The current issue and full text archive of this journal is available on Emerald Insight at:
https://www.emerald.com/insight/1746-5664.htm

A hybrid framework to prioritize the performance metrics for Blockchain technology adoption in manufacturing industries

Journal of Modelling in Management

Shweta V. Matey and Dadarao N. Raut
Department of Production Engineering, Veermata Jijabai Technological Institute (VJTI), Mumbai, India

Rajesh B. Pansare
Mechanical Engineering Department, K. J. Somaiya College of Engineering Vidyavihar, Mumbai, India, and

Ravi Kant
Mechanical Engineering Department, Sardar Vallabhbhai National Institute of Technology (SVNIT), Surat, India

Received 22 February 2024
Revised 29 June 2024
Accepted 23 August 2024

Abstract

Purpose – Blockchain technology (BCT) can play a vital role in manufacturing industries by providing visibility and real-time transparency. With BCT adoption, manufacturers can achieve higher productivity, better quality, flexibility and cost-effectiveness. The current study aims to prioritize the performance metrics and ranking of enablers that may influence the adoption of BCT in manufacturing industries through a hybrid framework.

Design/methodology/approach – Through an extensive literature review, 4 major criteria with 26 enablers were identified. Pythagorean fuzzy analytical hierarchy process (AHP) method was used to compute the weights of the enablers and the Pythagorean fuzzy combined compromise solution (Co-Co-So) method was used to prioritize the 17-performance metrics. Sensitivity analysis was then carried out to check the robustness of the developed framework.

Findings – According to the results, data security enablers were the most significant among the major criteria, followed by technology-oriented enablers, sustainability and human resources and quality-related enablers. Further, the ranking of performance metrics shows that data hacking complaints per year, data storage capacity and number of advanced technologies available for BCT are the top three important performance metrics. Framework robustness was confirmed by sensitivity analysis.

Practical implications – The developed framework will contribute to understanding and simplifying the BCT implementation process in manufacturing industries to a significant level. Practitioners and managers may use the developed framework to facilitate BCT adoption and evaluate the performance of the manufacturing system.

Originality/value – This study can be considered as the first attempt to the best of the author's knowledge as no such hybrid framework combining enablers and performance indicators was developed earlier.

Keywords Blockchain technology, Enablers, Performance metrics, Pythagorean fuzzy AHP, Pythagorean fuzzy Co-Co-So method

Paper type Research paper

Journal of Modelling in Management
© Emerald Publishing Limited
1746-5664
DOI 10.1108/JM2-02-2024-0058

1. Introduction

The term Industry 4.0 refers to the fourth industrial revolution in production and manufacturing processes. It aims to include advanced digital technologies with physical systems to make things work more efficiently and fast. This includes machine-to-machine communication and, a higher production rate with minimum wastage. Blockchain, introduced by Nakamoto (2008), is a distributed ledger technology created to deal with cryptocurrencies. It has since been successfully implemented in the finance sector and reached new heights. But now its impact has reached beyond finance and its features like transparency and immutability provide data security. It is now attempting to expand into new markets such as health care, real estate, education, logistics and transportation and government sectors. Blockchain can support Industry 4.0 by generating a transparent record of production processes, developing a secure and transparent supply chain and solving quality issues (Mukherjee *et al.*, 2021; Espinoza Pérez *et al.*, 2022; Shah *et al.*, 2022). Also, it helps to manage the complex value chain (Wan *et al.*, 2020). Industry 4.0 introduced the concepts of cyber-physical systems, machine-to-machine (M2M) communication and the Internet of Things into the industries. M2M communication refers to the exchange of information between industrial components without any human intervention. Authors used blockchain to enable M2M interactions and create an M2M electricity market for the chemical industry. The author concludes that blockchain technology (BCT) has significant potential to support and improve the efficiency gains of this industrial revolution when thoroughly explored (Sikorski *et al.*, 2017). Supply chain 4.0 is the digitalization of supply chains, that focuses on the use of diverse technologies such as Blockchain, Artificial Intelligence (AI), Internet of Things (IoT), Big Data Analytics, Augmented Reality, Cloud Computing, Robotics and Additive Manufacturing, to generate goods and services. These technologies are the enablers of Industry 4.0. Blockchain plays a very important role in the digitization of the supply chain by providing traceability and transparency (Gharaibeh *et al.*, 2022). BCT has evolved as one of the most unique and disruptive technology innovations in the 21st century. BCT embraces a great potential for transforming operations across various industries, from finance to, supply chain management, health care and beyond (Marengo and Pagano, 2023). The authors explained, how Blockchain and IoT technologies together can improve the agility in Industry 4.0. By using smart contracts and the immutability of blockchain, automation of transactions and optimization of processes reduction in intermediaries can be achieved which ultimately leads to improvement in agility, cost reduction and quick decision-making. The authors also mentioned scalability and interoperability issues (Rane and Narvel, 2019). In an article, the authors focus on the credibility and security of data in collaborative manufacturing supply chains (CMSC). Which may improve the efficiency of association among stakeholders. It is required that the manufacturing data should be shared between enterprises and customers to avoid unfair production decisions or unresponsive production management by CMSC. The authors suggested a blockchain-driven framework that focuses on a cross-enterprise CMSC. The authors established a six-layered blockchain-based manufacturing data sharing system (BMDSS) framework with two data upload algorithms and two smart contracts. A demonstrative case was also studied to authenticate the effectiveness of the suggested framework (Zheng *et al.*, 2024). The authors highlighted applications of blockchain to product life cycle management (PLM) with a smart manufacturing background. The unique features in data storage and computing like traceability, data security and decentralized consensus make blockchain a suitable technology for smart manufacturing, particularly in PLM. Authors proposed a framework based on which they have explored the applications of blockchain in four stages of product life cycle viz, product design, manufacturing, usage and recycling (Chen *et al.*, 2022). It is a challenge for many small-medium enterprises (SMEs) to improve the transparency in the manufacturing supply chain. In the supply chain, keeping track of the cooperation process between distributed SMEs is an important basis for the understanding of supply chain transparency. The authors demonstrated a Blockchain-based and event-driven tracking (BET) three-layered framework that could guide SMEs to create a blockchain-based cooperation tracking platform as per their requirements. The author also presented a case study to validate the framework (Liu *et al.*, 2024). In a study, authors used the resource-based view (RBV) and contingency theories in their framework to evaluate the relationship between transparency of the supply chain, alignment, adaptability, agility and willingness to implement blockchain among SMEs. And observed that the ability of blockchain to improve supply chain transparency and agility influences the intentions of SMEs to adopt blockchain. The data were obtained from 204 SMEs in Malaysia's manufacturing sector and analysis was carried out with the partial least squares technique (Iranmanesh *et al.*, 2023). In Industry 4.0, blockchain can secure all product information, spare parts, raw materials, sub-assemblies, sales, etc. It lowers the cost and minimizes supply chain disruptions (Javaid *et al.*, 2021). Blockchain is a relatively new invention that takes various forms. It is a distributed ledger technology that records every transaction that occurs on the network, arranges it chronologically and updates the recorded information according to predefined rules. Data hacking is prevented by the distributed nature of BCT, resulting in transparency and trust (Aghamohammadzadeh and Fatahi Valilai, 2020). In the modern era of Industry 4.0 and the IoT, manual work in industries is being automated. Manufacturers must update their work and publish manuals for repair and maintenance that become easier with blockchain. Blockchain allows for the secret sharing and storage of data related to confidential weapon and ammunition designs because it provides clear transactions (Iqbal *et al.*, 2020). BCT integration in industry can ensure data confidentiality and integrity by providing robust and secure communication systems (Elmamy *et al.*, 2020).

BCT can help to build a sustainable supply chain by improving traceability and transparency while adhering to environmental standards. However, managers' lack of awareness of BCT's essential features has prevented its effective use in this field (Yousefi and Mohamadpour Tosarkani, 2022). Although BCT has been lauded, it is not widely adopted. Despite its numerous benefits, the adoption rate of BCT among organizations has not reached a high level globally, necessitating additional research in this area (Malik *et al.*, 2022). Significant work must be done on this platform before organizations will accept BCT adoption. Organizational executives must recognize the benefits of BCT for their business This paper proposes a novel framework for overcoming the aforementioned challenges and facilitating the adoption of BCT in manufacturing industries (Javaid *et al.*, 2021). Few studies focus on supplier selection, production decisions and distributor location using circular economy principles and focusing on sustainability and refurbished products. The author uses a goal programming approach to address the problems. The proposed model includes multiple objectives such as minimization of cost, minimization of carbon footprints and maximizing profit from refurbished products (Muneeb *et al.*, 2023).

BCT is still in its early stages, so the literature on it is limited. Adoption of BCT is accompanied by many challenges and problems, all of which make implementation difficult. Several frameworks have been developed to assist in successful implementation; however, selecting an appropriate framework is also a difficult task. Researchers discovered that incorporating BCT into the supply chain can improve the operational performance of a manufacturing unit. Features such as real-time information sharing, cyber-security, transparency and traceability improve performance; however, the lack of a defined framework limits BCT adoption (Shoaib *et al.*, 2020). There is a notable increase in blockchain research, but more emphasis is placed on technical aspects, while practical issues related to blockchain implementation in organizations are ignored (Janssen *et al.*, 2020). Secure sharing of information and verification is important, which requires reliable technologies that can trace Supply Chains (Saberi *et al.*, 2019). Despite the numerous benefits of BCT, its adoption is slow in the manufacturing sector. To ensure successful BCT adoption, it is important to identify the enablers that accelerate the adoption process. Enablers can be defined as the factors that promote the integration, acceptance and effective implementation of new technologies, systems or processes (Pansare *et al.*, 2022). Enablers help to overcome barriers, lower risks and improve the atmosphere for invention and modernization. They also provide a conducive environment and facilitate the required resources, infrastructure and favorable working conditions. Detailed study and understanding of these factors provide valuable information that can help the stakeholders to take advantage and maximize the latency of the innovative technologies. Enablers help in decision-making, tactics planning, risk management, allocation of resources, etc. Thus, the study of enablers is necessary to boost the speed of implementation of a new technology. Several researchers mentioned in their study that, most challenges arise due to ignoring the importance of BCT adoption enablers. These enablers are the essential characteristics of BCT that increase the rate of adoption in supply chains (Yousefi and Mohamadpour Tosarkani, 2022).

Today organizations are becoming knowledgeable, but the awareness about the numerous benefits of making the supply chains digital is not yet fully known. Getting the benefits of new technologies in supply chains is not possible without a suitable implementation process, which demands an exhaustive preadoption analysis, including enablers and barrier identification (Vafadarnikjoo *et al.*, 2023; Sharabati and Jreisat, 2024). The authors discussed that detecting the enablers and barriers to technology adoption is vital for the effective implementation of technology and the sustainability of the mining industry. Past studies on technology adoption have mainly focused on service sector organizations. However, there is a lack of research that specifically addresses the barriers and enablers of technology adoption in the mining industry (Ediriweera and Wiewiora, 2021). Despite various advantages offered by BCT, there is limited adoption of this technology in manufacturing organizations. Earlier studies on BCT adoption have focused mainly on different organizations and service sectors and the identification of enablers and barriers. However, limited literature exists focusing on a hybrid framework to prioritize the performance metrics for BCT adoption in manufacturing industries with new MCDM methods. Also, it is necessary to check the effectiveness of the adoption of selected enablers on the manufacturing system and the overall improvement in the system due to the same. Hence, the present work focuses on the identification of performance metrics and ranking them as per the significant impact they have on performance.

To conduct a technology performance analysis, both qualitative and quantitative performance indicators must be identified. These factors are called performance metrics (Lahane and Kant, 2021; Pansare *et al.*, 2022), and they can be used to evaluate and improve the performance of a new technology or a system. Furthermore, prioritizing them is important for a system's successful evaluation. To enable BCT adoption, a framework is required that can identify enablers and evaluate their relative weights, performance metrics and ranking. Hence, the current research article has the following objectives:

- To identify the enablers of BCT adoption in manufacturing industries and prioritize them based on their weight computation.
- Prioritization and ranking of the performance metrics of BCT adoption in manufacturing industries.

To achieve these objectives, a thorough literature review of BCT articles was conducted, and 26 enablers and 17 performance metrics were identified. The Pythagorean fuzzy-AHP method was used to compute enabler weights, followed by the Pythagorean Fuzzy combined compromised solution technique (Co-Co-So) method to prioritize performance metrics based on expert opinion. Hence, the current study contributes to the domain of BCT by developing a framework for enablers and performance metrics. This may facilitate the practitioners during BCT adoption in manufacturing industries and evaluation of the effectiveness of the same.

The current article is divided into six sections, including this one. Section 2 discusses the literature review, enablers and performance metrics of BCT, while Section 3 defines the existing study's research methodology, including the Pythagorean fuzzy AHP and Co-Co-So method, as well as the various steps taken (including Flow chart for steps in PF-AHP and PF-CoCoSo). Section 4 includes data collection from experts and data analysis using a case application, while Section 5 presents the results and discussion. Finally, Section 6 includes the conclusions, limitations and future scope.

2. Literature review

This section describes the literature review on BCT adoption in manufacturing industries, including enablers and performance metrics, as well as the MCDM technique used. The section below presents some of the findings from the literature review.

2.1 Retrieval and selection of literature

The Scopus database was used to identify the research articles, and 671 articles were retrieved using keywords like "Blockchain Technology" and "Manufacturing Industries". After further filtering, the articles were reduced to 307 peer-reviewed research and review articles written in English. articles published in peer-reviewed journals and reputed conferences were considered for this study. Several articles were excluded from the study due to their lack of relevance to the current subject matter. The first stage of exclusion involved screening the abstracts and conclusions of the research articles, while the second stage required reading the entire paper. All relevant articles were segregated and stored separately for future reference. Articles containing various frameworks and enablers were considered relevant for the study. These articles were further divided into three categories: articles based on BCT frameworks, enablers of BCT adoption and various MCDM techniques used. None of the articles discussed performance metrics and their ranking relative to enablers. Hence, the 17 quantitative performance metrics and 26 enablers identified in the research articles can be classified as general because they apply to BCT applications in a wide range of fields and manufacturing industries.

2.2 Blockchain technology and its enablers

BCT is a peer-to-peer network system that stores data in a distributed ledger. The network's nodes can communicate without the need for a central authority. Distributed ledgers can be of two types: decentralized, which grants equal rights to all users, and centralized, which grants special rights to specific users (Esmaeilian *et al.*, 2020).

BCT was developed to enhance trust through its distinct features such as data immutability, transparency, traceability and secure record keeping (Mendhurwar and Mishra, 2023). Blockchain is widely regarded as one of the most important inventions since the internet. A record cannot be changed or deleted from the system after it has been created and approved by the blockchain, which prevents fraudulent transactions. The author also mentioned the most prominent use cases for BCT, such as cryptocurrency, smart contracts, machine-to-machine communication and the IoT (Efanov and Roschin, 2018). BCT allows multiple users to verify, preserve and synchronize transaction details. Also, BCT has provided significant benefits to industries by enabling better and more secure services (Ali *et al.*, 2021). The Fourth Industrial Revolution (Industry 4.0) enables blockchain applications in manufacturing and operations management. BCT aspires to provide transparency, disintermediation and visibility (Lohmer and Lasch, 2020). Manufacturers find it difficult to implement sustainable practices in today's Industry 4.0 environments due to challenges such as globalization and outsourcing. Blockchain can overcome sustainability challenges (Ahmad *et al.*, 2021). While changing or introducing a new production BCT network allows for enterprise resource planning and helps to integrate internal processes. To improve the quality of manufactured products and respond quickly to customer demands, virtual enterprises are created and BCT can meet these requirements thanks to its decentralized structure and secure and authenticated network (Balon *et al.*, 2022).

In the current Industry 4.0 scenarios, data transfer from one system to another is required using cutting-edge technology such as IoT, AI and M2M communication. Security and privacy of data are major concerns in areas where cyber fraud is prevalent. It is necessary to implement a technology that ensures data security. BCT has unique features such as immutability and transparency that can ensure the security of information. A framework that facilitates the rapid adoption of BCT in manufacturing industries is required. This section describes the enablers identified during an extensive literature review. Table 1 contains a brief description of the identified enablers.

Data provenance indicates the tracking of information, whereas immutability means that the data is not altered. Several authors consider these factors to be important in ensuring data safety and privacy while also facilitating the adoption of BCT (Bodkhe *et al.*, 2020). In manufacturing, it can assist in keeping records of products and producers from the beginning to the end of the supply chain (Helo and Shamsuzzoha, 2020; Orji *et al.*, 2020). Traceability in BCT refers to information traceability. Knowing the real-time location of a product or raw material from its point of origin, can save time and increase productivity (Brandín and Abrishami, 2021). Francisco and Swanson (2018) describes prediction capability as a benefit dimension of BCT as it is the ability to predict future requirements such as market demand and fault predictions which, if addressed promptly, can result in cost and time savings. The author also discusses the significant impact of Blockchain's secure data storage and transaction mechanisms on reducing human errors, fraud in transaction processes, fighting corruption, manipulation in e-voting, etc. by increasing people's trust in the government at both the public and private levels (Ali *et al.*, 2021). BCT also emphasizes clear ownership. Blockchain can be thought of as a permanent distributed directory that records all transactions and ownership transfers. It offers customers proof of ownership through tokenization, making the transaction process transparent and secure (Javaid *et al.*, 2021; Lee *et al.*, 2019). Data virtualization is the process of collecting data from various sources and then presenting it in one form to a single virtual view to provide reliable and real-time information. This feature is very effective in cloud manufacturing, supply chains and various Industry 4.0 applications by the authors (Kaynak *et al.*, 2020; Mendhurwar and Mishra, 2023; Shah *et al.*, 2022). Operation performance refers to the efficiency of the system's various processes. Better operational performance can be achieved by incorporating features such as transaction transparency into various applications where BCT has been successfully implemented (Nabipour and Ülkü, 2021).

Energy tracking is possible in BCT because it improves the security and transparency of energy transactions and allows for new forms of energy management and trading (Gerardi *et al.*, 2023). Digital Twins, when combined with BCT and AI analytics, can reduce energy consumption by encouraging users to reduce their carbon footprints and tracking energy-related data from sensors and smart infrastructures. The author also explained how decentralized marketplaces can be used to monetize data by tokenizing data ownership, which reduces intermediaries' interference and promotes fair business practices. Tendering

Table 1. Enablers of BCT

Major criteria enablers	Sub-criteria enablers	Description	References
Data security enablers (DSE)	Data provenance and immutability (DSE1)	Data provenance is the traceability of data from creation to use, while immutability is the ability of data to remain unchanged	Bodkhe *et al.* (2020); Orji *et al.* (2020); Helo and Hao (2019)
	Traceability (DSE2)	Ability to trace the movement of data or information	Brandín and Abrishami (2021); Francisco and Swanson (2018), Yang *et al.* (2020)
	Prediction capabilities (DSE3)	Blockchain system's capacity to make predictions about future events	Ali *et al.* (2021)
	Clear ownership (DSE4)	Transparent ownership records are provided by blockchain	Javaid *et al.* (2021); Lee *et al.* (2019
	Secure storage and transaction (DSE5)	Blockchain is a decentralized and distributed ledger that enables secure storage and transactions	Ali *et al.* (2021)
	Data virtualization (DSE6)	Data virtualization is the process of extracting data from various sources and presenting it in a unified, virtualized format	Mendhurwar and Mishra (2023); Shah *et al.* (2022); Kaynak *et al.* (2020)
	Operations performance (DSE7)	The efficiency and speed with which various processes within a blockchain system are executed is referred to as operation performance. Eg., a secure transaction, greater visibility, faster response time, etc	Nabipour and Ülkü (2021)
Quality-related enablers (QRE)	Prediction and preventive maintenance (QRE1)	BCT can assist in identifying equipment failures by securely storing data about equipment performance	Lallas *et al.* (2019)
	Quality assurance activities (QRE2)	It involves testing a variety of mechanisms and components, including transactions and data storage	Khanfar *et al.* (2021)
	Transaction transparency (QRE3)	Because of its decentralized nature, blockchain can record transactions throughout the network	Ko *et al.* (2018), Javaid *et al.* (2021)
	Customer satisfaction (QRE4)	Customer satisfaction is ensuring data security, traceability and transparency in transactions	Choi *et al.* (2020)
	Reliability (QRE5)	Blockchain provides tamperproof records that can improve reliability	Karamchandani *et al.* (2021)

(*continued*)

Table 1. Continued

Major criteria enablers	Sub-criteria enablers	Description	References
	Real-time capability (QRE6)	Capability to process transactions quickly and safely and automated record keeping	Mendhurwar and Mishra (2023); Shah *et al.* (2022)
	Timeliness (QRE7)	Timeliness relates to the system's capacity to provide accurate and real-time data throughout the process	Du *et al.* (2021); Karamchandani *et al.* (2021)
Sustainability and HR enablers (SHR)	Energy tracking (SHR1)	To manage energy consumption across the facilities data effectively and effectively to optimize energy usage	Gerardi *et al.* (2023), Teisserenc (2021)
	Sustainability practices (SHR2)	Blockchain provides a trustworthy, transparent, traceable and secure system that promotes sustainability practices	Saberi *et al.* (2019); Fu *et al.* (2018), Guo *et al.* (2023)
	Decentralized marketplace (SHR3)	This reduces dependency on intermediaries, reduces transaction costs and supports fair and sustainable business practices	Teisserenc (2021)
	Employee expertise and training (SHR4)	Skilled employees contribute to the improvement of efficiency and productivity	Sahebi *et al.* (2020)
	Disintermediation (SHR5)	It means the reduction or removal of middlemen that can ultimately result in cost savings and improve operational efficiency	Lohmer and Lasch (2020); Saberi *et al.* (2019); Zhu *et al.* (2022
	Supportive government policies (SHR6)	Government policies can help to encourage the adoption of BCT	Zhou *et al.* (2020); Nath *et al.* (2022)
Technology-oriented enablers (TOE)	Smart contracts (TOE1)	A smart contract is a self-executing agreement between the parties that helps to enhance security and transparency	Zafar *et al.* (2021); Orji *et al.* (2020)
	Advanced communication technology (TOE2)	In modern manufacturing, machine-to-machine communication can be achieved using servers, connecting cables, sensors, etc	O. Jimoh *et al.* (2019); Xie *et al.* (2019)
	Technological maturity (TOE3)	It represents the extent to which the technology has been used since its initial application. Mature technology ensures increased stability and reliability, making BCT more adaptable	Choi *et al.* (2020); Huang *et al.* (2022)

(*continued*)

Table 1. Continued

Major criteria enablers	Sub-criteria enablers	Description	References
	Interoperability (TOE4)	It allows blockchain networks to communicate in terms of data and values with other networks	Ghode *et al.* (2020); Espinoza Pérez *et al.* (2022)
	Service-oriented architecture (TOE5)	Service-oriented architecture allows applications to communicate and exchange data through loosely coupled and reusable services	Mendhurwar and Mishra (2023)
	Product customization (TOE6)	It refers to the capacity to use blockchain-based solutions to customize and personalize goods and services	Dutta *et al.* (2020); Lupi *et al.* (2023)

Source: Authors' own creation

and payment processes can be automated using Blockchain smart contracts. BCT improves trust, payment practices and the ability to trade digitized assets on decentralized marketplaces (Teisserenc, 2021).

Blockchain-enabled Emission Trading Schemes (ETS) and an innovative "emission link" system in the fashion apparel manufacturing industry can reduce carbon emissions for all stages of cloth production by exposing them to the public and adding emission-reducing features (B. Fu *et al.*, 2018). In a case study based on the fashion industry, the author compared traditional fashion supply chains (without blockchain support) to blockchain-supported supply chains and discovered that better information transparency and traceability of raw materials and sustainable products in the latter case helps to improve sustainability practices while also motivating customers to buy sustainable products (Guo *et al.*, 2023). The author observed four major abilities of blockchain that support sustainability:

(1) tracking ability reduces product rework;

(2) helps to trace the actual footprints of products;

(3) Enables recycling; and

(4) Reduces fraud and improves the efficiency of trading schemes (Saberi *et al.*, 2019).

The authors Sahebi *et al.* (2020) combined fuzzy Delphi and the Best Worst Method to identify nine barriers and calculate their weights. Furthermore, one of the most significant barriers to BCT adoption has been identified as a lack of knowledge/employee training. Skilled employees can increase profits for the industry and aid in the successful implementation of BCT. Disintermediation is regarded as one of the most promising aspects of Blockchain. It facilitates peer-to-peer trading of services and goods, minimizing the interference of third parties or middlemen, thus reducing transaction costs and time, as well as business waste reductions in supply chains (Lohmer and Lasch, 2020, Saberi *et al.*, 2019). For the successful implementation of BCT, the government should provide regulatory support, a legal framework and governance guidelines. Government support, initiatives and policies are key factors for the rapid adoption of BCT (Nath *et al.*, 2022; Zhou *et al.*, 2020).

Lallas *et al.* (2019) proposed a blockchain-supported cloud framework for real-time machine condition monitoring (MCM) and fault prediction (preventive maintenance), where computationally demanding tasks exist, as BCT has emerged as the most trusted technology for safely processing data. BCT allows customers to inspect the quality of products and promotes quality assurance practices. It also improves the performance of other techniques in fault prediction, diagnosis and decision-making (Khanfar *et al.*, 2021). BCT is based on distributed ledger technology and operates on an open peer-to-peer network. It promotes transparency and was initially used in the finance industry to replace manual transaction authentications. BCT improves traceability, data immutability and security, thereby ensuring transaction transparency (Javaid *et al.*, 2021; Ko *et al.*, 2018). BCT can improve supply chain efficiency and customer satisfaction by providing high-quality products (Choi *et al.*, 2020). The authors discussed the benefits of BCT, which can improve product quality, information quality and delivery reliability, resulting in profitability for the organization (Karamchandani *et al.*, 2021). BCT improves reliability due to its unique features such as immutability, disintermediation and data provenance (Ghode *et al.*, 2020). Real-time capability refers to a data processing system that includes hardware and software to collect and analyze data and perform real-time functions at a specific time. BCT can help achieve real-time capability (Mendhurwar and Mishra, 2023; Shah *et al.*, 2022). Du *et al.* (2021) discussed the use of smart contracts in smart grids to reduce processing time, and errors and improve reliability and timeliness through a traceability system. BCT properties such as data immutability, time stamping and distributed records can provide dependable services and timeliness (Karamchandani *et al.*, 2021).

Smart contracts are BCT features that can be programmed on the public platform. It has control over digital assets and authority to formulate customers' rights, which simplifies the process and reduces third-party costs (Orji *et al.*, 2020). Zafar *et al.* (2021) presented a case study from Nigeria and explained the importance of BCT adoption in developing countries. The authors observed that advanced information and communication technology plays an important role in increasing BCT awareness (Jimoh *et al.*, 2019). In the implementation of smart cities, information and communication technology is extremely important. The integration of BCT and communication technology can help to promote the development of smart cities (Xie *et al.*, 2019). Technological maturity is the extent to which a technology has been used since its initial application. Choi *et al.* (2020) explain that complex technology faces resistance during implementation and suggest that advances in technological maturity can reduce resistance to the adoption of new technologies. Technological maturity is important in BCT implementation in circular supply chain management (CSCM), and it includes evolving technologies, technical flexibility infrastructure, etc. (Huang *et al.*, 2022).

Interoperability refers to a system or software's ability to exchange and use information. BCT improves data interoperability. Thus, companies can easily share information with vendors, suppliers and manufacturers (Ghode *et al.*, 2020). In their study, the author discusses integrating various devices from different manufacturers on the shop floor to allow for communication and information exchange between them. Blockchain assists in recording this information in a ledger that is accessible to other users in the network, of course, by developing new appropriate protocols (Espinoza Pérez *et al.*, 2022). With the increased use of technologies such as IoT in manufacturing and Industry 4.0, large data transactions and exchanges are taking place, resulting in a service composition problem.

The author introduced a Blockchain-based service composition model (Block-SC) based on the service orientation approach (SOA). SOA has the potential to break down the software system into smaller, interoperable services (Aghamohammadzadeh and Fatahi Valilai, 2020). According to one study, blockchain can improve mass customization while also increasing organizational profitability. BCT transforms the manufacturing environment through distributed systems and facilitates the incorporation of agile manufacturing practices, resulting in product customization (Dutta *et al.*, 2020). Decentralized systems like BCT allow producers to exercise control over demand selection, which eventually results in resource customization and specialization (Lupi *et al.*, 2023).

2.3 Blockchain technology performance metrics

Performance metrics are used to measure the performance of a system or technology. Performance metrics are measures that quantify the productivity, efficiency, current status and success of an existing or emerging process or system (Pansare and Yadav, 2022). Customer complaint rate can be used as a perforce metric for BCT adoption in the manufacturing industry. BCT can improve product quality, and supplier performance and promote quality assurance practices, resulting in fewer customer complaints. Khanfar *et al.* (2021) identified an increase in data hacking cases in the health-care sector, suggesting that implementing BCT-based health-care models can reduce data hacking complaints (Jain *et al.*, 2020). Data storage capacity is also an important metric in terms of BCT adoption, as large amounts of data are collected and stored in each node regularly, necessitating more storage space (Tan *et al.*, 2020). BCT's distributed network effectively addresses issues such as server breakdown, cyber-attacks on a centralized server and network failure. An attack on a single server does not affect the network's other connected servers. Thus, the number of breakdowns is an important metric for evaluating BCT performance (Jimoh *et al.*, 2019). Lead time can be reduced by using BCT's robust traceability system and real-time data sharing, which allows for inventory optimization and effective resource utilization (Ada *et al.*, 2021; Aslam *et al.*, 2021). BCT can improve productivity by scheduling production and managing human resources. BCT can also be used to track the product's life cycle, from raw materials to finished product (Balon *et al.*, 2022).

Energy utilization can be monitored by distributed energy systems, which enable transparency, lower operation costs and tamperproof systems (Gerardi *et al.*, 2023; Wang and Su, 2020). By removing intermediaries from the system, transaction costs can be reduced and manufacturing firms can use BCT to create new network platforms (Ko *et al.*, 2018). Distributed ledger technology (DLT), such as blockchain, builds trust among network users by providing transparency, resulting in lower transaction costs (Roeck *et al.*, 2020). Kaushal *et al.* (2021) observed slow transaction speeds in blockchain networks and proposed improving the consensus algorithm and proof of work mechanism to improve them.

Staff training is viewed as an important success factor in BCT adoption. Mubarik *et al.* (2020) and Zhou *et al.* (2020) suggested that local governments design and organize training programs to meet the technical skill requirements for advanced emerging technologies. Direct communication among participants reduces transaction costs, time and business waste. BCT helps to reduce pollution and waste, and the traceability of data related to utilization and resources assists manufacturers in reducing production waste (Khanfar *et al.*, 2021; Saberi *et al.*, 2019). BCT assists in tracking the information of each component from its manufacturer and supplier, as well as in the maintenance, repair and overhaul of the parts or components (Asuncion *et al.*, 2021). The combined use of BCT and Artificial Intelligence, Internet of Things, Radio Frequency Identification (RFID) and Near-Field Communication (NFC) can help increase traceability in the food supply chain (Kamilaris *et al.*, 2019). BCT quickly identifies defective products, locates the source and removes the affected products, saving money and time in recalling the entire production line (Kshetri, 2018). According to Yang *et al.* (2019), micro-enterprises can use BCT to expand their market, provide quality services to customers and increase sales. Better service quality can help Micro and small enterprises (MSEs) increase sales. BCT's transparency and security features result in a flexible production system and a wide range of products that can be manufactured (Shoaib *et al.*, 2020). BCT has the potential to reduce labor costs while increasing an organization's profits. A brief description of the 17 identified performance metrics is given in Table 2.

3. Research methodology

The current section discusses the research journey. Initially, the research articles were retrieved from the Scopus database, and the hybrid Pythagorean fuzzy AHP - Co-Co-So technique was presented to the expert panel for feedback. The Pythagorean fuzzy AHP was used to calculate the major and sub-criteria weights, and the performance metrics were ranked using the Co-Co-So approach. Finally, a sensitivity analysis was performed, and a list of the study's implications was presented. The sensitivity study was designed to assess the robustness of the developed framework. The research methodology is depicted in Figure 1.

4. Case analysis

4.1 Data collection

The primary goal of this research was to create a framework to help practitioners and researchers identify BCT adoption enablers in manufacturing industries. Representatives from 15 different manufacturing companies were contacted, and the idea was thoroughly explained to them. Eleven representatives agreed to participate in the process, with nine from the industry and two from academia. However, because BCT implementation is still in its early stages, selecting representatives from various departments such as production, machining automation and manufacturing was difficult.

Following a lengthy discussion with the experts, it was decided to form an expert panel made up of eleven members from various industries to ensure the successful implementation of the proposed framework development procedure. Each expert was highly qualified and experienced in their field (see Appendix 3). The Academics are university professors and hold Ph.D. with research experience in the field of supply chain and manufacturing. Whereas the industry experts are in leadership positions and participate in the project work associated with manufacturing, and supply chain with blockchain. Following several discussions with the expert panel, experts were tasked with creating a pairwise comparison of major and sub-criteria practices. Experts were also consulted for the first pairwise comparison of the Co-Co-So technique. The weight computation and prioritization process was completed, the results were presented to the expert panel for discussion, and minor changes were made based on the panel's recommendations.

4.2 Development of framework

The expert panel advised categorizing the factors into four major criteria, as shown in Figure 1. The proposed framework includes four levels: Level 1 represents the built framework's objective, which is to investigate the impact of various factors on BCT adoption in manufacturing industries. Level 2 consists of four major criteria:

(1) Data security enablers.

(2) Quality-related enablers.

(3) Enablers related to sustainability and human resources, as well as

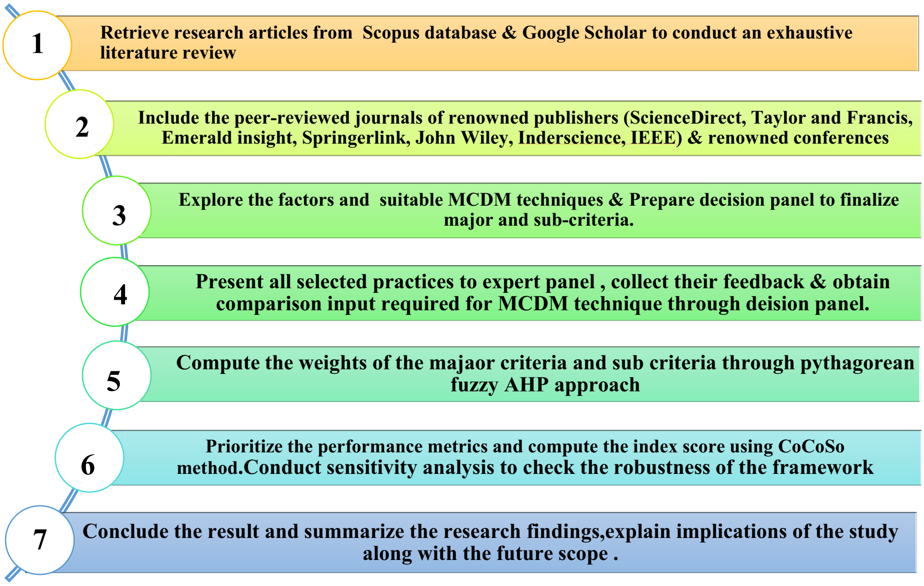
(4) Enablers focused on technology.

Level 2 outlines the major criteria, with a focus on organizing the selected enablers according to the expert panel's recommendations. Each major criterion denotes a specific area of

Table 2. Performance metrics of BCT

Code	Performance metrics	Description	References
PM1	Customer complaint rate	This metric is useful to measure customer satisfaction and its effect on the technology implementation	Khanfar *et al.* (2021)
PM2	Data hacking complaints per year	Monitoring of data hacking complaints is essential to check the reliability of the system	Jain *et al.* (2020)
PM3	Data storage capacity in systems	A large amount of data is to be handled and stored in the systems with an increase in the size of the blockchain	Tan *et al.* (2020)
PM4	Number of breakdowns per month	The breakdown is a failure in the functioning of a system or a process and can be considered an important metric to assess performance	O. Jimoh *et al.* (2019)
PM5	Lead time	It represents the time required from the start of a process to the completion of the product. In BCT adoption in manufacturing it is associated with the supplier's lead time	Ada *et al.* (2021); Aslam *et al.* (2021)
PM6	Productivity	Productivity is the measure of the efficiency of the process or a system. Productivity can be improved with good traceability and traceability of the supply chain	Balon *et al.* (2022)
PM7	Energy utilization rate	It is an important metric as energy savings and sustainability are the major considerations in manufacturing industries	Wang and Su (2020)
PM8	Transaction cost	It represents the network cost, data mining cost, data storage cost, administrative cost and overhead costs in carrying out the transaction	Roeck *et al.* (2020); Ko *et al.* (2018)
PM9	Transaction speed	It is the measure of number of transactions processed by a blockchain network in a given time. It is represented as transaction per second	Kaushal *et al.* (2021)
PM10	Number of training sessions conducted for employees	It indicates education to the employees through training sessions which may include basics of BCT, simulation workshops, information about smart contracts and consensus algorithms	Mubarik *et al.* (2020); Zhou *et al.* (2020)
PM11	Waste reduction	BCT can keep records of waste generation and waste disposal supporting recycling and remanufacturing. Leading to waste reduction	Khanfar *et al.* (2021); Saberi *et al.* (2019
PM12	Equipment repairs and maintenance	It represents the condition and the movement of the equipment that can be tracked efficiently by using BCT features	Asuncion *et al.* (2021)
PM13	Number of advanced technologies available for BCT	Smart contracts, consensus algorithms, hybrid blockchains and integration of advanced technologies like AI, and IoT with BCT can improve the efficiency of the system	Kamilaris *et al.* (2019)
PM14	Percentage of defective products	It is the measure of the quality of the products produced by the manufacturing process	Kshetri (2018)
PM15	Sales growth	It is a measure of an increase in revenue generation and growth of business	M. H. Yang *et al.* (2019)
PM16	Number of products being manufactured	This metric indicates the variety of products that can be manufactured and the flexibility of the production system	Shoaib *et al.* (2020)
PM17	Total manpower required	BCT implementation helps in reducing human intervention and manpower can be used for other productive tasks that make the system more productive	Y. Fu and Zhu (2019)

Source: Authors' own creation



Source: Authors' own creation

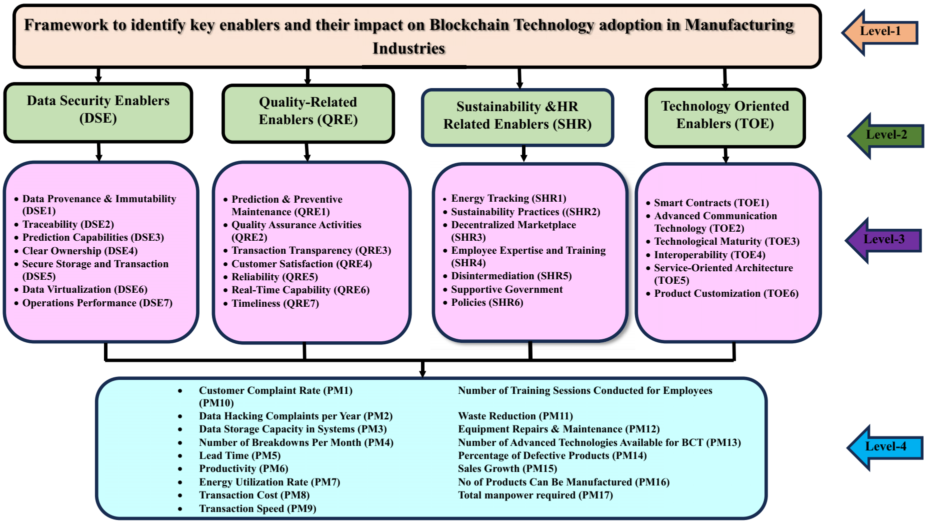
Figure 1. Research methodology

application. This can aid researchers in implementing their preferred practices. Level 3 displays the sub-criteria for each major criterion. This level is one of the most important in the framework because it includes several factors that can help with the successful implementation of BCT in the manufacturing industry. Level 4 includes performance matrices that can assist researchers and practitioners in determining what improvements are required and how effective the enables are in comparison to the corresponding major criteria. This can help practitioners identify areas for improvement and assess the effectiveness of adopted practices in the actual system. The framework depicted in Figure 2 shows how it can be gradually implemented within the company and evaluated using a set of performance metrics.

4.3 Analysis of framework

The hybrid Pythagorean fuzzy AHP-Co-Co-So method was used to calculate the weights of selected BCT enablers and rank performance metrics. The entire process is discussed in detail below.

4.3.1 Application of pythagorean fuzzy analytical hierarchy process technique. The AHP process is inaccurate and inconsistent in ranking (Pansare and Yadav, 2022). Pythagorean fuzzy sets can handle uncertainty and vagueness in expert-provided data, whereas intuitionistic fuzzy sets cannot. In Pythagorean fuzzy sets, the sum of membership and non-membership degrees can be greater than one, but the sum of their squares cannot be. Pythagorean fuzzy sets allow decision-makers to express their views on the problem's vagueness and impreciseness (Shete *et al.*, 2020). The following section explains the steps involved in the Pythagorean fuzzy AHP Technique (Lahane and Kant, 2021).



Source: Authors' own creation

Figure 2. Framework to identify key factors and their impact on BCT in manufacturing industries

4.3.2 Procedure of pythagorean fuzzy analytical hierarchy process technique

Step 1: Form a pairwise comparison matrix $A = (a_{ik})_{m \times n}$ with reference to the responses taken from the expert panel with the help of linguistic variables provided in Appendix 1. The sample pairwise comparison matrix prepared is shown in Table 3.

Step 2: Calculate the differences matrix $D = (d_{ik})_{m \times n}$ between lower and upper values of the membership and non-membership functions:

$$d_{ik_L} = \mu^2_{ik_L} - \vartheta^2_{ik_U} \tag{1}$$

$$d_{ik_U} = \mu^2_{ik_U} - \vartheta^2_{ik_L} \tag{2}$$

Table 3. Sample pairwise comparison matrix for data security enablers

Criteria	DSE1	DSE2	DSE3	DSE4	DSE5	DSE6	DSE7
DSE1	EE	AAI	AAI	BAI	AAI	AAI	AAI
DSE2	AAI	EE	AAI	BAI	AI	AAI	AAI
DSE3	BAI	BAI	EE	BAI	BAI	BAI	AAI
DSE4	AAI	AAI	BAI	EE	AAI	BAI	BAI
DSE5	AAI	CHI	AI	AAI	EE	BAI	LI
DSE6	BAI	AI	AAI	BAI	BAI	EE	AAI
DSE7	AAI	AI	AAI	BAI	LI	BAI	EE

Source: Authors' own creation

Step 3: Calculate the Interval multiplicative matrix S = $(s_{ik})_{m \times n}$

$$s_{ik_L} = \sqrt{1000^{dik_L}} \tag{3}$$

$$s_{ik_U} = \sqrt{1000^{d_{ikU}}} \tag{4}$$

Step 4: Compute determinacy value $\tau = (\tau_{ik})_{m \times n}$ of the a_{ik} using equation (5):

$$\tau_{ik} = 1 - \left(\mu^2_{ik_U} - \mu^2_{ik_L}\right) - \left(\vartheta^2_{ik_U} - \vartheta^2_{ik_L}\right) \tag{5}$$

Step 5: Compute the matrix of weights T = $(t_{ik})_{m \times m}$ before normalization by multiplying the determinacy degrees with S = $(s_{ik})_{m \times m}$ matrix:

$$t_{ik} = \left(\frac{s_{ik_L} + s_{ik_U}}{2}\right)\tau_{ik} \tag{6}$$

Step 6: Evaluate the normalized priority weight, w_i:

$$w_i = \frac{\sum_{k=1}^{m} t_{ik}}{\sum_{i=1}^{m}\sum_{k=1}^{m} t_{ik}} \tag{7}$$

Hence, the obtained global weights are shown in Table 4.

4.3.3 Application of pythagorean fuzzy Co-Co-So technique. Pythagorean fuzzy Co-Co-So approach is an innovative and effective approach to deal with MCDM problems. It was first introduced by (Yazdani *et al.*, 2019). This method is a combination of two models: exponentially weighted product (EWP) and simple additive weighting (SAW) model (Pansare and Yadav, 2022). Integration of Pythagorean fuzzy sets helps to efficiently deal with uncertainty issues and provide the best alternative (Lahane and Kant, 2021). The Pythagorean fuzzy Co-Co-So steps are as follows (Lahane and Kant, 2021).

Step 1: Frame the decision matrix D = $(D_{ij})_{m \times n}$ (i = 1, 2 … m; j = 1, 2 … n) with the help of expert's opinion by assigning the linguistic scale of Pythagorean fuzzy Co-Co-So is given in Appendix 2. The sample pairwise comparison for selected performance matrix is shown in Appendix 4.

Step 2: Convert the linguistic decision matrix into the Pythagorean fuzzy decision matrix:

$$P = (P_{ij})_{m \times n}\ (i = 1, 2 \ldots m;\ j = 1, 2 \ldots n) \tag{8}$$

Step 3: Calculate the score function R = $(r_{ij})_{mxn}$ of each Pythagorean fuzzy number (PFN) p_{ij} = (μ_{ij}, v_{ij}):

$$r_{ij} = \mu^2_{ij} - \nu^2_{ij} - \ln(1 + \pi^2_{ij}) \tag{9}$$

Step 4: Convert the score function matrix R = $(r_{ij})_{mxn}$ into an orthonormal Pythagorean fuzzy matrix R = $(r_{ij})_{mxn}$:

$$\begin{cases} \dfrac{r_{ij} - r_j^-}{r_j^+ - r_j^-}, \ if\ j \in B \\ \dfrac{r_j^+ - r_{ij}}{r_j^+ - r_j^-}, \ if\ j \in C \end{cases} \tag{10}$$

where, r_j^- = mini r_{ij}, and r_j^+ = maxi r_{ij}

Table 4. Global weights of major and Sub-criteria enablers

Major criteria	Major criteria weights	Sub-criteria	Sub-criteria local weights	Global weights
Data security enablers (DSE)	0.3881	Data Provenance and Immutability (DSE1)	0.2083	0.0808
		Traceability (DSE2)	0.1525	0.0592
		Prediction Capabilities (DSE3)	0.0760	0.0295
		Clear Ownership (DSE4)	0.1120	0.0435
		Secure Storage and Transaction (DSE5)	0.2578	0.1000
		Data Virtualization (DSE6)	0.1044	0.0405
		Operations Performance (DSE7)	0.0891	0.0346
Quality-related enablers (QRE)	0.1441	Prediction And Preventive Maintenance (QRE1)	0.1159	0.0164
		Quality Assurance Activities (QRE2)	0.2954	0.0417
		Transaction Transparency (QRE3)	0.1305	0.0184
		Customer Satisfaction (QRE4)	0.1066	0.0150
		Reliability (QRE5)	0.1843	0.0260
		Real-Time Capability (QRE6)	0.1005	0.0142
		Timeliness (QRE7)	0.0668	0.0094
Sustainability & HR related enablers (SHR)	0.1848	Energy Tracking (SHR1)	0.2612	0.0483
		Sustainability Practices (SHR2)	0.2272	0.0420
		Decentralized Marketplace (SHR3)	0.1285	0.0238
		Employee Expertise and Training (SHR4)	0.1145	0.0212
		Disintermediation (SHR5)	0.0913	0.0169
		Supportive Government Policies (SHR6)	0.1772	0.0327
Technology oriented enablers (TOE)	0.2860	Smart Contracts (TOE1)	0.2333	0.0667
		Advanced Communication Technology (TOE2)	0.1340	0.0383
		Technological Maturity (TOE3)	0.2875	0.0822
		Interoperability (TOE4)	0.1568	0.0449
		Service Oriented Architecture (TOE5)	0.1086	0.0311
		Product Customization (TOE6)	0.0797	0.0228

Source: Authors' own creation

Step 5: Calculate the total of the weighted comparability sequence for each alternative:

$$s_i = \sum_{j=1}^{n} w_j * r'_{\mathrm{ij}} \tag{11}$$

Step 6: Calculate the whole of the power weight of comparability sequences for each alternative:

$$Pi = \sum_{j=1}^{n} \left(r'_{\mathrm{ij}}\right)^{w_j} \tag{12}$$

Step 7: Determine the relative weight of the alternatives using aggregation score strategies:

$$K_{ia} = \frac{P_i + S_i}{\Sigma_{\mathrm{i}=1}^{m}(P_i + S_i)} \tag{13}$$

$$K_{ib} = \frac{S_i}{\min_i S_i} + \frac{P_i}{\min_i P_i} \tag{14}$$

$$K_{ic} = \frac{\lambda S_i + (1-\lambda)P_i}{\lambda \max_i S_i + (1-\lambda) \max_i P_i} 0 \leq \lambda \leq 1, \quad (15)$$

where,

- K_{ia} = Arithmetic mean of sums of weighted sum method (WSM) and weighted product model (WPM) scores.
- K_{ib} = Denote a sum of relative scores of WSM and WPM compared to the best.
- K_{ic} = Balanced compromise of WSM and WPM model scores.

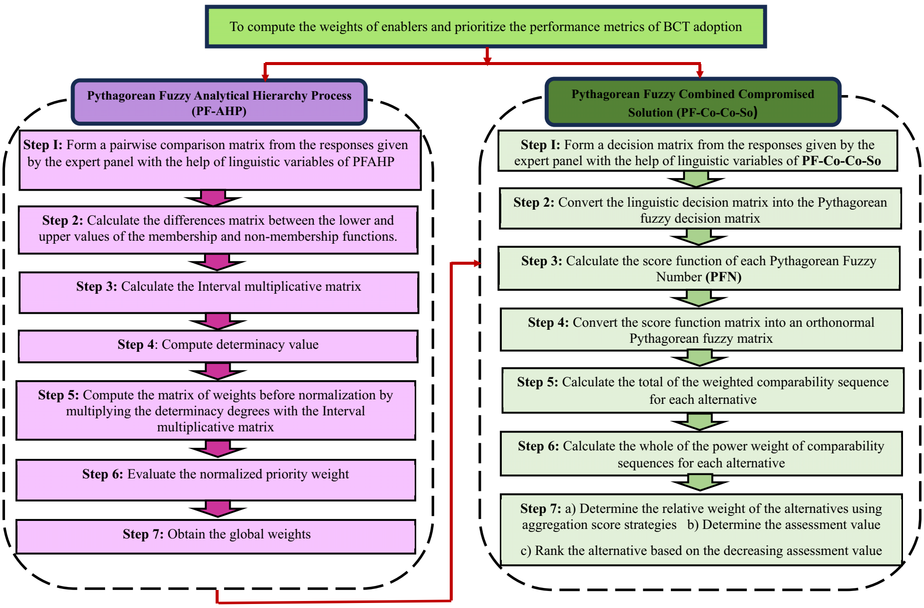
Step 8: Determine the assessment value K_i:

$$K_i = \sqrt[3]{K_{ia}K_{ib}K_{ic}} + \frac{K_{ia} + K_{ib} + K_{ic}}{3} \quad (16)$$

Step 9: Rank the alternative based on the decreasing value of K_i (i = 1, 2… m)

The steps to be followed during Pythagorean fuzzy AHP and Pythagorean fuzzy Co-Co-So method are described in Section 4.3.2 and 4.3.3 respectively. These steps are also represented using a flowchart in Figure 3. These steps are followed to obtain the ranking of the selected performance metrics as shown in Table 5.

4.3.4 Sensitivity analysis It is essential to check the behavior of the framework under variable conditions (Lahane and Kant, 2021). Hence, a sensitivity analysis is performed to ensure that the framework is robust. The ranking is accomplished by varying the weights



Source: Authors' own creation

Figure 3. Flow chart for steps in PF AHP and PF Co-Co-So

Table 5. Ranking obtained using pythagorean fuzzy Co-Co-So method

Code	Performance metrics	K_{ia}	K_{ib}	K_{ic}	K_i	Rank
PM1	Customer complaint rate	0.0214	2.0000	0.3175	1.0183	17
PM2	Data hacking complaints per Year	0.0674	19.3652	1.0000	7.9039	1
PM3	Data storage capacity in systems	0.0673	18.9540	0.9981	7.7570	2
PM4	Number of breakdowns per Month	0.0621	11.0519	0.9206	4.8695	11
PM5	Lead time	0.0592	9.6588	0.8775	4.3263	12
PM6	Productivity	0.0534	7.3535	0.7924	3.4108	15
PM7	Energy utilization rate	0.0642	16.7253	0.9528	6.9219	5
PM8	Transaction cost	0.0628	12.5790	0.9321	5.4278	9
PM9	Transaction speed	0.0664	16.3735	0.9850	6.8314	4
PM10	Number of training sessions conducted for employees	0.0550	7.3192	0.8161	3.4203	14
PM11	Waste reduction	0.0658	14.4049	0.9766	6.1239	7
PM12	Equipment repairs and maintenance	0.0659	14.4930	0.9767	6.1553	6
PM13	Number of advanced technologies available for BCT	0.0666	17.0956	0.9884	7.0906	3
PM14	Percentage of defective products	0.0310	4.2072	0.4591	1.9568	16
PM15	Sales growth	0.0656	13.7806	0.9728	5.8977	8
PM16	Number of products can be manufactured	0.0612	9.1364	0.9080	4.1664	13
PM17	Total manpower required	0.0646	11.2313	0.9584	4.9708	10

Source: Authors' own creation

from 2% to 25% and 17 trials were conducted. Figure 4 shows that there are no significant changes in the ranking of performance metrics.

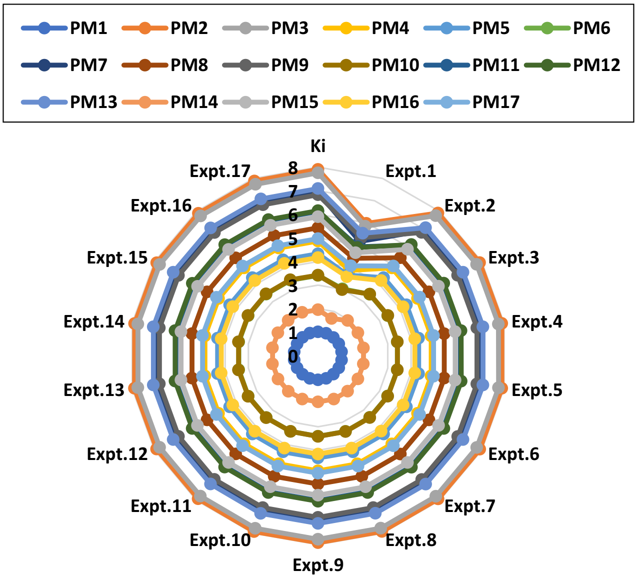
Table 5 shows that the ranking was determined based on K_i values; thus, the weights were varied as previously discussed, and the variation in K_i values and ranking was observed, as shown in Figure 4. Figure 4 shows that there are very few intersecting lines observed during the experiments, implying that there are no significant changes in the ranking of performance metrics. This demonstrates that variations in enabler weights have little impact on the ranking. As a result, the obtained rankings are robust.

5. Results and discussion

The current section discusses the findings of the study and its implications in detail.

5.1 Study findings

The current study seeks to prioritize performance metrics for BCT adoption in manufacturing industries. Several researchers in this field have also attempted to develop frameworks for a variety of applications. This includes the framework developed by Patel *et al.* (2024), whose authors attempted to develop a framework for integrating BCT and artificial intelligence in manufacturing organizations. Furthermore, Zheng *et al.* (2024) proposed a framework for data sharing in manufacturing organizations to support collaborative supply chains. Such enablers made significant contributions to the study's selected domain and attempted to improve BCT adoption and performance in manufacturing organizations. However, unlike the current study, none of the previous studies attempted to identify the enablers of BCT at a glance or provide performance metrics for the same. In addition, the literature did not include the computation of the relative significance of the selected enablers or the prioritization of performance metrics. As a result, the focus of this article is on developing a framework that can help practitioners adopt BCT and evaluate its performance. The developed framework is



Source: Authors' own creation

Figure 4. Sensitivity analysis of Ki values

unique in that it may assist in preparing systematic BCT adoption plans as well as evaluating the effectiveness of the same. The obtained results are discussed below.

Among the major criteria enablers, DSE received the highest weight, indicating that DSE enablers are extremely important and beneficial to BCT implementation. In a study on blockchain enablers, Valle and Oliver (2020) mention BCT as a sustainable innovation rather than a disruptive technology. The authors identify five enablers, with the first, "Access enabler," focusing on identity and digital signatures, which are an important part of data security and may boost BCT adoption in industries. Iqbal *et al.* (2020) and Yousefi and Mohamadpour Tosarkani (2022) identified enablers such as immutability and data security as important for BCT adoption. TOE appears second, emphasizing the importance of the technologies required for BCT. Valle and Oliver (2020) discussed the importance of interoperability, technological maturity and other factors in promoting BCT adoption in industries. SHR ranked third, followed by energy tracking (SHR1). Shoaib *et al.* (2020) acknowledged that blockchain promotes sustainability by lowering energy consumption and carbon emissions through precise tracking and control. QRE was ranked fourth, with sub-criteria enablers such as maintenance, quality assurance, customer satisfaction, reliability and timeliness. According to Shoaib *et al.* (2020), BCT ensures quality fairness, improves process quality and guarantees customer satisfaction.

Secure storage and transactions received the most weight globally. According to Gupta *et al.* (2021), BCT is a shared ledger that allows for unchangeable data storage through approved and verified transactions. Technological maturity, Data provenance and immutability were ranked second and third, respectively. According to Huang *et al.* (2022), AHP results show that technological success factors such as technological maturity, feasibility and technical capability play important roles in BCT adoption. Gupta *et al.* (2021)

state that BCT enablers such as transparency and visibility, integrity and validation can help achieve data provenance and immutability. Smart contracts and traceability ranked fourth and fifth, respectively. Valle and Oliver (2020) described smart contracts as a fundamental asset of BCT in industry, stating that because they are deterministic, they always produce the same output for the same input. Kamble *et al.* (2020) identified traceability as one of the most important enablers in the agricultural supply chain because it allows for auditability, immutability and provenance.

Further the performance metrics were ranked by using the Pythagorean fuzzy Co-Co-So method, presented in descending order as shown,

PM2>PM3>PM13>PM7>PM9>PM12>PM11>PM15>PM8>PM17>PM4>PM5>PM16 >PM10>PM6>PM14>PM1.

Data hacking complaints per year (PM2) ranked first, with data storage capacity in systems (PM3) coming in second. The security of data from hacking is a major concern with advanced Industry 4.0 technologies such as Industrial Internet of Things (IIoT). According to Iqbal *et al.* (2020), Blockchain is made up of many nodes that store information, and the nodes are interconnected in such a way that data hacking or maltreatment would result in complete failure because data is not directly stored at one location. Also, due to the decentralized nature of data storage, a large amount of storage space is required.

The number of advanced technologies available for BCT (PM13) and energy utilization rate (PM7) were ranked third and fourth respectively. IIOT, AI and Machine Learning (ML) can be integrated with BCT to make the system tamper-proof. Smart contracts, consensus algorithms and hybrid blockchain are some of the technologies used to make blockchain more trustworthy. Iqbal *et al.* (2020) stated that combining IIOT and blockchain can help with data security concerns in cloud storage. The author also mentioned the need for an advanced power (energy) setup. There is always a need for higher-level software and advanced power setup, which is lacking in many industries. According to Karaarslan and Konacaklı (2020), mining operations in blockchain require very high energy input. Replacing conventional proof of work (PoW) blockchain with a Proof of Stake (POS) consensus protocol can reduce energy consumption. Furthermore, Transaction Speed (PM9) and Equipment repairs and maintenance (PM12) are ranked fifth and sixth, respectively. High transaction speed is regarded as desirable for the efficient and effective processing of transactions. According to Habib *et al.* (2022), shifting blockchain systems to an accelerating hardware system is required to improve transaction speed. This allows for the distribution of load across multiple parts, resulting in increased transaction speed and accuracy.

BCT can handle equipment maintenance and repair efficiently. Because transaction records are immutable, BCT allows for tracking of parts delivery and installation. Maintenance and removal, as well as the identification of counterfeit parts, all result in lower maintenance costs (Hasan *et al.*, 2020). Practitioners can make decisions and evaluate blockchain systems using a set of performance metrics and their ranking.

5.2 Implications of the study

The current study demonstrates the application of hybrid Pythagorean fuzzy AHP and Pythagorean fuzzy Co-Co-So techniques that can be also applied in similar domains of the study. Hence, the study results in the theoretical enrichment of the selected domain. According to the obtained global weights, the enabler Secure Storage and Transaction (DSE5) has obtained the highest weight which means the practitioners must focus on these enablers so that the performance metrics like Data Hacking Complaints per Year will be improved. Similarly, the performance metric Data Hacking Complaints per Year has the topmost ranking indicating the importance of data security in manufacturing organizations. Hence, the practitioners must focus on the enablers related to data security like Secure Storage and Transaction (DSE5), Advanced Communication Technology (TOE2), etc. This can assist in improving the performance of the manufacturing organization and the same can be evaluated using prioritized performance metrics. In this way, the developed framework can be used by practitioners to prepare long-term strategic improvement plans for their organizations. This may also result in the increased adoption of BCT technology in the manufacturing organization. The practitioners must also try to improve the data storage capacity and use of advanced technologies in the organization. For this, they may refer to the enablers like Secure Storage and Transaction (DSE5), Advanced Communication Technology (TOE2), Technological Maturity (TOE3), etc. and this can assist the improvement of the relevant performance metrics like Data Storage Capacity in Systems, Number of Advanced Technologies Available for BCT, etc. and the same is reflected in the results of prioritization. The developed framework also considers factors such as technology, data security, economy, sustainability and environmental benefits. This can motivate practitioners to implement sustainable practices along with BCT in manufacturing organizations.

6. Conclusion and future scope

This current research provides an innovative framework for BCT adoption in manufacturing industries. To fulfill the research objectives discussed in the first section, 26 enablers categorized under 4 major criteria and 17 performance metrics were identified, followed by the computation of weights using the Pythagorean fuzzy AHP method and prioritization of performance metrics using the Pythagorean fuzzy Co-Co-So technique. The thoughtfully selected performance metrics reflect the quantifiable measures of the performance of BCT over time from the adoption point of view. This resulted in the development of a framework that can help in BCT adoption in manufacturing industries. Results show that the top five favorable factors in BCT adoption were secure storage and transaction, technological maturity, data provenance and immutability, smart contracts and traceability. The above factors belong to data security and technology-oriented enablers. This suggests that the decentralized nature of Blockchain leads to an advanced level of data security and supporting technology like smart contracts, consensus algorithms and collaboration with advanced technologies like AI, ML, IoT, etc. makes Blockchain a trustworthy technology. Furthermore, in the ranking of performance metrics, the top 5 metrics were data hacking complaints per year, data storage capacity in systems, number of advanced technologies available for BCT, energy utilization rate and transaction speed. Considering the transaction cost metric, it stood ninth in the ranking. Research scholars and industrial practitioners may set their strategic goals more efficiently with the help of this prioritization. Moreover, BCT implementation in manufacturing industries can reduce manufacturing costs through sustainability practices, waste reduction, timely maintenance and repair, improving the traceability in the supply chain, and removing the middleman from the transaction, thus providing better communication in the network and better-quality products.

Nevertheless, the existing research may have a few limitations that may be attempted by researchers in the near future. The framework was developed using the MCDM technique and expert opinions; however, these opinions are arbitrary and may have an impact on the results because the panel includes experts from specific geographical locations and areas of expertise. Furthermore, the developed framework may not be generalizable to industries other than manufacturing, and operational scales may limit its applicability. More progressive MCDM techniques can also be used for the same and results can be compared. In spite of all the benefits offered by BCT, a huge percentage of organizations have not implemented it. This shows that there are some barriers to the adoption and identifying the barriers to the BCT adoption can be done in the future.

References

Ada, N., Ethirajan, M., Kumar, A., Vimal, K.E.K., Nadeem, S.P., Kazancoglu, Y. and Kandasamy, J. (2021), "Blockchain technology for enhancing traceability and efficiency in automobile supply chain—a case study", *Sustainability (Switzerland)*, Vol. 13 No. 24, pp. 1-21, doi: 10.3390/su132413667.

Aghamohammadzadeh, E. and Fatahi Valilai, O. (2020), "A novel cloud manufacturing service composition platform enabled by blockchain technology", *International Journal of Production Research*, Vol. 58 No. 17, pp. 5280-5298, doi: 10.1080/00207543.2020.1715507.

Ahmad, R.W., Hasan, H., Jayaraman, R., Salah, K. and Omar, M. (2021), "Blockchain applications and architectures for port operations and logistics management", *Research in Transportation Business and Management*, Vol. 41 (January), p. 100620, doi: 10.1016/j.rtbm.2021.100620.

Ali, O., Jaradat, A., Kulakli, A. and Abuhalimeh, A. (2021), "A comparative study: blockchain technology utilization benefits, challenges and functionalities", *IEEE Access*, Vol. 9, pp. 12730-12749, doi: 10.1109/ACCESS.2021.3050241.

Aslam, J., Saleem, A., Khan, N.T. and Kim, Y.B. (2021), "Factors influencing blockchain adoption in supply chain management practices: a study based on the oil industry", *Journal of Innovation and Knowledge*, Vol. 6 No. 2, pp. 124-134, doi: 10.1016/j.jik.2021.01.002.

Asuncion, F., Brinckman, A., Cole, D., Curtis, J., Davis, M., Dunlevy, T., Farmer, C., Harrison, A., Johnson, D.P., Joyce, J., Klubertanz, C., Lane, J., Martin, J., Nabrzyski, J., Neidig, J., Olivares, D., Robinson, G., Rodriguez, G., Root, C. and Warren, D. (2021), "Connecting supplier and DoD blockchains for transparent part tracking", *Blockchain: Research and Applications*, Vol. 2 No. 3, doi: 10.1016/J.BCRA.2021.100017.

Balon, B., Kalinowski, K. and Paprocka, I. (2022), "Application of blockchain technology in production scheduling and management of human resources competencies", *Sensors*, Vol. 22 No. 8, doi: 10.3390/s22082844.

Bodkhe, U., Tanwar, S., Parekh, K., Khanpara, P., Tyagi, S., Kumar, N. and Alazab, M. (2020), "Blockchain for industry 4.0: a comprehensive review", *IEEE Access*, Vol. 8, pp. 79764-79800, doi: 10.1109/ACCESS.2020.2988579.

Brandín, R. and Abrishami, S. (2021), "Information traceability platforms for asset data lifecycle: blockchain-based technologies", *Smart and Sustainable Built Environment*, Vol. 10 No. 3, pp. 364-386, doi: 10.1108/SASBE-03-2021-0042.

Chen, S., Cai, X., Wang, X., Liu, A., Lu, Q., Xu, X. and Tao, F. (2022), "Blockchain applications in PLM towards smart manufacturing", *The International Journal of Advanced Manufacturing Technology*, Vol. 118 Nos 7/8, pp. 2669-2683, doi: 10.1007/s00170-021-07802-z.

Choi, D., Chung, C.Y., Seyha, T. and Young, J. (2020), "Factors affecting organizations' resistance to the adoption of blockchain technology in supply networks", *Sustainability (Switzerland)*, Vol. 12 No. 21, pp. 1-37, doi: 10.3390/su12218882.

Du, X., Qi, Y., Chen, B., Shan, B. and Liu, X. (2021), "The integration of blockchain technology and smart grid: Framework and application", *Mathematical Problems in Engineering*, Vol. 2021, doi: 10.1155/2021/9956385.

Dutta, P., Choi, T.M., Somani, S. and Butala, R. (2020), "Blockchain technology in supply chain operations: applications, challenges and research opportunities", *Transportation Research Part E: Logistics and Transportation Review*, Vol. 142, p. 102067, doi: 10.1016/j.tre.2020.102067.

Ediriweera, A. and Wiewiora, A. (2021), "Barriers and enablers of technology adoption in the mining industry", *Resources Policy*, Vol. 73 No. May, p. 102188, doi: 10.1016/j.resourpol.2021.102188.

Efanov, D. and Roschin, P. (2018), "The all-pervasiveness of the blockchain technology", *Procedia Computer Science*, Vol. 123, pp. 116-121, doi: 10.1016/j.procs.2018.01.019.

Elmamy, S.B., Mrabet, H., Gharbi, H., Jemai, A. and Trentesaux, D. (2020), "A survey on the usage of blockchain technology for cyber-threats in the context of industry 4.0", *Sustainability (Switzerland)*, Vol. 12 No. 21, pp. 1-19, doi: 10.3390/su12219179.

Esmaeilian, B., Sarkis, J., Lewis, K. and Behdad, S. (2020), "Blockchain for the future of sustainable supply chain management in industry 4.0", *Resources*, *Conservation and Recycling*, Vol. 163 No. June, p. 105064, doi: 10.1016/j.resconrec.2020.105064.

Espinoza Pérez, A.T., Rossit, D.A., Tohmé, F. and Vásquez, Ó.C. (2022), "Mass customized/personalized manufacturing in industry 4.0 and blockchain: research challenges, main problems, and the design of an information architecture", *Information Fusion*, Vol. 79 No. September 2021, pp. 44-57, doi: 10.1016/j.inffus.2021.09.021.

Francisco, K. and Swanson, D. (2018), "The supply chain has no clothes: technology adoption of blockchain for supply chain transparency", *Logistics*, Vol. 2 No. 1, p. 2, doi: 10.3390/logistics2010002.

Fu, Y. and Zhu, J. (2019), "Big production enterprise supply chain endogenous risk management based on blockchain", *IEEE Access*, Vol. 7, pp. 15310-15319, doi: 10.1109/ACCESS.2019.2895327.

Fu, B., Shu, Z. and Liu, X. (2018), "Blockchain enhanced emission trading framework in fashion apparel manufacturing industry", *Sustainability (Switzerland)*, Vol. 10 No. 4, pp. 1-19, doi: 10.3390/su10041105.

Gerardi, M., Fallucchi, F. and Orecchini, F. (2023), "Blockchain technology for monitoring energy production for reliable and secure big data", *Electronics (Switzerland)*, Vol. 12 No. 22, pp. 1-22, doi: 10.3390/electronics12224660.

Gharaibeh, L., Eriksson, K. and Lantz, B. (2022), "Supply chain digitalization in the wood manufacturing industry: a bibliometric literature review", *Advances in Transdisciplinary Engineering*, *21*, pp. 617-628, doi: 10.3233/ATDE220180.

Ghode, D., Yadav, V., Jain, R. and Soni, G. (2020), "Adoption of blockchain in supply chain: an analysis of influencing factors", *Journal of Enterprise Information Management*, Vol. 33 No. 3, pp. 437-456, doi: 10.1108/JEIM-07-2019-0186.

Guo, S., Sun, X. and Lam, H.K.S. (2023), "Applications of blockchain technology in sustainable fashion supply chains: operational transparency and environmental efforts", *IEEE Transactions on Engineering Management*, Vol. 70 No. 4, pp. 1312-1328, doi: 10.1109/TEM.2020.3034216.

Gupta, H., Kumar, S., Kusi-Sarpong, S., Jabbour, C.J.C. and Agyemang, M. (2021), "Enablers to supply chain performance on the basis of digitization technologies", *Industrial Management and Data Systems*, Vol. 121 No. 9, pp. 1915-1938, doi: 10.1108/IMDS-07-2020-0421.

Habib, G., Sharma, S., Ibrahim, S., Ahmad, I., Qureshi, S. and Ishfaq, M. (2022), "Blockchain technology: benefits, challenges, applications, and integration of blockchain technology with cloud computing", *Future Internet*, Vol. 14 No. 11, pp. 1-22, doi: 10.3390/fi14110341.

Hasan, H.R., Salah, K., Jayaraman, R., Ahmad, R.W., Yaqoob, I. and Omar, M. (2020), "Blockchain-Based solution for the traceability of spare parts in manufacturing", *IEEE Access*, Vol. 8, pp. 100308-100322, doi: 10.1109/ACCESS.2020.2998159.

Helo, P. and Hao, Y. (2019), "Blockchains in operations and supply chains: a model and reference implementation", *Computers and Industrial Engineering*, Vol. 136, pp. 242-251, doi: 10.1016/j.cie.2019.07.023.

Helo, P. and Shamsuzzoha, A.H.M. (2020), "Real-time supply chain—a blockchain architecture for project deliveries", *Robotics and Computer-Integrated Manufacturing*, Vol. 63 No. December 2018, p. 101909, doi: 10.1016/j.rcim.2019.101909.

Huang, L., Zhen, L., Wang, J. and Zhang, X. (2022), "Blockchain implementation for circular supply chain management: evaluating critical success factors", *Industrial Marketing Management*, Vol. 102 No. 99, pp. 451-464, doi: 10.1016/j.indmarman.2022.02.009.

Iqbal, A., Amir, M., Kumar, V., Alam, A. and Umair, M. (2020), "Integration of next generation IIoT with blockchain for the development of smart industries", *Emerging Science Journal*, Vol. 4 No. Special Issue, pp. 1-17, doi: 10.28991/esj-2020-SP1-01.

Iranmanesh, M., Maroufkhani, P., Asadi, S., Ghobakhloo, M., Dwivedi, Y.K. and Tseng, M.L. (2023), "Effects of supply chain transparency, alignment, adaptability, and agility on blockchain adoption in supply chain among SMEs", *Computers and Industrial Engineering*, Vol. 176 No. November 2022, p. 108931, doi: 10.1016/j.cie.2022.108931.

Jain, S., Anand, A., Gupta, A., Awasthi, K., Gujrati, S. and Channegowda, J. (2020), "Blockchain and machine learning in health care and management", 2020 International Conference on Mainstreaming Block Chain Implementation, ICOMBI 2020, doi: 10.23919/ICOMBI48604.2020.9203483.

Janssen, M., Weerakkody, V., Ismagilova, E., Sivarajah, U. and Irani, Z. (2020), "A framework for analysing blockchain technology adoption: integrating institutional, market and technical factors", *International Journal of Information Management*, Vol. 50 No. July 2019, pp. 302-309, doi: 10.1016/j.ijinfomgt.2019.08.012.

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, p. 100027, doi: 10.1016/j.bcra.2021.100027.

Jimoh, F., Abdullahi, U. and Ibrahim, I. (2019), "An overview of blockchain technology adoption", *Journal of Computer Science and Information Technology*, Vol. 7 No. 2, pp. 26-36, doi: 10.15640/jcsit.v7n2a4.

Kamble, S.S., Gunasekaran, A. and Sharma, R. (2020), "Modeling the blockchain enabled traceability in agriculture supply chain", *International Journal of Information Management*, Vol. 52 No. May, pp. 1-16, doi: 10.1016/j.ijinfomgt.2019.05.023.

Kamilaris, A., Fonts, A. and Prenafeta-Boldύ, F.X. (2019), "The rise of blockchain technology in agriculture and food supply chains", *Trends in Food Science and Technology*, Vol. 91 No. July, pp. 640-652, doi: 10.1016/j.tifs.2019.07.034.

Karaarslan, E. and Konacaklı, E. (2020), "Data storage in the decentralized world: blockchain and derivatives", *Who Runs the World: Data*, pp. 37-69, doi: 10.26650/b/et06.2020.011.03.

Karamchandani, A., Srivastava, S.K., Kumar, S. and Srivastava, A. (2021), "Analysing perceived role of blockchain technology in SCM context for the manufacturing industry", *International Journal of Production Research*, Vol. 59 No. 11, pp. 3398-3429, doi: 10.1080/00207543.2021.1883761.

Kaushal, R.K., Kumar, N. and Panda, S.N. (2021), "Blockchain technology, its applications and open research challenges", *Journal of Physics: Conference Series*, Vol. 1950 No. 1, p. 12030, doi: 10.1088/1742-6596/1950/1/012030.

Kaynak, B., Kaynak, S. and Uygun, Ö. (2020), "Cloud manufacturing architecture based on public blockchain technology", *IEEE Access*, Vol. 8, pp. 2163-2177, doi: 10.1109/ACCESS.2019.2962232.

Khanfar, A.A.A., Iranmanesh, M., Ghobakhloo, M., Senali, M.G. and Fathi, M. (2021), "Applications of blockchain technology in sustainable manufacturing and supply chain management: a systematic review", *Sustainability*, Vol. 13 No. 14, p. 7870, doi: 10.3390/su13147870.

Ko, T., Lee, J. and Ryu, D. (2018), "Blockchain technology and manufacturing industry: real-time transparency and cost savings", *Sustainability (Switzerland)*, Vol. 10 No. 11, pp. 1-20, doi: 10.3390/su10114274.

Kshetri, N. (2018), "1 Blockchain's roles in meeting key supply chain management objectives", *International Journal of Information Management*, Vol. 39 No. December 2017, pp. 80-89, doi: 10.1016/j.ijinfomgt.2017.12.005.

Lahane, S. and Kant, R. (2021), "A hybrid pythagorean fuzzy AHP – CoCoSo framework to rank the performance outcomes of circular supply chain due to adoption of its enablers", *Waste Management*, Vol. 130, pp. 48-60, doi: 10.1016/j.wasman.2021.05.013.

Lallas, E.N., Xenakis, A. and Stamoulis, G. (2019), "A generic framework for a peer to peer blockchain based fog architecture in industrial automation", 2019 4th South-East Europe Design Automation, Computer Engineering, Computer Networks and Social Media Conference, SEEDA-CECNSM 2019, pp. 1-5, doi: 10.1109/SEEDA-CECNSM.2019.8908360

Lee, J., Azamfar, M. and Singh, J. (2019), "A blockchain enabled Cyber-Physical system architecture for industry 4.0 manufacturing systems", *Manufacturing Letters*, Vol. 20, pp. 34-39, doi: 10.1016/j.mfglet.2019.05.003.

Liu, J., Jiang, P. and Zhang, J. (2024), "A blockchain-enabled and event-driven tracking framework for SMEs to improve cooperation transparency in the manufacturing supply chain", *Computers and Industrial Engineering*, Vol. 191 No. November 2023, p. 110150, doi: 10.1016/j.cie.2024.110150.

Lohmer, J. and Lasch, R. (2020), "Blockchain in operations management and manufacturing: potential and barriers", *Computers and Industrial Engineering*, Vol. 149 No. August, p. 106789, doi: 10.1016/j.cie.2020.106789.

Lupi, F., Cimino, M.G.C.A., Berlec, T., Galatolo, F.A., Corn, M., Rožman, N., Rossi, A. and Lanzetta, M. (2023), "Blockchain-based shared additive manufacturing", *Computers and Industrial Engineering*, Vol. 183 No. December 2022, p. 109497, doi: 10.1016/j.cie.2023.109497.

Malik, S., Chadhar, M., Chetty, M. and Vatanasakdakul, S. (2022), "Adoption of blockchain technology: exploring the factors affecting organizational decision", *Human Behavior and Emerging Technologies*, Vol. 2022, p. 7320526, doi: 10.1155/2022/7320526.

Marengo, A. and Pagano, A. (2023), "Investigating the factors influencing the adoption of blockchain technology across different countries and industries: a systematic literature review", *Electronics (Switzerland)*, Vol. 12 No. 14, doi: 10.3390/electronics12143006.

Mendhurwar, S. and Mishra, R. (2023), "Un'-blocking the industry 4.0 value chain with cyber-physical social thinking", *Enterprise Information Systems*, Vol. 17 No. 2, pp. 1-48, doi: 10.1080/17517575.2021.1930189.

Mubarik, M., Rasi, R.Z., Binti, R.M. and Mubarak, M.F. (2020), "Fostering supply chain integration through blockchain technology: a study of Malaysian manufacturing sector", *International Journal of Management and Sustainability*, Vol. 9 No. 3, pp. 135-147, doi: 10.18488/journal.11.2020.93.135.147.

Mukherjee, A.A., Singh, R.K., Mishra, R. and Bag, S. (2021), "Application of blockchain technology for sustainability development in agricultural supply chain: justification framework", *Operations Management Research*, Vol. 123456789, doi: 10.1007/s12063-021-00180-5.

Muneeb, S.M., Asim, Z., Hajiaghaei-Keshteli, M. and Abbas, H. (2023), "A multi-objective integrated supplier selection-production-distribution model for re-furbished products: towards a circular economy", *Renewable and Sustainable Energy Reviews*, Vol. 175 No. December 2022, p. 113156, doi: 10.1016/j.rser.2023.113156.

Nabipour, M. and Ülkü, M.A. (2021), "On deploying blockchain technologies in supply chain strategies and the COVID-19 pandemic: a systematic literature review and research outlook", *Sustainability (Switzerland)*, Vol. 13 No. 19, doi: 10.3390/su131910566.

Nakamoto, S. (2008), "Bitcoin: a peer-to-peer electronic cash system 1-9", available at: http://git.dhimmel.co./bitcoin-whitepaper/

Nath, S.D., Khayer, A., Majumder, J. and Barua, S. (2022), "Factors affecting blockchain adoption in apparel supply chains: does sustainability-oriented supplier development play a moderating role?", *Industrial Management and Data Systems*, Vol. 122 No. 5, pp. 1183-1214, doi: 10.1108/IMDS-07-2021-0466.

Orji, I.J., Kusi-Sarpong, S., Huang, S. and Vazquez-Brust, D. (2020), "Evaluating the factors that influence blockchain adoption in the freight logistics industry", *Transportation Research Part E: Logistics and Transportation Review*, Vol. 141, pp. 1-45, doi: 10.1016/j.tre.2020.102025.

Pansare, R. and Yadav, G. (2022), "Repurposing production operations during COVID-19 pandemic by integrating industry 4.0 and reconfigurable manufacturing practices: an emerging economy perspective", *Operations Management Research*, Vol. 15 Nos 3/4, pp. 1270-1289, doi: 10.1007/s12063-022-00310-7.

Pansare, R., Yadav, G. and Nagare, M.R. (2022), "A hybrid framework to prioritize the performance metrics of reconfigurable manufacturing system (RMS) using fuzzy AHP–TOPSIS method", *The International Journal of Advanced Manufacturing Technology*, Vol. 124 Nos 3/4, pp. 863-885, doi: 10.1007/s00170-022-10440-8.

Patel, D., Sahu, C.K. and Rai, R. (2024), "Security in modern manufacturing systems: integrating blockchain in artificial intelligence-assisted manufacturing", *International Journal of Production Research*, Vol. 62 No. 3, pp. 1041-1071, doi: 10.1080/00207543.2023.2262050.

Rane, S.B. and Narvel, Y.A.M. (2019), "Re-designing the business organization using disruptive innovations based on blockchain-IoT integrated architecture for improving agility in future industry 4.0", *Benchmarking: An International Journal*, Vol. 28 No. 5, pp. 1883-1908, doi: 10.1108/BIJ-12-2018-0445.

Roeck, D., Sternberg, H. and Hofmann, E. (2020), "Distributed ledger technology in supply chains: a transaction cost perspective", *International Journal of Production Research*, Vol. 58 No. 7, pp. 2124-2141, doi: 10.1080/00207543.2019.1657247.

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, doi: 10.1080/00207543.2018.1533261.

Sahebi, I.G., Masoomi, B. and Ghorbani, S. (2020), "Expert oriented approach for analyzing the blockchain adoption barriers in humanitarian supply chain", *Technology in Society*, Vol. 63 No. October, p. 101427, doi: 10.1016/j.techsoc.2020.101427.

Shah, K., Patel, N., Thakkar, J. and Patel, C. (2022), "Exploring applications of blockchain technology for industry 4.0", *Materials Today: Proceedings*, Vol. 62 No. P13, pp. 7238-7242, doi: 10.1016/j.matpr.2022.03.681.

Sharabati, A.A.A. and Jreisat, E.R. (2024), "Blockchain technology implementation in supply chain management: a literature review", *Sustainability (Switzerland)*, Vol. 16 No. 7, pp. 1-21, doi: 10.3390/su16072823.

Shete, P.C., Ansari, Z.N. and Kant, R. (2020), "A pythagorean fuzzy AHP approach and its application to evaluate the enablers of sustainable supply chain innovation", *Sustainable Production and Consumption*, Vol. 23, pp. 77-93, doi: 10.1016/j.spc.2020.05.001.

Shoaib, M., Lim, M.K. and Wang, C. (2020), "An integrated framework to prioritize blockchain-based supply chain success factors", *Industrial Management and Data Systems*, Vol. 120 No. 11, pp. 2103-2131, doi: 10.1108/IMDS-04-2020-0194.

Sikorski, J.J., Haughton, J. and Kraft, M. (2017), "Blockchain technology in the chemical industry: machine-to-machine electricity market", *Applied Energy*, Vol. 195, pp. 234-246, doi: 10.1016/j.apenergy.2017.03.039.

Tan, B.Q., Wang, F., Liu, J., Kang, K. and Costa, F. (2020), "A blockchain-based framework for green logistics in supply chains", *Sustainability (Switzerland)*, Vol. 12 No. 11, doi: 10.3390/su12114656.

Teisserenc, B. (2021), "Twins in the construction industry 4.0", pp. 1-51.

Vafadarnikjoo, A., Badri Ahmadi, H., Liou, J.J.H., Botelho, T. and Chalvatzis, K. (2023), "Analyzing blockchain adoption barriers in manufacturing supply chains by the neutrosophic analytic hierarchy process", *Annals of Operations Research*, Vol. 327 No. 1, pp. 129-156, doi: 10.1007/s10479-021-04048-6.

Valle, F.D. and Oliver, M. (2020), "Blockchain enablers for supply chains: how to boost implementation in industry", *IEEE Access*, Vol. 8, pp. 209699-209716, doi: 10.1109/ACCESS.2020.3038463.

Wan, P.K., Huang, L. and Holtskog, H. (2020), "Blockchain-Enabled information sharing within a supply chain: a systematic literature review", *IEEE Access*, Vol. 8, pp. 49645-49656, doi: 10.1109/ACCESS.2020.2980142.

Wang, Q. and Su, M. (2020), "Integrating blockchain technology into the energy sector - from theory of blockchain to research and application of energy blockchain", *Computer Science Review*, Vol. 37, p. 100275, doi: 10.1016/j.cosrev.2020.100275.

Xie, J., Tang, H., Huang, T., Yu, F.R., Xie, R., Liu, J. and Liu, Y. (2019), "A survey of blockchain technology applied to smart cities: research issues and challenges", *IEEE Communications Surveys and Tutorials*, Vol. 21 No. 3, pp. 2794-2830, doi: 10.1109/COMST.2019.2899617.

Yang, M.H., Lee, T.R. and Chang, T.C. (2019), "Key success factors of blockchain platform for micro-enterprises", *The Journal of Asian Finance, Economics and Business*, Vol. 6 No. 3, pp. 283-293, doi: 10.13106/jafeb.2019.vol6.no3.283.

Yang, J., Bi, H., Liang, Z., Zhou, H. and Yang, H.J. (2020), "A survey on blockchain: Architecture, applications, challenges, and future trends", Proceedings - IEEE Congress on Cybermatics: 2020 IEEE International Conferences on Internet of Things, IThings 2020, IEEE Green Computing and Communications, GreenCom 2020, IEEE Cyber, Physical and Social Computing, CPSCom 2020 and IEEE Smart Data, SmartD, pp. 749-754, doi: 10.1109/iThings-GreenCom-CPSCom-SmartData-Cybermatics50389.2020.00129.

Yazdani, M., Zarate, P., Kazimieras Zavadskas, E. and Turskis, Z. (2019), "A combined compromise solution (CoCoSo) method for multi-criteria decision-making problems", *Management Decision*, Vol. 57 No. 9, pp. 2501-2519, doi: 10.1108/MD-05-2017-0458.

Yousefi, S. and Mohamadpour Tosarkani, B. (2022), "An analytical approach for evaluating the impact of blockchain technology on sustainable supply chain performance", *International Journal of Production Economics*, Vol. 246 No. May 2021, p. 108429, doi: 10.1016/j.ijpe.2022.108429.

Zafar, S., Alamgir, Z. and Rehman, M.H. (2021), "An effective blockchain evaluation system based on entropy-CRITIC weight method and MCDM techniques", *Peer-to-Peer Networking and Applications*, Vol. 14 No. 5, pp. 3110-3123, doi: 10.1007/s12083-021-01173-8.

Zheng, K., Ding, K., Hui, J., Zhang, F., Lv, J. and Chan, F.T.S. (2024), "Blockchain-based credible manufacturing data sharing for a collaborative manufacturing supply chain", *International Journal of Production Research*, Vol. 62 No. 6, pp. 2233-2254, doi: 10.1080/00207543.2023.2217292.

Zhou, Y., Soh, Y.S., Loh, H.S. and Yuen, K.F. (2020), "The key challenges and critical success factors of blockchain implementation: policy implications for Singapore's Maritime industry", *Marine Policy*, Vol. 122 No. October, p. 104265, doi: 10.1016/j.marpol.2020.104265.

Zhu, Q., Bai, C. and Sarkis, J. (2022), "Blockchain technology and supply chains: the paradox of the atheoretical research discourse", *Transportation Research Part E: Logistics and Transportation Review*, Vol. 164 No. June, p. 102824, doi: 10.1016/j.tre.2022.102824.

Further reading

Han, X. and Rani, P. (2022), "Evaluate the barriers of blockchain technology adoption in sustainable supply chain management in the manufacturing sector using a novel Pythagorean fuzzy-CRITIC-CoCoSo approach", *Operations Management Research*, Vol. 15 Nos 3/4, pp. 725-742, doi: 10.1007/s12063-021-00245-5.

Corresponding author

Shweta V. Matey can be contacted at: mateyshweta@gmail.com

Appendix 1

Table A1. Linguistic scale for pythagorean fuzzy AHP

Linguistic terms used in pythagorean fuzzy AHP	Pythagorean fuzzy number			
	μ_L	μ_U	v_L	v_U
Certainly low importance (CLI)	0	0	0.9	1
Very low importance (VLI)	0.1	0.2	0.8	0.9
Low importance (LI)	0.2	0.35	0.65	0.8
Below average importance (BAI)	0.35	0.45	0.55	0.65
Average importance (AI)	0.45	0.55	0.45	0.55
Above average importance (AAI)	0.55	0.65	0.35	0.45
High importance (HI)	0.65	0.8	0.2	0.35
Very high importance (VHI)	0.8	0.9	0.1	0.2
Certainly high importance (CHI)	0.9	1	0	0
Exactly equal (EE)	0.1965	0.1965	0.1965	0.1965

Source: Lahane and Kant, 2021

Appendix 2

Table A2. Linguistic scale for pythagorean fuzzy Co-Co-So

Linguistic terms used in pythagorean fuzzy Co-Co-so		Pythagorean fuzzy number	
		μ_L	μ_U
Extremely low	EL	0	1
Very low	VL	0.1	0.9
Low	L	0.2	0.8
Middle low	ML	0.3	0.7
Below middle	BM	0.4	0.6
Middle	M	0.5	0.5
Above middle	AM	0.6	0.4
Middle high	MH	0.7	0.3
High	H	0.8	0.2
Very high	VH	0.9	0.1
Extremely high	EH	1	0

Source: Lahane and Kant, 2021

Appendix 3

Table A3. Details of expert panel

Expert code	Age group	Educational qualification	Role in industry/ academics	Department	Work experience (years)
E1	41–45	Ph.D. Pursuing	Professor	Mechanical engineering	20
E2	31–35	Ph.D. Pursuing	Asst. Professor	Mechanical engineering	10
E3	45–50	Ph.D	Owner/proprietor	Manufacturing	06
E4	41–45	Graduate	Senior project manager	Production	19
E5	41–50	Ph.D	DGM	Manufacturing	27
E6	45–50	Postgraduate	General manager	Manufacturing	25
E7	48	BE and PG diploma in advanced computing	Associate Director – Projects	Software development	20
E8	45–50	Postgraduate	Director-technology	Administration	24
E9	45–50	Postgraduate	Director	Machining	21
E10	49	B. E.	Partner	Automation	24
E11	21–30	Postgraduate	Sales manager	Sales	4

Source: Authors' own Creation

Appendix 4

Table A4. Linguistic decision matrix (linguistic) for pythagorean fuzzy Co-Co-so method

Enablers	Data security enablers (DSE)							Quality-related enablers (QRE)							Sustainability and HR related enablers (SHR)						Technology oriented enablers (TOE)					
code	DSE1	DSE2	DSE3	DSE4	DSE5	DSE6	DSE7	QRE1	QRE2	QRE3	QRE4	QRE5	QRE6	QRE7	SHR1	SHR2	SHR3	SHR4	SHR5	SHR6	TOE1	TOE2	TOE3	TOE4	TOE5	TOE6
PM1	ML	ML	ML	L	ML	ML	ML	ML	MH	ML	H	ML	L	ML	ML	ML	L	ML	L	ML	ML	ML	ML	ML	ML	ML
PM2	VH	VH	MH	H	VH	H	M	MH	MH	H	H	H	MH	H	H	H	H	H	H	H	VH	VH	VH	MH	H	MH
PM3	VH	VH	AM	H	VH	MH	M	AM	MH	H	H	H	MH	H	H	H	H	H	H	H	VH	VH	VH	MH	H	MH
PM4	AM	MH	BM	AM	MH	ML	H	H	MH	M	MH	M	BM	ML	H	MH	AM	MH	M	ML	AM	M	AM	M	M	BM
PM5	M	MH	ML	M	AM	M	H	H	MH	AM	MH	BM	BM	MH	L	MH	BM	MH	M	ML	AM	M	AM	M	M	BM
PM6	M	M	BM	BM	M	BM	AM	H	MH	M	AM	ML	M	AM	L	M	BM	MH	AM	L	M	BM	AM	BM	ML	BM
PM7	MH	H	AM	MH	VH	AM	H	AM	AM	M	H	M	H	BM	VH	VH	MH	H	MH	H	H	H	VH	MH	MH	MH
PM8	AM	MH	MH	AM	MH	AM	AM	AM	MH	AM	H	M	MH	MH	MH	L	AM	AM	AM	MH	MH	MH	MH	AM	AM	BM
PM9	H	H	MH	H	H	MH	AM	M	H	AM	H	MH	MH	MH	MH	ML	MH	MH	H	H	MH	H	H	MH	MH	H
PM10	BM	ML	M	AM	BM	AM	AM	L	H	ML	MH	ML	BM	ML	ML	M	ML	VH	BM	ML	AM	BM	BM	BM	BM	M
PM11	AM	H	M	H	MH	AM	AM	H	H	MH	M	MH	MH	MH	AM	MH	MH	H	AM	AM	MH	H	MH	MH	AM	AM
PM12	AM	AM	MH	H	H	MH	MH	AM	H	MH	MH	MH	M	AM	M	AM	MH	MH	AM	AM	MH	MH	MH	MH	AM	MH
PM13	VH	H	MH	VH	H	MH	AM	ML	MH	H	MH	H	H	H	MH	H	H	H	MH	H	M	H	H	H	H	AM
PM14	M	L	BM	L	ML	ML	MH	H	MH	ML	L	ML	L	L	ML	M	L	L	L	L	BM	BM	BM	M	BM	M
PM15	AM	MH	MH	MH	H	MH	MH	MH	MH	BM	MH	MH	M	MH	MH	AM	M	AM	M	AM	AM	MH	MH	MH	AM	MH
PM16	BM	AM	M	AM	M	AM	MH	MH	MH	MH	M	BM	M	M	L	M	AM	ML	BM	ML	AM	M	AM	M	M	AM
PM17	AM	H	M	MH	AM	AM	AM	H	H	BM	M	AM	AM	M	AM	M	M	AM	M	M	AM	M	AM	AM	BM	M

Source: Authors' own Creation