of maintenance on circular economy", In J. Aaltonen, R. Virkkunen, K. T. Koskinen, and R. Kuivanen (Eds.), *Proceedings of the 2nd Annual SMACC Research Seminar 2017,* (pp. 20-23). Tampere University of Technology. available at: https://publications.vtt.fi/julkaisut/muut/2017/OA-Impact-of-maintenance.pdf

Venkatesh, V. G., Kang, K., Wang, B., Zhong, R. Y. and Zhang, A. (2020), "System architecture for blockchain based transparency of supply chain social sustainability", *Robotics and Computer-Integrated Manufacturing*, Vol. 63, pp. 101896.

Vukadinovic, S., Macuzic, I., Djapan, M. and Milosevic, M. (2019), "Early management of human factors in lean industrial systems", *Safety Science*, Vol. 119, pp. 392-398.

Wang, H., Yan, Q., and Wang, J. (2021), "Blockchain-secured multi-factory production with collaborative maintenance using Q learning-based optimisation approach", *International Journal of Production Research*, pp. 1-18.

Wang, G., Wang, Y., Ju, X. and Rui, X. (2022), "Effects of political networking capability and strategic capability on exploratory and exploitative innovation: Evidence from traditional manufacturing firms in China", *Journal of Manufacturing Technology Management*, Vol. 33 No. 3, pp. 618-642.

Wilde, S. and Cox, C. (2008), "Principal factors contributing to the competitiveness of tourism destinations at varying stages of development", in Richardson, S., Fredline, L., Patiar A., and Ternel, M. (Ed.s), CAUTHE 2008: Where the 'bloody hell' are we?, Griffith University, Gold Coast, Qld, pp.115-118.

Wudhikarn, R. (2012), "Improving Overall Equipment Cost Loss Adding Cost of Quality", *International Journal of Production Research*, Vol. 50 No. 12, pp. 3434–3449.

Yildizbasi, A. (2021), "Blockchain and renewable energy: Integration challenges in circular economy era", *Renewable Energy*, Vol. 176, pp. 183–197.

Figures

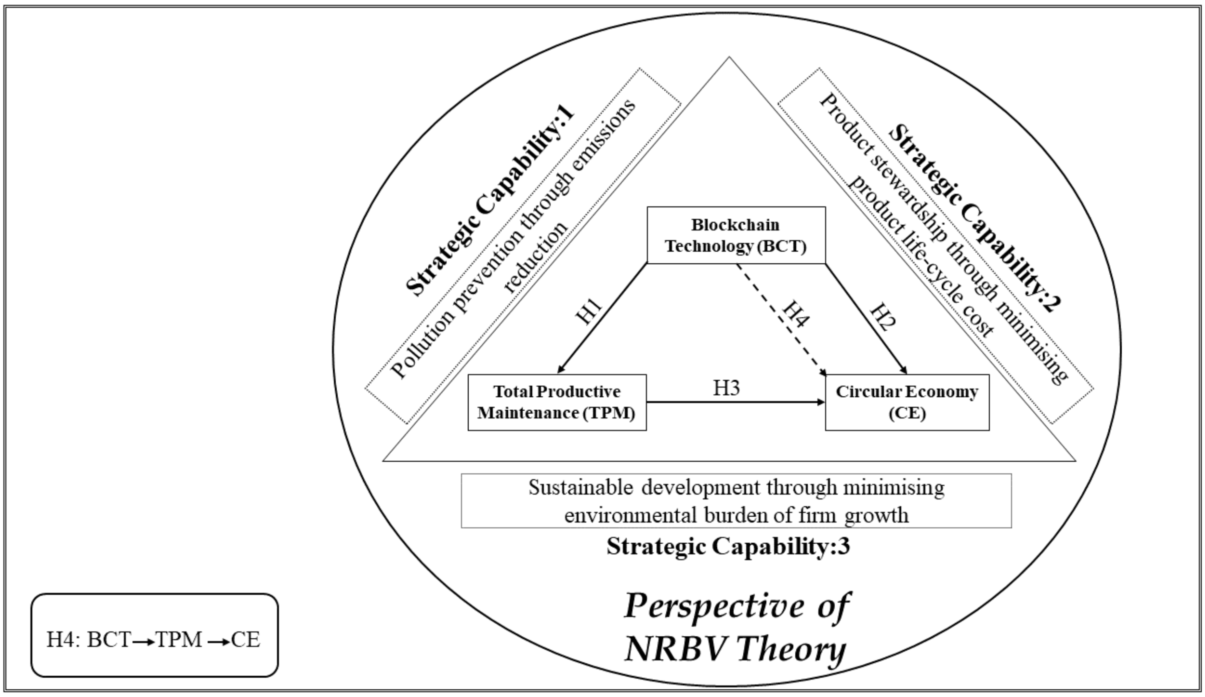

Figure 1: Conceptual Research Framework

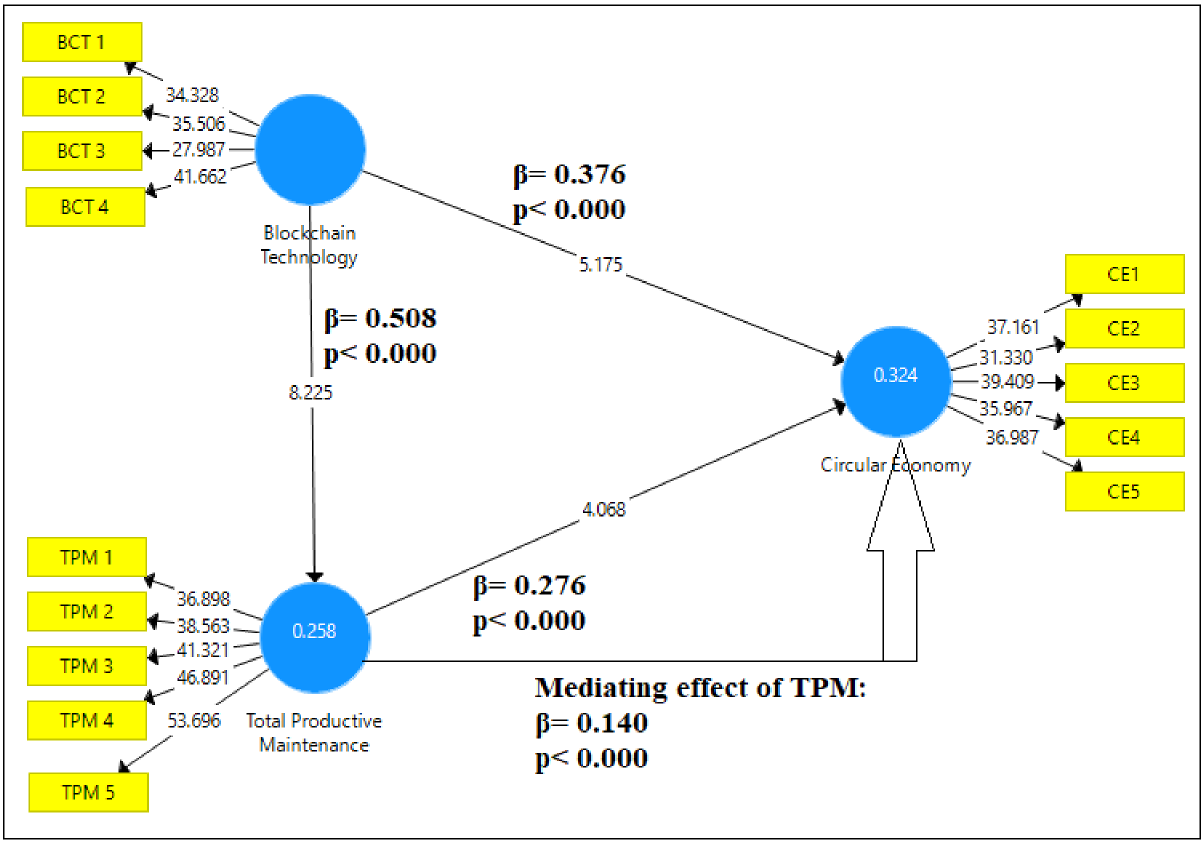

Figure 2: Empirical validation of the conceptual research framework

Tables

Table 1: Items adapted from the past literature to define the constructs

Constructs	Item code	Item statements	References
Blockchain Technology (BCT)	BCT 1	Do you agree that data in your company is obtained in real-time?	Cottrill (2018)
	BCT 2	Do you agree that activities information of the supply chain in your company could be tracked and traced?	
	BCT 3	Do you agree that your company use digital transactions throughout the supply chain to speed up the transactions and reduce the errors of manual documentation?	
	BCT 4	Do you agree that your company is using a consensus mechanism to provide data timely, authentic and secure throughout the supply chain?	
Circular Economy (CE)	CE 1	Do you agree that your firm focuses on waste minimisation in its process design?	Cheng *et al.* (2021)
	CE 2	Do you agree that your firm generates environmental reports for internal evaluation purposes?	
	CE 3	Do you agree that your firm reduces the use of hazardous products?	
	CE 4	Do you agree that your firm follows pollution prevention programmes?	
	CE 5	Do you agree that your firm reduces the consumption of materials and energy focus in design?	
Total Productive Maintenance (TPM)	TPM 1	Do you agree that your firm implements eight pillars of TPM on the shop floor?	Farrukh et al. (2022); Ahuja and Khamba (2008)
	TPM 2	Do you agree that maintenance practices in your company lead to the reduction of various losses related to the manufacturing system?	
	TPM 3	Do you agree that maintenance practices in your company reduces the ecological degradation?	
	TPM 4	Do you agree that maintenance practices in your company are associated with product stewardship and pollution prevention?	
	TPM 5	Do you agree that maintenance practices in your company improve the life cycle of equipment?	

Table 2: Summary of approached and responded manufacturing industries

S. No.	Firms type	Number of the approached individual firm	Number of received responses from an individual firm	Percentage of a responded firm to the approached firm	The particular firm response rate to the overall films
1.	Industrial machinery	86	29	33.72%	9.17%
2.	Pharmacy	77	35	45.45%	11.07%
3.	Material handling equipment	65	28	43.07%	8.86%
4.	Automobile ancillaries	84	17	20.23%	5.37%
5.	Air conditioning machines/systems	69	34	49.27%	10.75%
6.	Chemicals and petrochemicals	78	28	35.89%	8.86%
7.	Textiles	17	7	41.17%	2.21%
8.	Wiring harness and parts	23	11	47.82%	3.48%
9.	Rubber and rubber products	54	29	53.70%	9.17%
10.	Reservoirs, tanks and other fabrications	38	17	44.73%	5.37%
11.	Solar modules	32	14	43.75%	4.43%
12.	Construction machinery	41	16	39.02%	5.06%
13.	Ceramic products	63	23	36.50%	7.27%
14.	Polyester or contract resins	56	28	50%	8.86%
TOTAL		783	316		

Table 3: Profile of respondents

S.No.	Respondent designation	Total number	Percentage
1.	Operations manager	93	29.43%
2.	Plant manager	90	28.48%
3.	General manager	32	10.12%
4.	Vice president	21	6.64%
5.	Production planner	39	12.35%
6.	Functional manager	41	12.98%
	Experience		
1.	3-5 years	23	7.27%
2.	5-10 years	41	12.98%
3.	10-25 years	83	26.27%
4.	20-30 years	98	31.02%
5.	> 30 years	71	22.46%

Table 4: Representation of PLS-SEM results for items loadings, reliability, and validity

Constructs	**Item code**	**Outer loadings**	**CA**	**rho_A**	**CR**	**AVE**
Blockchain Technology (BCT)	BCT 1	0.824	0.839	0.841	0.892	0.674
	BCT 2	0.823				
	BCT 3	0.800				
	BCT 4	0.835				
Circular Economy (CE)	CE 1	0.825	0.879	0.882	0.912	0.674
	CE 2	0.806				
	CE 3	0.824				
	CE 4	0.829				
	CE 5	0.821				
Total Productive Maintenance (TPM)	TPM 1	0.830	0.896	0.902	0.923	0.707
	TPM 2	0.822				
	TPM 3	0.829				
	TPM 4	0.858				
	TPM 5	0.864				

Table 5: Measuring discriminant validity through HTMT criteria

	BCT	**CE**
CE	0.598	
TPM	0.581	0.520

Table 6: Inner VIF values

	CE	**TPM**
BCT	1.347	1.000
TPM	1.347	

Table 7: Results of the saturated model

Constructs	R^2	R^2 **Adjusted**	Q^2	**SRMR**
CE	0.324	0.319	0.213	0.055
TPM	0.258	0.255	0.177	

Table 8: Summary of algorithm and bootstrapping tests results

Hypothesis (Path)	**Coefficient (β)**	**T Statistics**	***p*-Value**	**Acceptance of hypothesis**
Direct effects				
H1: BCT→TPM	0.508	8.225	0.000	Yes
H2: BCT→CE	0.376	5.175	0.000	Yes
H3: TPM→CE	0.276	4.068	0.000	Yes
Mediating effects				
H4: BCT→TPM→CE	0.140	3.579	0.000	Yes