IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

Towards Intelligent And Traceable Supply Chains: A Comprehensive Exploration Of Blockchain Integration With Smart Manufacturing And Artificial Intelligence

P Venkata Siva Praveen[1] , Atul Pandey[2], Glenn Castellino[3], Rahul Sarkar[4] , Akash Ghosh[5]

[1] Btech Graduate, Rajiv Gandhi University of Knowledge Technologies, Nuzvid,Andhra Pradesh,India

[2] Btech Graduate, (Electrical & Electronics Engineering), Vellore Institute of Technology, Vellore, Tamil Nadu, India

[3] Analyst - Marine & Logistics, AGR Knowledge Services Pvt. Ltd., Mumbai, India

[4] Undergraduate Student, Bachelors of Computer Applications, Kalinga Institute of Industrial Technology, Odisha ,India

[5] Machine Learning Engineer,Astergo Information Technology Pvt. Ltd., Kolkata, India

Abstract—Smart manufacturing endeavors to optimize capabilities for enhanced performance in manufacturing enterprises, targeting cost, delivery, and quality objectives. This necessitates integrating product development, production systems, and business cycles within the supply chain management framework. While considerable data is generated in manufacturing, the adoption of blockchain, despite success in financial industries, has been sluggish in non-financial sectors. This research presents a methodology for establishing a traceable and intelligent supply chain, emphasizing the realization of traceability for enterprise entities through smart manufacturing systems. Stakeholders in the supply chain are required to incorporate blockchain to record critical control data, enhancing transparency. The integration of Artificial Intelligence (AI) further empowers supply chain stakeholders to derive meaningful insights collectively. This collaborative data access contributes to the evolution of an intelligent supply chain. This study explores the potential of blockchain in coordinating activities for efficient supply chain management beyond financial transactions. The study aims to advance the understanding of blockchain in the context of supply chains, providing insights for both researchers and practitioners to consider its application in diverse future studies. The integration of blockchain and artificial intelligence (AI) has gained prominence, particularly for enhancing security, efficiency, and productivity in volatile business environments. This is particularly evident in the supply chain, where the combined use of blockchain and AI contributes to improved information and process resilience, cost-efficient product delivery, and enhanced traceability. This paper conducts a comprehensive review of the integration of blockchain and AI in supply chains with a proposed framework.

Keywords—Blockchain, AI, supply chain integration, Industry 4.0, Business Process Optimization

I. INTRODUCTION

Blockchain, recognized as a decentralized digital ledger, operates on a distributed network, commonly referred to as a peer-to-peer (P2P) or decentralized network, structured as a continuous sequence of blocks. Swan et al. posit that the terms "blockchains" and "digital ledgers" are often used interchangeably. Within a blockchain network, all participants can concurrently share and record blocks, necessitating validation and verification by all users in the network [15]. The linkage of blocks is facilitated through a cryptographic hash function, enabling the traceability of every transaction by scrutinizing the interconnected block information via hash keys [16]. Advocates of blockchain assert that transparency, speed, accessibility, and tamper resistance constitute the foundational tenets of this emergent paradigm. Sultan and Lakhani contend that blockchain serves as a decentralized database housing sequential, cryptographically linked blocks of digitally signed asset transactions, guided by a consensus model [17].

Supply chain management represents the holistic coordination of material, information, and financial streams within a network comprising various companies or organizations. The collaborative efforts of multiple partners within the supply chain are imperative for the production and delivery of products and services to the end consumer. The conceptual framework of supply chain management entails a fundamental transformation in the organizational structure of a firm. Control mechanisms shift away from direct oversight of internal business processes to a model centered on integration across member organizations within the broader supply chain network [18].

Contemporary supply chains face a myriad of challenges due to their heavy reliance on centralized and often disparate systems of information management, notably enterprise resource planning systems [19]. The inherent vulnerability of such centralized systems to single-point failures pose a significant drawback, rendering the entire system susceptible to errors, hacking, corruption, or malicious attacks [20]. The prerequisite for a high level of trust within the supply chain entities to entrust sensitive and valuable data to a singular organization or broker further complicates this paradigm [21].

Additionally, ongoing pressures in the realm of supply chain practices necessitate the acknowledgment and certification of sustainability. The triple-bottom-line concept mandates a comprehensive consideration of environmental, social, and business dimensions to achieve sustainability [22]. Supply chain sustainability, recognized as a strategic and competitive imperative, entails the confirmation and verification of adherence to specific sustainability criteria and certifications in processes, products, and activities [23]. Evaluation of existing supply chain information systems is imperative to determine their capacity to furnish secure, transparent, and reliable data essential for tracing the timely provenance of goods and services.

Addressing these complex issues hinges on enhancing supply chain security, transparency, long-term viability, and process integrity. Blockchain technology emerges as a potential solution, as recent technological advancements and applications rooted in the blockchain concept render these objectives more achievable from organizational, technological, and financial perspectives. With its decentralized 'trustless' database characteristics, blockchain technology stands poised to facilitate global-scale transactional and process disintermediation and decentralization among diverse stakeholders [24].

In the contemporary era, the realization of Industry 4.0 has become feasible owing to significant advancements in embedded systems, cloud computing, smart devices, and, notably, Cyber-Physical Systems (CPS) [1]. The advent of the Internet of Things (IoT) in 2012, facilitated by the introduction of the internet protocol IPv6, further enables unique identification and interaction with smart objects, marking the inception of a transformative phase in manufacturing referred to as Industry 4.0 [2]. At its core, Industry 4.0 places a paramount emphasis on data utilization and the insights derived from it. The indispensability of data becomes evident in the seamless integration of existing information technologies within and beyond enterprise boundaries. This integration materializes through the implementation of horizontal integration across value networks, end-to-end digital integration of engineering throughout the entire value chain, and vertical integration within networked manufacturing systems. Concomitantly, smart manufacturing is dedicated to optimizing capabilities to achieve multiple objectives, encompassing cost, delivery, and quality, within manufacturing enterprises [3]. This optimization necessitates the comprehensive incorporation of the product development lifecycle, production system lifecycle, and business cycle, particularly within the framework of supply chain management [4]. Consequently, a substantial volume of data is generated within a given manufacturing enterprise as a natural byproduct of these integrated processes.

Industry 4.0 and smart manufacturing underscore the significance of achieving end-to-end digital integration of engineering processes throughout the entire value chain of a product, coupled with horizontal integration facilitated by value networks. This integration, however, introduces complex challenges, including establishing trust among collaborating enterprises, defining the scope of information exchange, safeguarding intellectual property and data, and ensuring the security of products, resources, and processes, among other considerations [5]. While these challenges are pertinent to manufacturing enterprises in general, they assume critical importance in highly regulated sectors such as pharmaceuticals. As previously noted, extensive data is stored in local databases to support the day-to-day operations of manufacturing enterprises. Leveraging this data through the application of Artificial Intelligence/Machine Learning (AI/ML) algorithms holds the potential to yield valuable insights, thereby enhancing the efficiency and effectiveness of operational processes. Nevertheless, a notable limitation arises from the inherently siloed nature of the data, which is specific to the stakeholder within the supply chain under consideration. For instance, a tier-1 supplier may lack visibility into how the manufacturer utilizes its products or components, resulting in a dearth of feedback and a narrow contextual understanding of processes. Consequently, this limitation diminishes the capacity to derive insights with a broader context and impedes initiatives aimed at process improvement.

II. LITERATURE REVIEW

The exchange of information at enterprise boundaries is a complex endeavor, particularly in the context of manufacturing enterprises seeking critical data, such as the quality of incoming raw materials or semi-finished products from suppliers. Access to this information is essential for achieving traceability, building trust, and mitigating costs associated with retesting, among other advantages. However, obtaining such information is often challenging, and even when available, the susceptibility to manipulation is a prevalent concern. This challenge extends to regulators, certifiers, and customers who face similar difficulties in acquiring and verifying pertinent information. The fundamental questions in this regard revolve around the nature of the information to be exchanged and the methodologies employed for this exchange.

The genesis of blockchain technology can be traced back to the introduction of Bitcoin [6]. This technology, along with distributed ledger systems, has garnered significant attention across various industries, with financial institutions emerging as primary adopters. Notably, the data (or transactions) stored in a blockchain is cryptographically signed, ensuring its immutability once written [7]. Each block in a blockchain can be analogized to a page in a ledger book, with transactions encompassing a spectrum from monetary transactions to operations on a database [8]. The use of Merkle trees to encode blockchain data provides an efficient and secure architecture for data storage. Upon submission of a transaction to the blockchain, verification becomes imperative. Consensus algorithms, such as Proof of Work (PoW) and Proof of Stake (PoS), represent methodologies for achieving collective agreement across the network to generate a new block.

The blockchain network protocol is structured into four distinct layers: the protocol of data and network organization, protocols of distributed consensus, a framework of autonomous organization based on distributed virtual machines (VMs), exemplified by smart contracts [9], and the implementation of the user interface for interactions. At the foundational layer, the data organization layer endows nodes with various unique functionalities, employing cryptographic mechanisms to fortify the security of each node

[10]. In the nascent stages of blockchain technology, transactions were digitally signed and arbitrarily encapsulated with cryptographic functions, enabling miners to discern potential tampering attempts. This encapsulation is denoted as a "block." Chronologically arranged blocks collectively form a chain, giving rise to the term "blockchain."

The network protocols within the blockchain architecture establish an interconnected structure where nodes interact within the network. This results in the formation of a peer-to-peer network wherein each participant holds equal authority. The primary functions of this protocol encompass peer discovery, route identification to peers, and the secure transmission of encrypted data across the peer-to-peer network. Serving as the cognitive and essential core of the blockchain, the consensus protocol ensures and sustains consistency, chronological ordering, and the overall integrity of the system. The consensus protocol achieves Byzantine agreement within the network [11]. When selecting an access control system, blockchain networks commonly adopt Byzantine fault-tolerant consensus protocols, such as practical Byzantine fault tolerance in the case of consensus within a small group of authenticated nodes [12]. This is particularly applicable to permissioned blockchain networks. In contrast, permissionless blockchains leverage a combination of techniques, including cryptographic zero knowledge, and incentivized designs for miners to achieve consensus. Smart contracts, acting as programmatically defined agreements, enforce adherence to specified rules and conditions among contracting parties [13]. These contracts are deployed on the blockchain, accessible by any participant in a public blockchain and authorized users in a private blockchain. The robustness of the consensus protocols instills confidence in the implementation of smart contracts. Operating within a distributed virtual machine (VM) architecture, smart contracts exhibit consistency across different platforms. The VM layer, encompassing consensus, data, and network protocols, remains concealed, with only the application layer visible to end-users. Numerous distributed applications are emerging to leverage blockchain architecture for cryptocurrency transactions.

Artificial Intelligence (AI) has significantly contributed to the optimization of supply chain management [14]. Within the realm of Supply Chain Management (SCM), AI manifests its applications through various mechanisms. Primarily, it facilitates demand forecasting by leveraging historical data, enhancing precision in predicting future demands. Furthermore, in the production phase, AI demonstrates its value by optimizing processes, thereby fostering improved efficiency. This optimization extends to team-building aspects, encompassing the collaboration between robots and human workers. Additionally, AI imparts valuable insights, enabling more accurate predictions for optimal times for product promotions and pricing adjustments. The implementation of AI in smart retailing proves advantageous, minimizing wastages through the application of video analysis and early-stage tracking, allowing for the timely identification and disposal of unusable products. In sum, AI assumes a pivotal role in reshaping and enhancing various facets of supply chain management.

III. RESEARCH METHODOLOGY

A supply chain is characterized by the involvement of diverse stakeholders, including suppliers, manufacturers, regulators, and certifiers, each possessing distinct priorities aligned with their respective objectives. Addressing these individual priorities often necessitates the implementation of tailored services utilizing appropriate Artificial Intelligence/Machine Learning (AI/ML) algorithms. This underscores the prominence of data in the supply chain landscape, wherein the implementation of both horizontal and vertical integration strategies becomes imperative. Horizontal integration, entailing the amalgamation of various enterprise applications across the supply chain, requires a concerted effort to address interoperability challenges. Achieving this integration facilitates the seamless flow of information and operations across diverse stakeholders. Conversely, vertical integration involves the integration of applications across different enterprise levels within and across entities, ranging from sensors and actuators to sophisticated Enterprise Resource Planning (ERP) systems. This vertical integration demands the reconciliation of temporal and semantic gaps among the diverse enterprise levels, ensuring the cohesive functioning of the entire supply chain ecosystem. In essence, the realization of both horizontal and vertical integration is essential for harmonizing the objectives and operations of the multifaceted stakeholders within the supply chain. A simplified layered framework with the integration of blockchain and AI is illustrated in Figure 1. In this framework, the initial management of the supply chain is handled at Basic Function Layer, Advance Function Layer, Smart Layer, and PLM, PDM Layer. AI is employed at the Edge Layer of the framework. Whereas Blockchain is employed at each step of the proposed pipeline. As, ERP systems are discussed above, this framework's PLM/PDM performs the same job.

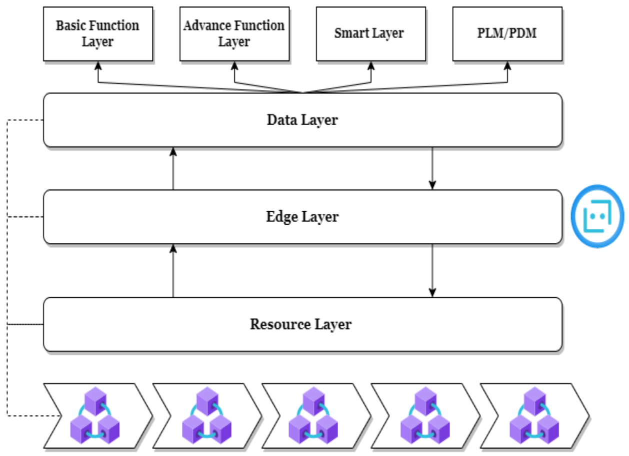

Figure 1. Simplified layered framework enhanced with the integration of blockchain & artificial intelligence

Illustrated in Figure 2 is a layered framework tailored specifically for a particular stakeholder, such as a tier-1 supplier. This framework is meticulously designed to address the dual imperatives of horizontal integration and vertical integration within the purview of Industry 4.0, leveraging the three-tier architecture of the Industrial Internet of Things (IIoT). It is essential to underscore that this layered framework is highly stakeholder-specific, necessitating all relevant stakeholders (except regulators and certifiers) to develop and implement systems that align with their distinctive requirements, guided by a similar layered framework. The individual layers within this framework are succinctly explicated in the subsequent paragraphs, outlining the key components and functionalities encapsulated within each stratum.

- **Process Layer:** This layer denotes the processes (e.g., operations) employed by the enterprises to fulfill the customer requirements. It is crucial to model the processes and the underlying data models using various tools (e.g., Unified Modeling Language (UML) and Entity Relationship Diagrams (ERDs)). Overall, the processes and model help carry out root cause analysis and support in building AI/ML models.
- **Resource Layer:** Resources are required to execute the previously defined processes. As part of smart manufacturing, most of the resources are automated systems with sensors and actuators. These sensors and actuators can send and receive data, respectively, utilizing various communication protocols (e.g., Profibus).
- **Edge Layer:** Data needs to move seamlessly across the layers. The edge layer is responsible for establishing a connection with the resources located in the resource layer and databases in the data layer. Additionally, the edge layer implements different communication protocols to acquire data from sensors and dispatch control data to actuators, involving preprocessing to address interoperability issues.
- **Data Layer:** Data is crucial for downstream activities (e.g., performance computation). Hence, data need to be stored in databases hosted either locally or in the cloud. Apart from automation systems, data can also be acquired from other enterprise applications (e.g., ERP System).
- **Basic Function Layer:** The previously stored data might contain data islands. Hence, it is crucial to establish relationships between data islands through tracking and traceability functionalities. It is also required to compute numerous financial and non-financial (or operational) Key Performance Indicators (KPIs) to provide a comprehensive view of an enterprise. Likewise, numerous reports for the

managers, line supervisors, and so forth can be generated.

- **Advanced Function Layer:** The functionalities required for managing the production, inventory, quality, and maintenance are encompassed in this layer. Here, the concerned operators are involved with day-to-day operations with manual decision-making. It is also possible to introduce automated decision-making through the features of the Complex Event Processing (CEP) engine, which in turn addresses the temporal and semantic gaps of vertical integration.
- **Smart Layer:** Industry 4.0 focuses on data and insights derived from the data. The layers mentioned above provide the data with the necessary context. Advances in AI/ML algorithms have been made, which can be employed to derive new insights to solve various issues of an enterprise.

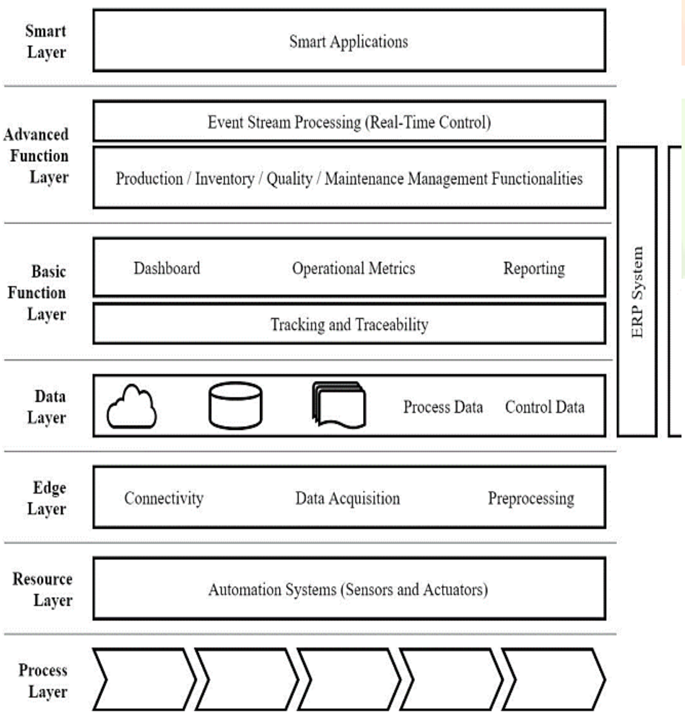

Fig 2. Horizontal and vertical integration within a stakeholder of a supply chain.

Traceability assumes a critical role post-data acquisition by establishing relationships among enterprise entities, including products and customer orders. These relationships serve as a foundation for higher layers of the framework, facilitating efficient root cause analysis, recall processes, and other functionalities. The establishment of traceability relationships is heavily reliant on essential components such as the Bill of Materials (BoM) and production routing, in addition to process modeling. The granularity of traceability is subject to variation based on factors like the product and production strategy. Item-level traceability, achieved through the unique tagging of a product or component for precise identification, proves advantageous in root-cause analysis and product recall. However, its implementation presents numerous technical challenges. In contrast, batch-level traceability involves the unique identification of identical products or components within a batch, ranging from a few to thousands. While offering less precise identification in root-cause analysis and product recall, its implementation entails fewer technical challenges, albeit incurring higher costs due to imprecise identification. Furthermore, traceability can encompass different types of traceable elements, including trade units and logistic units. Regardless of the chosen traceability granularity, the generation of unique identifications within and across enterprises is imperative. To facilitate this process, generic standards such as GS1 and AIM have been defined.

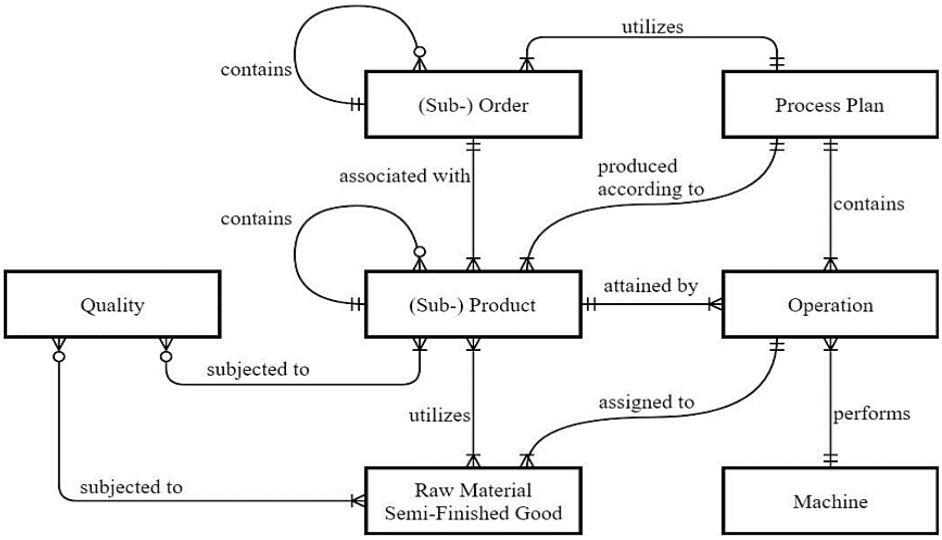

Fig 3. The entity-relationship diagram of enterprise entities.

Events or transactions, whether manual or automated, necessitate storage in a database with meticulous traceability, resulting in a substantial volume of data either stored locally or in the cloud. Leveraging AI/ML algorithms on this data can enhance internal processes' efficiency and effectiveness, albeit with a narrow context specific to the stakeholder in question. While useful in the short run, acquiring critical data feedback from diverse supply chain stakeholders is essential to establish a broader context. Blockchain technology has become paramount in addressing this need. Each supply chain stakeholder operates in a dual-mode environment, encompassing their existing IT infrastructure with numerous enterprise applications and an external environment involving suppliers, distributors, regulators, auditors, certifiers, and customers. These two sides are interconnected through blockchain, serving as a repository for critical control data from various stakeholders. While stakeholders store a significant amount of data in their respective databases, selected critical control data is stored in the blockchain, and accessible to other supply chain participants.

The data layer interacts with the blockchain component, facilitating the writing of data from the blockchain as transactions. Each transaction encapsulates corresponding critical control data, influencing performance and identified through collaborative efforts with other stakeholders. Similarly, stakeholders can read and store critical control data from the blockchain into their local databases, facilitating the exchange of information. This necessitates the implementation of suitable read-and-write services. The encoded blocks are immutable, ensuring security. The decentralized nature of the databases storing these blocks contributes to the overall robustness. Suppliers, responsible for preparing raw materials and semi-finished products, verify and store relevant information in blockchain blocks, focusing on monitoring processes from external entities' perspectives.

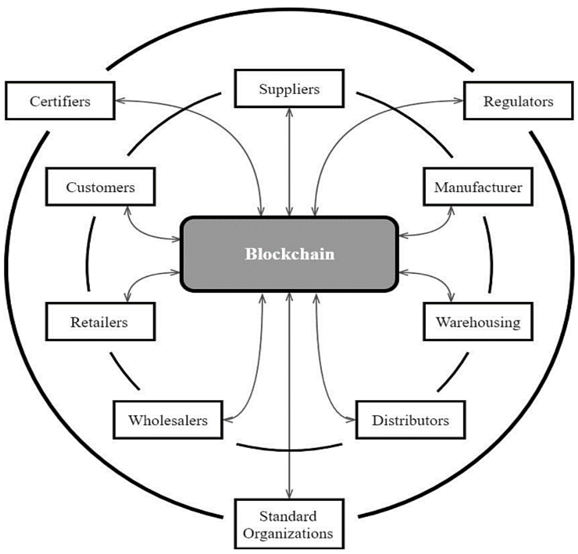

Figure 4. Exchange of information among stakeholders of a supply chain employing blockchain

Regulators, auditors, certifiers, and other authorized entities, having access to the blockchain, can retrieve information stored in the blocks to validate operations. For instance, certifiers can verify if operations align with the prescribed procedures or identify any deviations. They can also ascertain whether a machine was calibrated as per specifications before initiating operations. This fosters increased trust among partners, enhances transparency regarding products, and ensures the security of products. The application of suitable AI/ML algorithms becomes pivotal in realizing an intelligent supply chain, incorporating the use of a Complex Event Processing (CEP) engine. Initially, AI/ML algorithms will be implemented on data specific to a single stakeholder, facilitating the identification of new insights and the initiation of corrective actions. The discovery of new insights can be significantly amplified when the data is extracted from the blockchain to establish a broader context. In summary, AI/ML algorithms will be extended to operate on data associated with multiple stakeholders following the implementation of blockchain.

IV. RESULTS & DISCUSSION

Recent technological advancements, exemplified by blockchain, AI, cloud computing, IoT, cyber-physical systems, and robotics, collectively constitute the components of Industry 4.0. These developments pave the way for the integration of diverse advancements in the supply chain, culminating in intelligent and connected Systems of Systems. Such technologies have the potential to fortify supply chain management, fostering a transition towards data-driven, agile, intelligent, and automated operations. Table 3 elucidates recent studies showcasing applications across various sectors, encompassing healthcare, business, financial services, the automobile industry, and humanitarian logistics. For instance, researchers have emphasized the criticality of integrating disparate technologies in the humanitarian supply chain to realize tangible benefits. Proposing a framework, these scholars aim to enhance the flow of information, products, and financial resources within humanitarian supply chains through the integration of three disruptive technologies: blockchain, AI, and 3D printing. Their analysis underscores the framework's potential to mitigate supply chain congestion, facilitate simultaneous collaboration among stakeholders, reduce lead times, enhance accountability, traceability, and transparency of material and financial resources, and empower victims to actively contribute to fulfilling their needs. Moreover, applications extend to combining blockchain with machine learning, enabling continuous system improvement, rapid response to disruptions, and the anticipation of potential failures. This amalgamation of technologies holds promise for systems to evolve dynamically, ensuring heightened responsiveness and predictive capabilities in the face of uncertainties.

The enhancement of data quality, transparency, traceability, and security through blockchain technology contributes to the augmentation of capabilities in other domains such as AI and IoT, particularly in processes involving monitoring, trend prediction, and decision-making. The synergistic integration of blockchain, AI, and supply chain functionalities holds the potential to refine information management for interconnected devices. A recent study has proposed a pragmatic approach by integrating blockchain with federated learning, thereby ensuring private and secure big data analytics services. In the context of supply chains, the confluence of blockchain and AI is driven by the imperative of information management. Utilizing blockchain facilitates the establishment of a reliable and secure digital infrastructure, capable of digitizing various operational facets within the supply chain. The integration of blockchain and AI in information management tasks yields administrative benefits, including time savings, enhanced information quality, and heightened security. Ongoing research endeavors are dedicated to further exploring and refining these developments.

Blockchain-based smart contracts represent computer programs designed to execute contract terms when specific conditions are met. This technology holds potential applications in automating auditing processes, managing medical supply chains, tracking outbreaks, and monitoring patients remotely. The implementation of smart contracts on blockchain can enhance pharmaceutical supply chains, ensuring improved quality and regulatory compliance while streamlining auditing procedures. The integration of blockchain-based smart contracts and AI technologies has been explored in various domains, particularly in addressing public health challenges such as the Covid-19 pandemic. These technologies offer solutions for conventional public health strategies, including contact tracing, outbreak estimation, coronavirus detection and analysis, clinical data management, and supply chain optimization. This integrated approach, facilitated by blockchain and AI, can reshape healthcare towards a more patient-centered model, optimizing treatment distribution and pandemic management. The synergistic utilization of blockchain and AI technologies enables the creation of comprehensive predictive systems, enhancing a country's ability to mitigate the threat of pandemics. Furthermore, by combining blockchain with AI and geographic information systems, the public surveillance system can be fortified, creating a more efficient and robust framework for monitoring and responding to public health challenges.

In recent years, the complexity of supply chain networks, coupled with external factors, has led to disruptions in the supply chain. The most notable event underscoring the vulnerability of supply chains occurred with the onset of the COVID-19 pandemic in early 2020, drawing renewed attention to sustainability. The pharmaceutical and medical supply chain, in particular, experienced significant disruptions due to the sudden emergence and uncontrolled global spread of COVID-19. This crisis exposed the shortcomings of healthcare systems worldwide in effectively and promptly responding to public health emergencies. In response to these challenges, breakthrough technologies such as blockchain and AI have emerged as viable and sustainable solutions to address the pandemic's impact. Researchers have increasingly focused on exploring the applications of these technologies in the context of medical supply chains and pharmaceutical supply chain management. This research endeavors to uncover innovative approaches to enhance the resilience and efficiency of supply chains in the face of unforeseen disruptions, particularly in the healthcare sector.

V. CONCLUSION

The article introduces a layered framework designed to actualize smart manufacturing within a specific stakeholder of a supply chain. Given the interconnected nature of supply chain operations, effective data exchange and feedback mechanisms among various stakeholders become imperative to enhance overall efficiency and meet customer requirements efficiently. This necessitates a collaborative effort to agree upon and define critical control data that will be exchanged within the network of supply chain stakeholders. Subsequently, the initial framework is refined to incorporate blockchain technology, facilitating seamless information exchange among diverse stakeholders within the supply chain. The incorporation of blockchain enhances the transparency, security, and integrity of data shared among stakeholders. This curated dataset serves as a valuable resource for the development of Artificial Intelligence/Machine Learning (AI/ML) models, specifically tailored to address identified challenges or situations within the supply chain. These AI/ML models, once developed, are seamlessly integrated into the layered framework as smart applications. This integration augments the decision-making capabilities and operational efficiency of the stakeholders within the supply chain, contributing to the overarching goal of achieving smart manufacturing. The symbiotic relationship between blockchain, data exchange, and AI/ML applications within the layered framework underscores a comprehensive approach to enhancing the intelligence and adaptability of manufacturing processes within the given stakeholder's domain.

Blockchain and AI technologies are rapidly advancing, ushering in unprecedented opportunities for data utilization that were hitherto inconceivable. This dynamic tandem is spearheading innovation and instigating a transformative paradigm shift across diverse industries. While the intersection of blockchain and AI has been explored within the extant literature on operations management, a comprehensive state-of-the-art review specifically addressing their integration in the domain of supply chain management is notably absent. This article seeks to fill this gap by presenting the first comprehensive overview and evaluation of existing studies in this realm. The ensuing discussion outlines several prospective research directions, aiming to address the third research question posed in this study.

Primarily, the majority of the reviewed works exhibit a conceptual rather than empirical nature, signifying a dearth of empirical studies dedicated to the practical implementation of blockchain-AI applications in real-world scenarios. This conceptual bias limits the robustness of discussions on the subject. Given the nascent stage of blockchain and its integration with emerging technologies like AI, numerous challenges must be systematically addressed before realizing tangible benefits and enduring effects. Future research should, therefore, focus on empirical studies aimed at deploying AI-driven blockchain technology within supply chain contexts, thereby shedding light on its practical implications and long-term performance.

Secondly, the symbiotic integration of blockchain and AI holds significant promise, particularly in the healthcare sector, where it can potentially address prevailing ethical concerns. The tandem utilization of blockchain's data storage capabilities and AI's analytical prowess presents an opportunity for expeditious data analysis. Moreover, combining blockchain and AI with other technologies, such as cloud computing, can create more comprehensive and efficient systems. The convergence of these technologies holds potential for advanced medical systems that can be instrumental in managing future pandemics akin to the challenges posed by the coronavirus.

Thirdly, the analysis underscores the need for additional studies that delve into the integration of blockchain and AI from a triple bottom-line perspective, encompassing environmental sustainability, social implications, and economic considerations. Recognizing that blockchain and AI are fundamental tools, their long-term impact hinges on the overarching vision and strategies adopted by companies in governing daily operations. It is imperative to acknowledge the limitations of the analysis and findings, which are confined to the Scopus scientific database. While Scopus is chosen for its consistent citation metrics and precision, the insights are constrained by the database's scope. However, given Scopus's status as the largest repository of peer-reviewed literature, especially in Business, Economics, Management, and Social Sciences, there is confidence that the identified works offer a comprehensive snapshot of the current state of research on the integration of blockchain and artificial intelligence in the supply chain domain. Future studies can augment this work by exploring additional databases and expanding on the challenges and limitations of existing research. This study, nonetheless, aspires to serve as a foundational reference for subsequent research endeavors in this burgeoning field.

REFERENCES

[1] Kagermann H, Wahlster W and Helbig J 2013 Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0 Tech. Rep. Acatech

[2] Kagermann H 2018 Industrie 4.0 - Perspektiven für den Standort Deutschland Die zweite Welle der Digitalisierung Deutschlands Zukunftsprojekte Tech. Rep. Acatech

[3] Lu Y, Morris K and Frechette S 2016 Current Standards Landscape for Smart Manufacturing Systems vol 8107 (National Institute of Standards and Technology) ISBN 1069600690287

[4] Leiva C 2018 Three Functional Dimensions Converge on Smart Manufacturing Tech. Rep. Whitepaper 59 MESA International

[5] Dasaklis T K, Casino F and Patsakis C 2019 Defining granularity levels for supply chain traceability based on IoT and blockchain ACM International Conference Proceeding Series Part F1481 184–190

[6] Nakamoto S 2008 Bitcoin: A Peer-to-Peer Electronic Cash System URL https://bitcoin.org/bitcoin.pdf

[7] Wang W, Hoang D T, Hu P, Xiong Z, Niyato D, Wang P, Wen Y and Kim D I 2019 A Survey on Consensus Mechanisms and Mining Strategy Management in Blockchain Networks IEEE Access 7 22328–70

[8] Castro M and Liskov B 2002 Practical byzantine fault tolerance and proactive recovery ACM Transactions on Computer Systems 20 398–461

[9] Christidis K and Devetsikiotis M 2016 Blockchains and Smart Contracts for the Internet of Things IEEE Access 4 2292–2303

[10] Merkle R C 1988 A Digital Signature Based on a Conventional Encryption Function pp 369–78

[11] Galvez J F, Mejuto J C and Simal-Gandara J 2018 Future challenges on the use of blockchain for food traceability analysis TrAC - Trends in Analytical Chemistry 107 222–232

[12] Pournader M, Shi Y, Seuring S and Koh S C L 2020 Blockchain applications in supply chains, transport and logistics: a systematic

review of the literature International Journal of Production Research 58 2063–2081

[13] Manupati V K, Schoenherr T, Ramkumar M, Wagner S M, Pabba S K and Inder Raj Singh R 2020 A blockchain-based approach for a multi-echelon sustainable supply chain International Journal of Production Research 58 2222–2241

[14] Dash R, Rebman C and Kar U K 2019 Application of Artificial Intelligence in Automation of Supply Chain Management Journal of Strategic Innovation and Sustainability 14 43–53

[15] Swan, M. (2017). Anticipating the Economic Benefits of Blockchain. Technology Innovation Management Review, 7(10), 6-13. https://doi.org/10.22215/timreview/1109

[16] Chen, G., Xu, B., Lu, M., & Chen, N.-S. (2018). Exploring blockchain technology and its potential applications for education. Smart Learning Environments, 5(1), 1-10. https://doi.org/10.1186/s40561-017-0050-x

[17] Sultan, K., & Lakhani, R. (2018). Conceptualizing Blockchains: Characteristics & Applications. arXiv.org.

[18] Porter, M. G. (2019). Supply Chain Integration: Does Organizational Culture Matter? Operations and Supply Chain Management: An International Journal 12(1), 49-59. https://doi.org/10.31387/oscm0360222

[19] Saberi, S., Kouhizadeh, M., Sarkis, J., & Shen, L. (2019). Blockchain technology and its relationships to sustainable supply chain management. International Journal of Production Research, 57(7), 2117–2135.

[20] Dong, F., Zhou, P., Liu, Z., Shen, D., Xu, Z., & Luo, J. (2017). Towards a fast and secure design for enterprise-oriented cloud storage systems. Concurrency and Computation: Practice and Experience, 29(19), e4177.

[21] Abeyratne, S. A., & Monfared, R. P. (2016). Blockchain ready manufacturing supply chain using distributed ledger. International Journal of Renewable Energy Technology, 5(9), 1–10.

[22] Seuring, S., Sarkis, J., Müller, M., & Rao, P. (2008). Sustainability and supply chain management—an introduction to the special issue. Journal of Cleaner Production, 16(15), 1545–1551.

[23] Grimm, J. H., Hofstetter, J. S., & Sarkis, J. (2016). Exploring sub-suppliers' compliance with corporate sustainability standards. Journal of Cleaner Production, 112, 1971–1984.

[24] Crosby, M., Pattanayak, P., Verma, S., & Kalyanaraman, V. (2016). Blockchain technology: Beyond bitcoin. Applied Innovation, 2, 6–9.