Application of Blockchain in Supply Chain Management with Verification via Smart Contract and Automation

Divyansh Mulchandani Raghavendra Tiwary Shrey Gupta

Abstract

Blockchain is a distributed and decentralized ledger system that enables secure, permanent, and transparent verification of value exchanges among participants. While it was initially designed for financial transactions, its potential applications span a wide array of industries. One significant area of impact is supply chain management, where the involvement of multiple entities and complex business relationships often leads to challenges such as limited transparency, inadequate traceability, difficulties in risk and disruption management, and the need to establish trust among stakeholders.

To address these issues, blockchain offers a decentralized, immutable ledger and a consensus mechanism that ensures the accurate and tamper-proof recording of transactions—effectively mitigating risks related to the Byzantine Generals Problem and double-spending inconsistencies. This allows businesses to reliably track and document the movement of goods across the supply chain, from suppliers to end consumers.

Moreover, integrating Internet of Things (IoT) technologies with blockchain can enhance visibility by enabling real-time tracking of ownership, condition, and location of goods, as well as monitoring quality metrics. When paired with automated systems, machine learning (ML) techniques further support supply chain optimization through predictive analytics such as demand forecasting. Therefore, this study aims to explore how the integration of blockchain, IoT, and machine learning can enhance supply chain management by improving transparency, efficiency, and decision-making.

Keywords: Supply Chain Management (SCM), Digital Twin, Distributed Ledger Technology (DLT), Blockchain, Smart Contract, IoT, Artificial Intelligence

Paper Type: Book Chapter

Introduction

The Internet of Things (IoT) allows for the connection of common things to the internet. Without requiring any human-to-human or human-to-machine interaction, it enables us to collect monitored data from these devices across a network. In addition to having only sensors, effective IoT solutions with actuators can also assist us in directly controlling these devices from our control devices like phones or tablets. So, it can be in a variety of domains, including supply chain, agriculture, transportation, sports, health, the military, energy, and entertainment. [1][2]

As production goes globally, the supply chain gets increasingly complicated. Additionally, since the supply chain operations are hidden, unethical actors are free to tamper, corrupt, or substitute products as they move through the system. Therefore, it is also necessary to look into blockchain technologies based on the Internet of Things for the supply chain's challenges, which also helps us in the accurate and precise prediction of the Supply Chain Industry. Hence, the complete digitized process may help in accountability with safeguarding and reduce losses, but there may be weaknesses that are discovered through security mechanisms, fraud detection, digital forensics, and trend forecasting. [3][4][5]

Although centralised systems are acceptable in current architecture, they are not scalable, do not offer protection against reputation fraud, and are not fault-tolerant. So, it is necessary to transition from a centralised architecture to a decentralised architecture. For this, Blockchain is a distributed and decentralised network for computing and transferring knowledge that permits cooperation, coordination, and collaboration of numerous authoritative authorities in a logical decision-making process, even while they do not trust one another. For this, the blockchain ensures a variety of factors, including protocols for commitment, consensus, security, privacy, and authenticity. All transactions are recorded on the blockchain, which ultimately uploads the data to a distributed and decentralised ledger, which can take the form of an Interplanetary File Storage System, in order to maintain traceability, trust, and delivery mechanisms in the supply chain (IPFS). This can help us reduce the risks associated with cooperative relationships by providing a complete ecosystem of a supply chain, which typically consists of suppliers, regulators, production facilities, warehouses, distribution networks, wholesalers, retailers, and customers. [5][6][7][8]

The study can also help stakeholders assess their current supply chain procedures in order to enhance the supply chain. For this, blockchain maintains a distributed and decentralised record of digital transactions, which can further assist us in developing smart contracts with conditions and time locks. The basic concept behind the blockchain in this study is to provide the system with distributed architecture, consensus methods, and smart contracts so that it can have properties like decentralisation, and persistence. Furthermore, IoT, AI, edge computing, and the blockchain are some of the emerging technologies that are expected to make industry more intelligent, enable the traceability, transfer, integration, and mining of the data produced during industrial production, improve supply chain sustainability with optimization and forecasting, and finally automate procedures like supply chain smart contracts. [9][10][11][12]

Unfortunately, the reality is that there aren't many successful blockchain applications to draw from. In 2017, just 8% of the 26,000 blockchain projects that had been launched in 2016 were still being actively worked on. Major obstacles are posed by technological uncertainty, scaling problems, and development costs. Thus, the fundamental assumptions of transaction cost theory are not altered by blockchain, but, the ideal governance structure can change. [13][14][15]

The planning and supervision model used in supply chain management encourages the acquisition, supply, and procurement by diverse stakeholders in both logistical operations and adaption. It also incorporates theory and channel partner collaboration, which could encompass suppliers, middlemen, outside professional institutes, and customers. As a result, the study will further explore the effects of implementing automation using artificial intelligence in a supply chain framework. Automation also solves the problem of human interference, data inconsistencies, and tampering with Blockchain and IoT technologies. [16][17][18][19]

Related Work

In this section, we discuss and evaluate related supply chain system proposals that are based on IoT, Blockchain, and AI.

a) MQTT Protocol

For message queues and message queuing services, MQTT (MQ Telemetry Transport) is a lightweight publish-subscribe machine-to-machine network protocol. It is designed for communications with remote sites that have limited network bandwidth or resource-constrained devices, such as the Internet of Things (IoT). Its operation must be based on a transport protocol, most frequently TCP/IP, that allows organised, lossless, bidirectional connections.

The most recent version of the MQTT protocol, version 5.0, uses the unencrypted port 1883 or the encrypted port number 8883 by default. TLS is used for this to encrypt and protect the communicated data from interception, modification, and forgery, which can offer additional security feature.

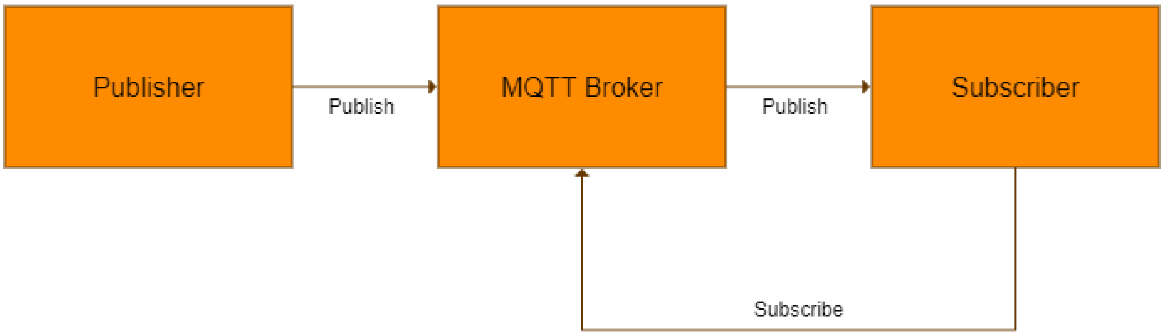

Figure 1. Working of MQTT Protocol.

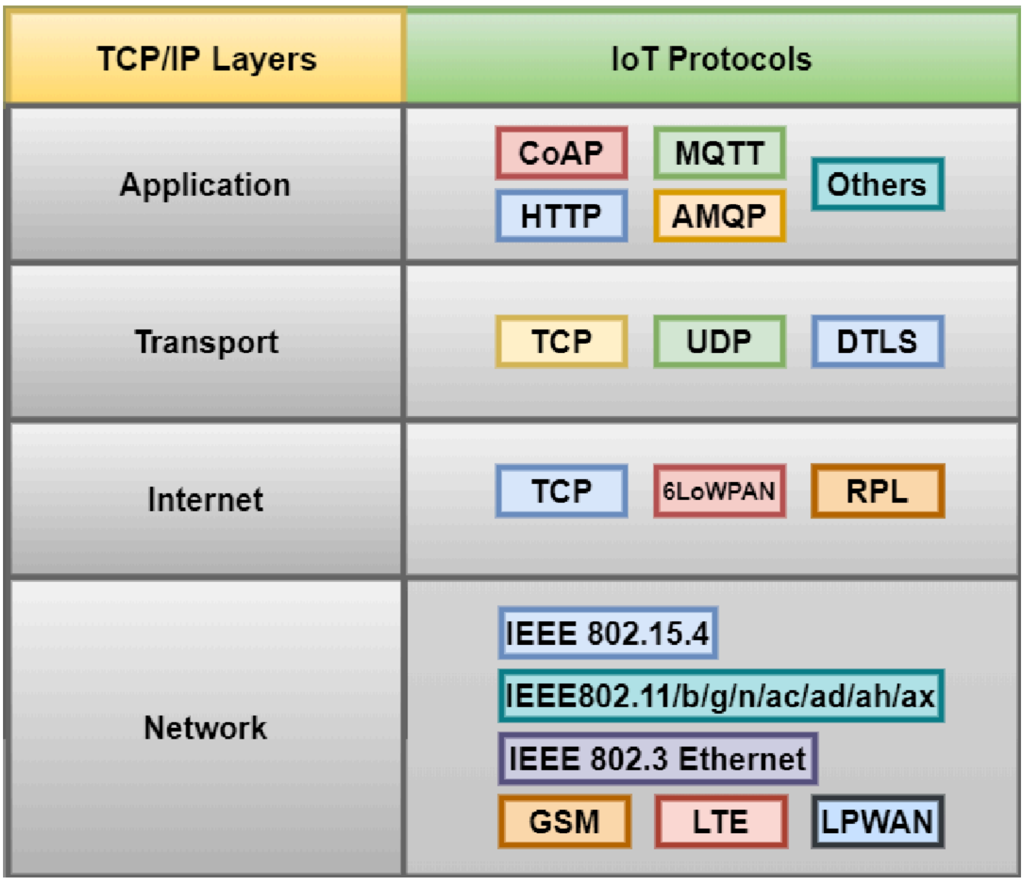

Figure 2. TCP/IP Model-Main IoT Protocols.

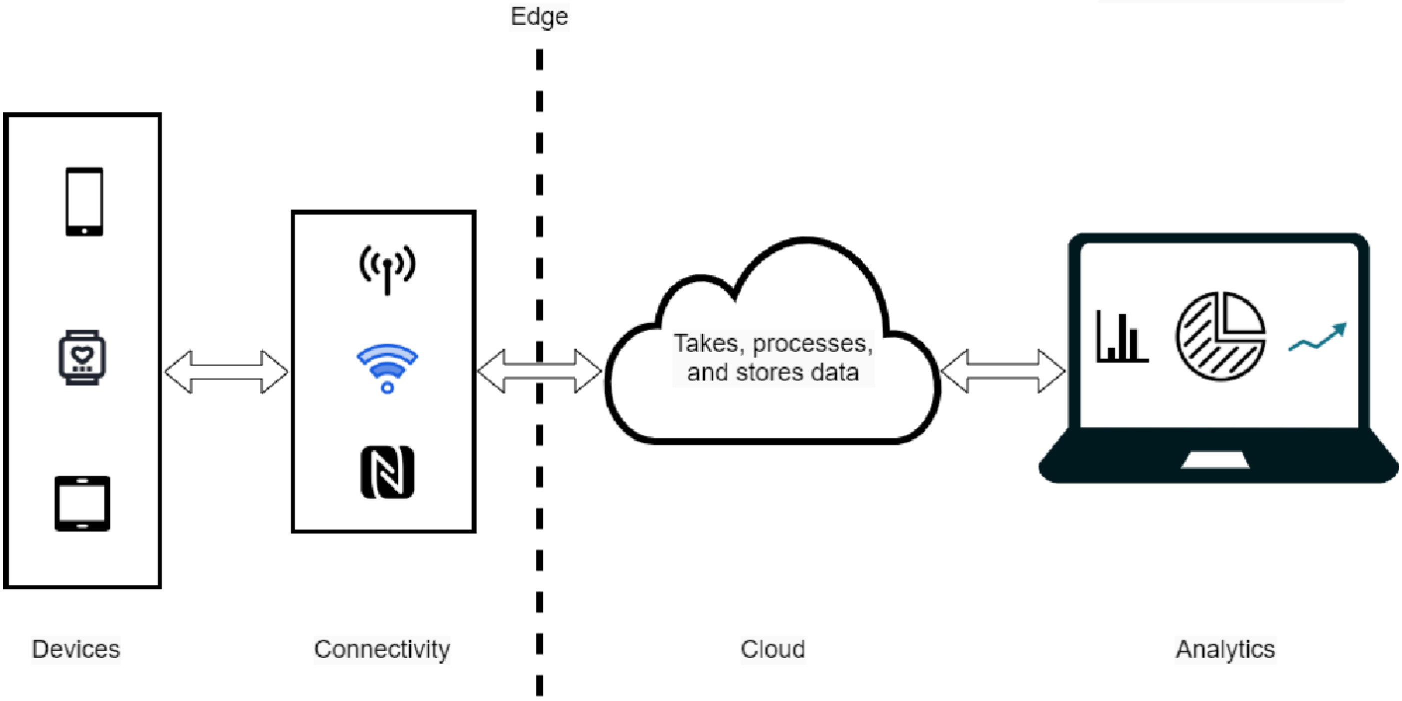

Figure 3. A general IoT architecture.

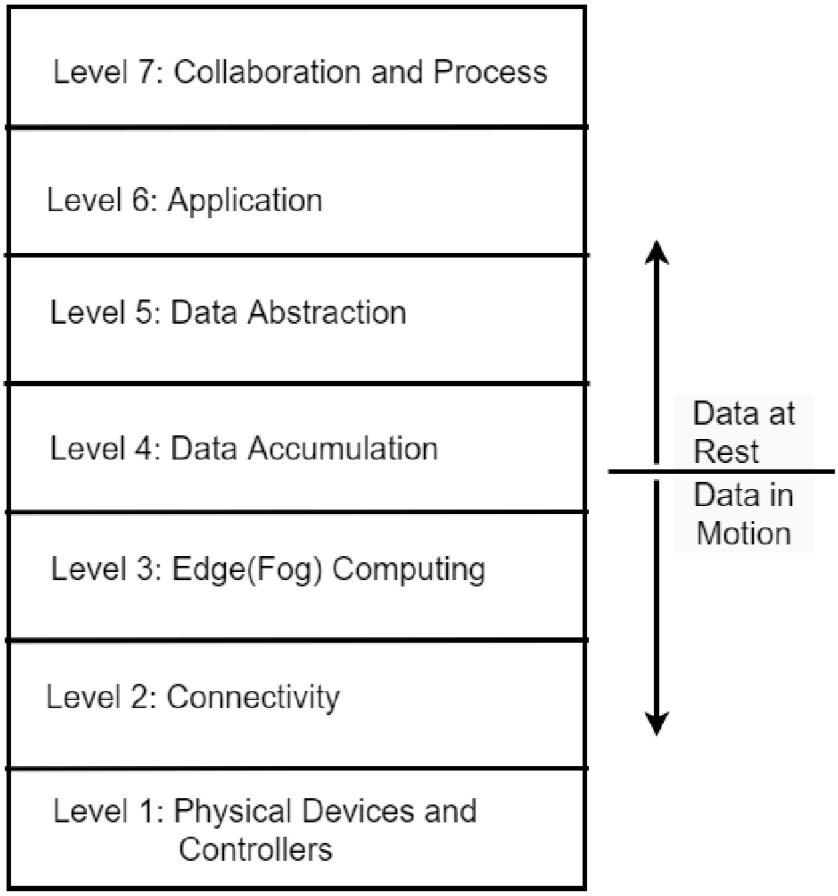

Figure 4. Different layers of the IoT Reference Model.

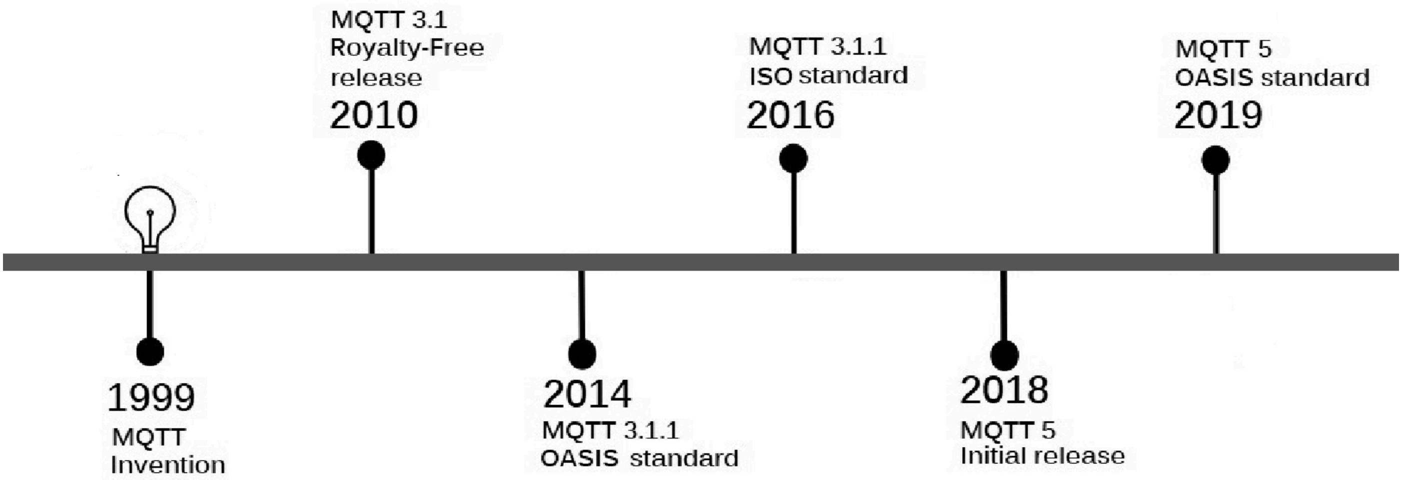

Figure 5. Timeline of MQTT development.

b) IoT based supply chain requirements

The supply chain-specific needs listed below must be met by the traceability system.

i) IoT data history: In order to create an event and object history, the traceability system must be able to manage and store data from various sensor devices.
ii) Completeness: In a traceability system, completeness refers to everything being present and correct when identifying data tracing lines throughout the supply chain.
iii) Accuracy: The accuracy of the traceability path to confirm the data's original source.
iv) Provenance: With a traceability system, it should be simple and quick to verify where the data came from and how it was processed.
v) Optimum update: The rate at which updates are detected and data is propagated during production events.
vi) Scalability: In an IoT world, the traceability system must be able to handle the expanding number of data sources.

c) IoT challenges

The primary difficulties with IoT domain traceability are listed below.

i) Complicated traceability: Given the multitude of interconnected devices, it is difficult to manage item tracing.
ii) Inability to detect erroneous data propagation: The lack of adequate solutions for the detection of faulty data propagation is one of the main issues and obstacles in the IoT.

d) IoT Traceability System Model

In order to satisfy these needs, authors have offered an IoT-based supply chain traceability solution. The main goal of supply chain traceability is to obtain an item's whole lifespan quickly and effectively. In order for traceability to deliver on its promise to business partners, it must be backed by adequate architectural and technical implementation solutions, as well as by relevant operational services. Hence, the architecture is presented below.

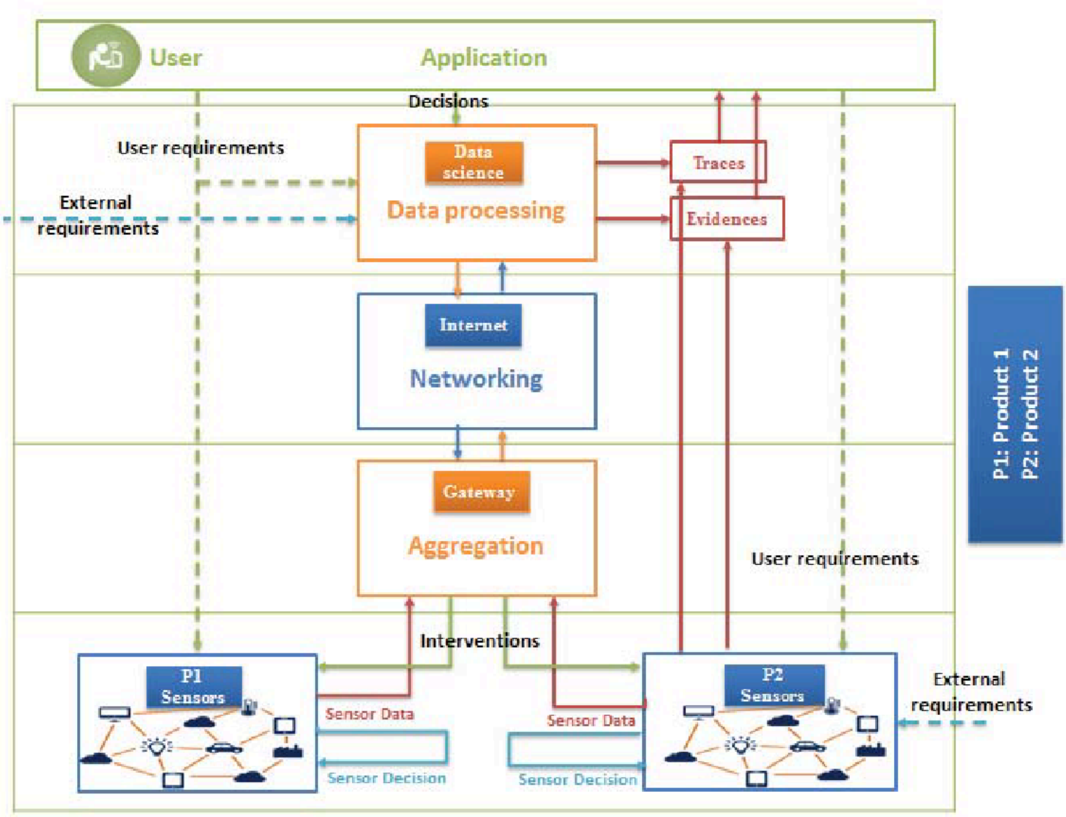

Figure 6. IoT based traceability system model and data flow.

e) IoT and Blockchain based Supply Chain Implementation

There are several checkpoints in the supply chain where fraud or poor management may take place, notably at the following 4 levels to provide adulterated, expired, low quality, or alternate counterfeit material.

i) Level 1

The first level of problems might start when the supplier delivers and supports processes relating to the raw materials (or/and business support) needed to make the product.

ii) Level 2

The Manufacturer is the next step in the management of the supply chain. The majority of fake goods and scams enter the market at this level since there are numerous ways to counterfeit a product or do the frauds.

iii) Level 3

The distributor is the third link in the supply chain management system. The operations are highly sophisticated, such as the employment of tracking tools to penetrate frauds and counterfeits into the real networks in addition to false networks.

iv) Level 4

Retailers and related affiliates make up the fourth link in the supply chain management chain. They are the root of the issue as a whole. Governments have repeatedly closed down these vendors, yet despite this, they continue to operate because of the low prices and convenience they provide.

For this, in the authentication procedure, both public and private keys are employed for authorized stakeholders and secured communication. In this, one entity's private key encrypts the message's content so that another entity can decrypt it using its own private key. The cryptography used to secure the protocol is based on asymmetric encryption modulo math, in which the key used to encrypt a transaction differs from the key used to decrypt it.

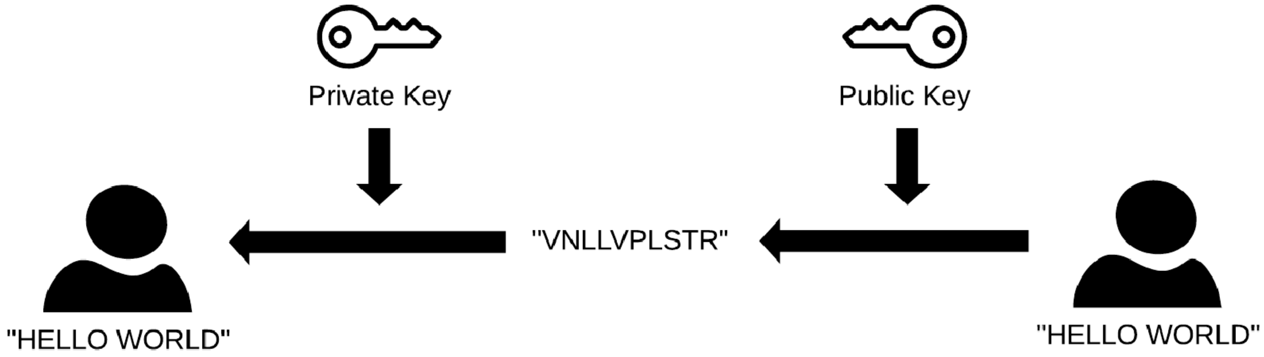

Figure 7. Asymmetric Cipher Schema.

Figure 8. Third-Party Centralized System.

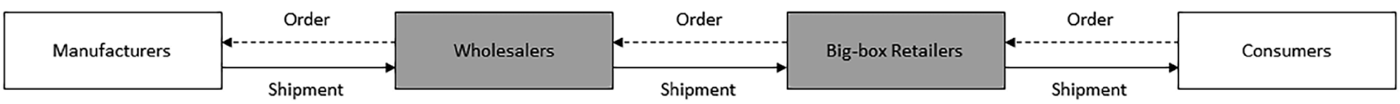

Figure 9. A two-stage supply chain conceptual model.

But nonetheless, a decentralised system of entities is networked, and each of them is in connection with transactions for a product or a service that has been verified and approved. Every time a node or entity takes any action, all other entities are alerted, and the consensus mechanism is then used to assess the validity of the action. A new block will be added to the chain once the entities have authenticated it. Due to the availability of substitute proofs, which are automated and faster, for document exchange and paperwork, this idea lowers risk and fraud, increases traceability, and removal of escrows through smart contract mechanisms.

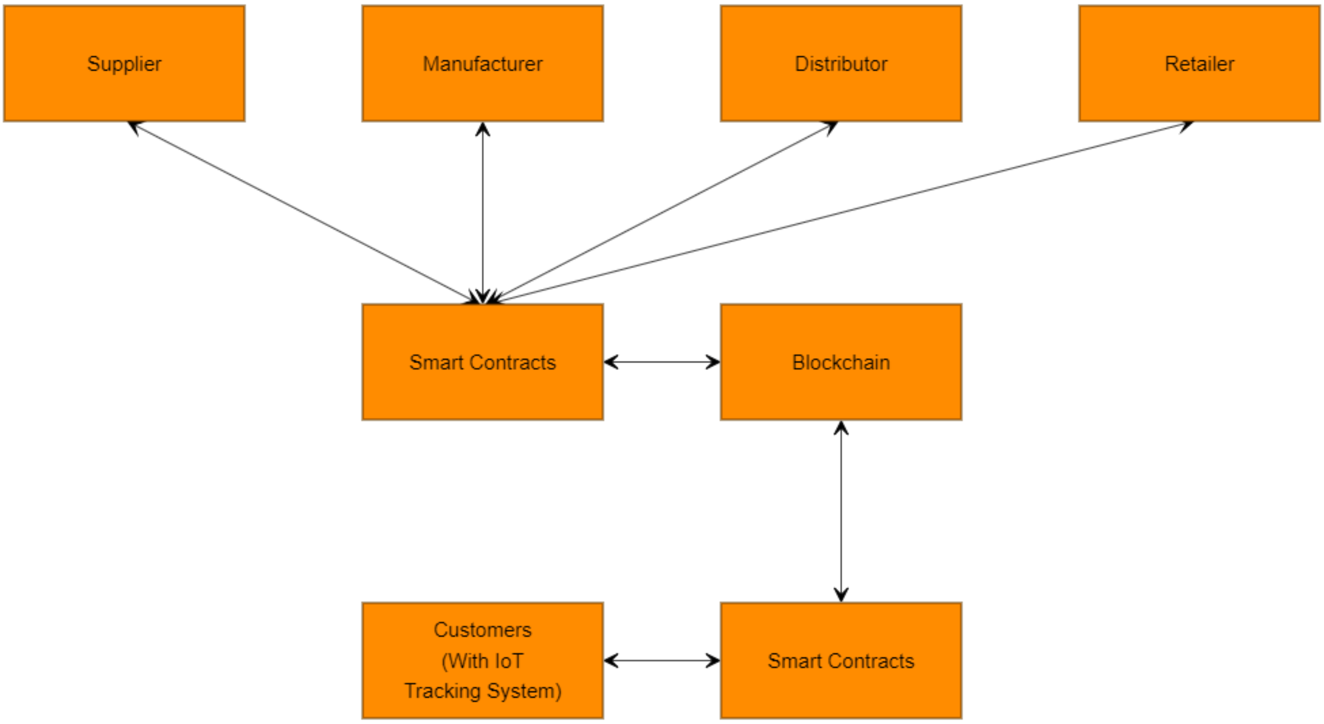

Figure 10. Decentralized Blockchain System with Smart Contract.

Nevertheless, given the lack of data brought on by the novelty of the blockchain and in keeping with a request for the use of innovative research techniques. Thus, researchers have also suggested using design science, based on cost theory, in supply chain management with recent technological advancements. Here, design science is a kind of research that focuses on creating solutions for real-world problems.

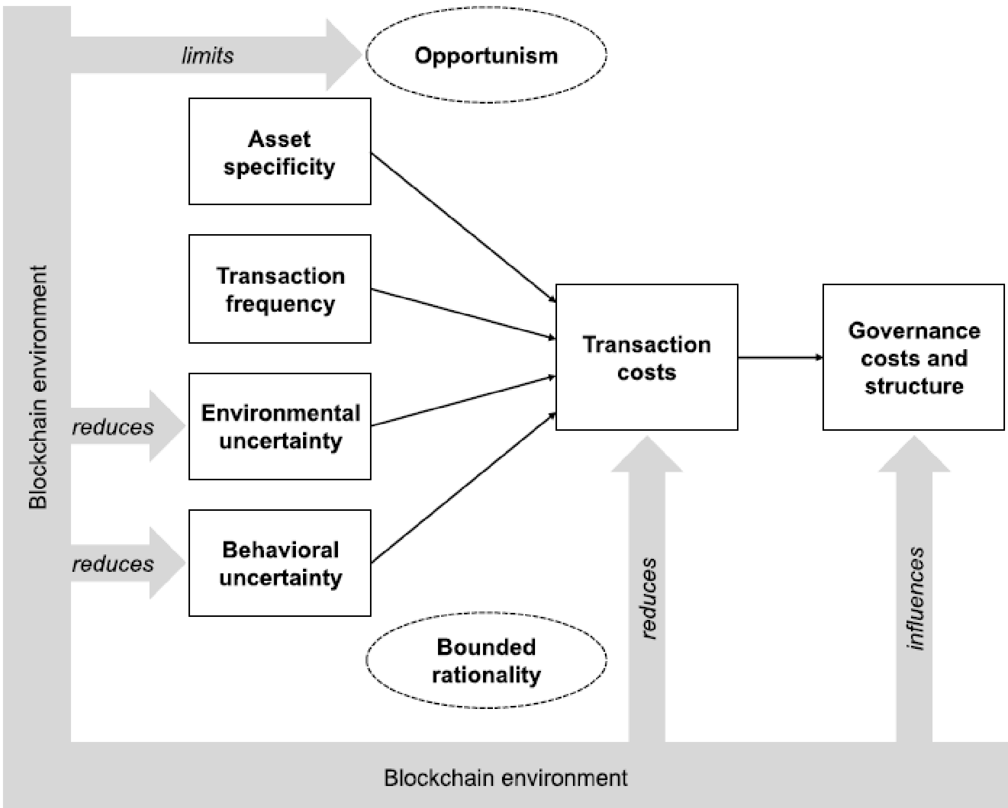

Figure 11. Framework of potential blockchain implications.

f) Artificial intelligence in Supply Chain Management

Artificial intelligence is crucial to supply chain management and global logistics. Because it creates opportunities for cost savings through demand forecasting, purchasing requirement planning, production planning, inventory, packaging, transportation, warehousing, and distribution planning, as it can offer more automated risk management and competitive advantages over rivals. Additionally, risks and uncertainties linked to information acquisition and consistent aspects that artificial intelligence cannot handle, which can be eliminated by carrying out related data activities based on the blockchain mechanism of block time, lock-in duration, and smart contract conditions.

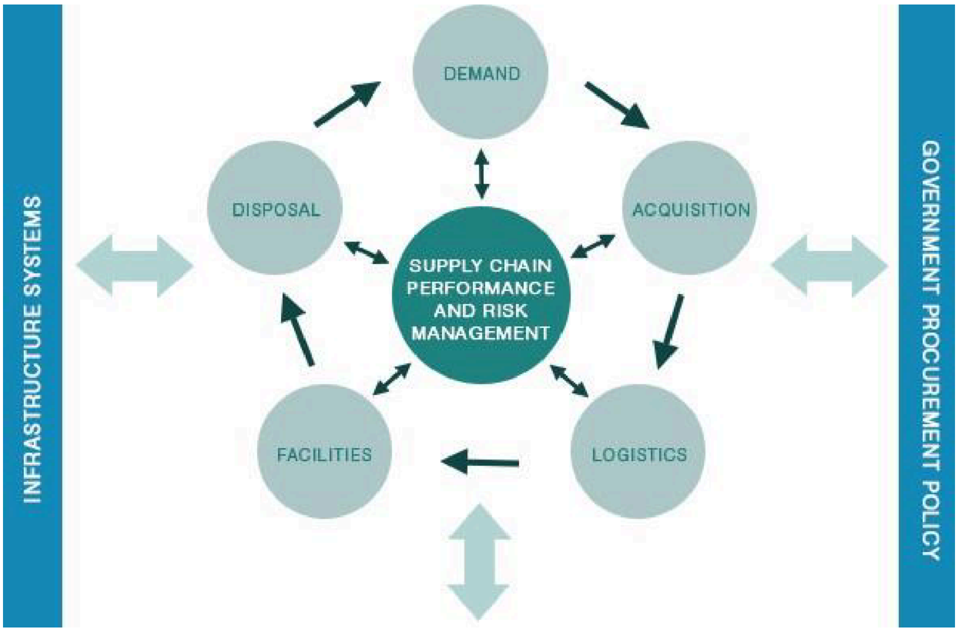

Figure 12. Supply Chain Management Framework.

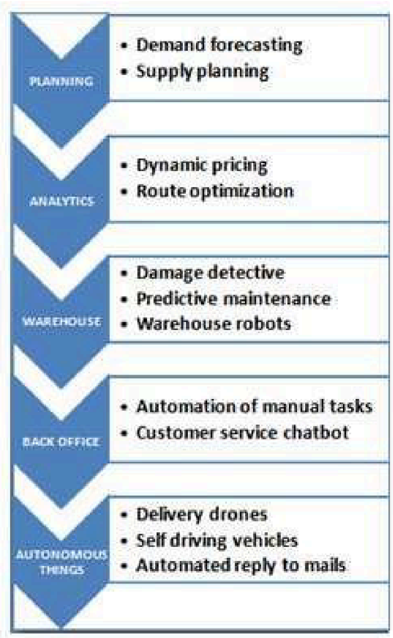

Figure 13. Allied applications of Artificial Intelligence.

Proposed Methodology

a) Dataset

Exploratory studies offer a suitable strategy to progress the topic and launch an academic discussion because there are many unstudied and novel technologies and how it will affect supply chain management. So, the purpose of this exploratory study is to identify and describe the patterns that are brought about by blockchain, IoT, and AI in supply chain management. For this systematic exploratory investigation, custom empirical data is being developed and used for the study.

b) Materials and Method

Making the decision to adopt a certain blockchain is a crucial decision that necessitates consideration of both its cost and general dependability.

Ethereum is one of the few blockchains that supports smart contracts, which let users run quick and easy applications on the blockchain using the EVM (Ethereum Virtual Machine). The blockchain network's machines (nodes) all run these programs, guaranteeing the accuracy of the output, which cannot be changed by just one or a small number of nodes. Through a consensus system, users of the created blockchain keep this ledger up to date (it can only be added to, not changed), and the more users there are, the more successful the network is. In fact, a large number of participants is necessary to guarantee the data's immutability.

c) System Architecture and Working

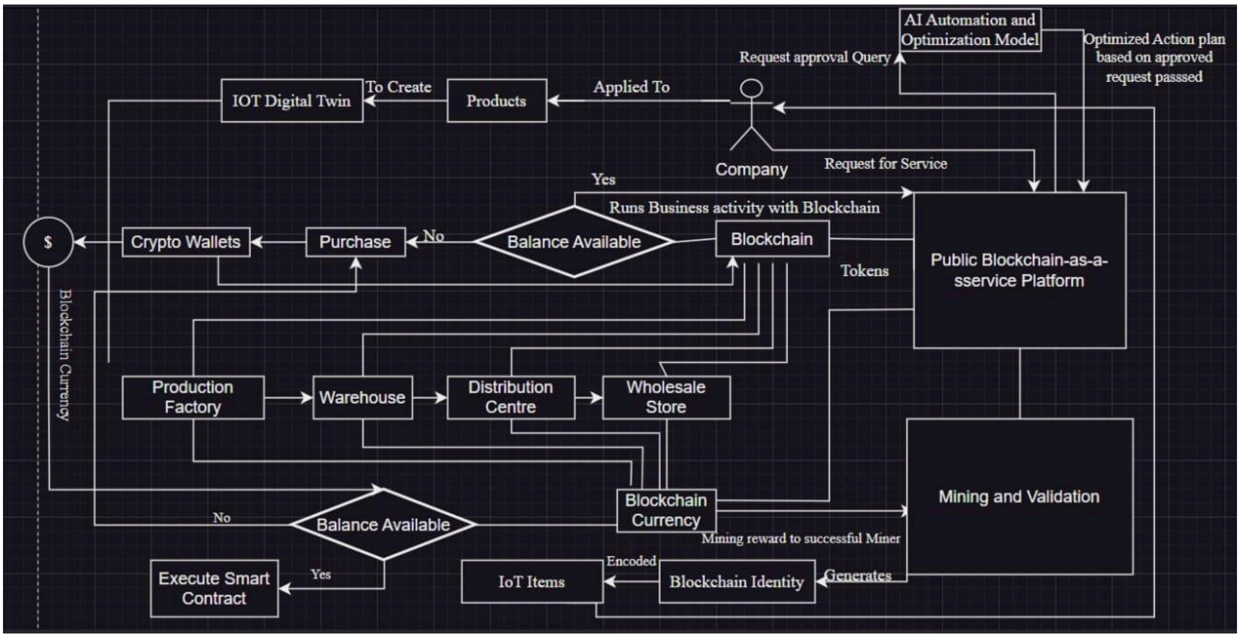

Figure 14. System Design of the Research Model.

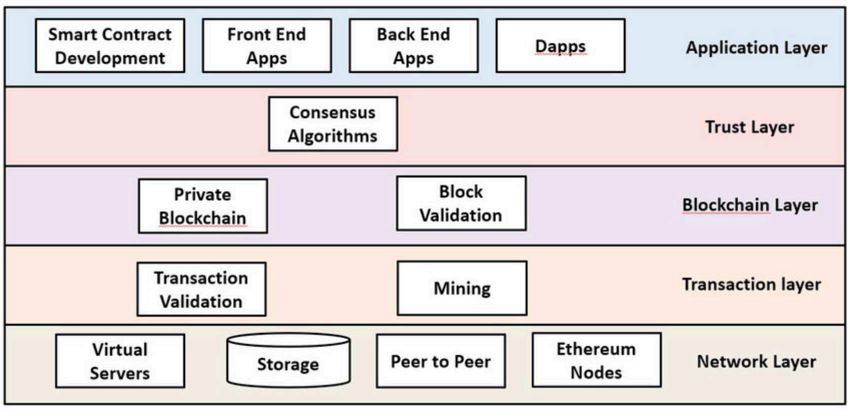

Figure 15. Proposed System Model, through private, or managed blockchain network.

The system model is described below in more detail.

i) A business that wants to use blockchain to track the products it sells asks for a track and trace solution for their supply chain.
ii) The request is passed to AI for getting the optimized action plan.
iii) The system that generates a BID is told how many items there are (Blockchain Identity). The mining procedure that yields the BIDs uses a mining algorithm such as delegated PoS, delegated PoA, or PoW.
iv) The successful miner is rewarded with a Blockchain token.
v) The BID is encoded into the custom IoT items that are produced in-house (such as RFID trackers, QR codes, etc.) to track the item over its lifetime.
vi) The organization integrates these IoT devices with their products and upgrades them to the status of the system's digital twin.
vii) The Blockchain service provider updates relevant information as the products are transferred to departments and stakeholders.
viii) The collected data is passed to AI for analysis.
ix) Smart contracts contain programmed logic relating to transactions and business agreements between the stakeholders, and their execution requires blockchain tokens.
x) The smart contracts executed are used by AI for further model training.
xi) If there aren't enough blockchain tokens, more can be bought and converted to blockchain tokens. Through Blockchain wallets, FIAT money is converted to bitcoin, which is then converted, for instance, through Binance, into blockchain tokens.
xii) Blockchain tokens are used for commercial operations and for blockchain interaction. Any deficiency is remedied by purchasing it from wallets, converting FIAT money into Bitcoin, and then transferring it to the blockchain tokens.

d) Evaluation

The simulation model computes the order fill rate, the inventory on hand, the total inventory costs, the average inventory cost per day and per item, revenues, expenses, and net profit as part of supply chain performance metrics. For this, just after the close of business, both wholesalers and big-box retailers compute their fill rates as the ratio of the number of fully satisfied orders, FSOik(t), to the total number of orders, TOik(t).

$$FRik(t)=FSOik(t)/\ TOiK(t)\ \forall i,k,t$$

Formula 1. Performance metric rates

as the proportion of fully fulfilled and satisfied orders to total orders.

Highlighted Results

This chapter explores the transformative potential of blockchain in supply chain management, with a focus on verification through smart contracts and process automation. It introduces a comprehensive architecture that integrates Blockchain, IoT, and Artificial Intelligence (AI) to improve traceability, transparency, and operational efficiency across complex, multi-tier supply chains.

The study proposes a decentralized framework powered by Ethereum-based smart contracts, digital twins, and predictive analytics to enable real-time decision making. Through systematic evaluation and defined performance metrics, the model illustrates how blockchain enabled automation can overcome trust deficits, reduce fraud, and optimize workflows in intricate supply chain ecosystems.

To support such systems, cloud native technologies, combined with data engineering pipeline logic, are leveraged for parallel and distributed processing. This facilitates efficient handling of asynchronous task queues and modular data flows within service oriented architectures. When integrated with vector databases, the platform supports advanced AI, deep learning, and large language model driven predictions, driving the development of high performance autonomous decision systems.

Additionally, platforms commonly utilize Redis and in-memory databases such as ASDB to enhance interprocess communication, distributed computing, and task scheduling. For fault tolerance and high availability, dual boot partitions spanning one or more disks contribute to resilience in both standalone systems and multi node clustered environments.

From a functional standpoint, wholesalers with varying levels of system visibility can access near real time insights into product demand. Meanwhile, end users are empowered to track every stage of the product journey throughout the supply chain, ensuring its authenticity and integrity. This seamless data flow enables robust real time analytics and informed decision making across all tiers.

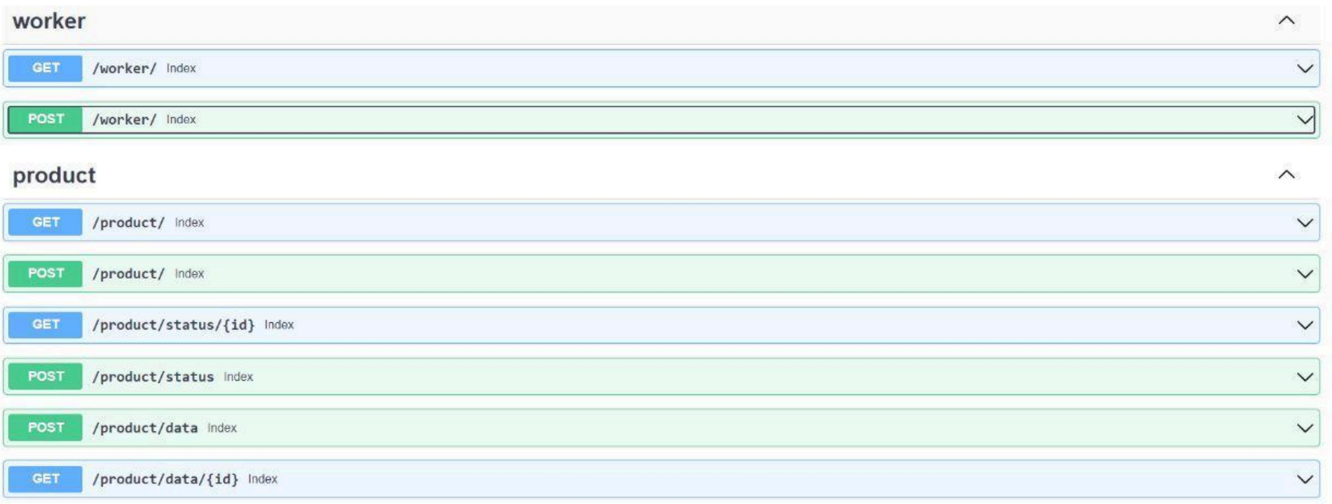

Figure 16. Backend APIs for Frontend and Blockchain integration.

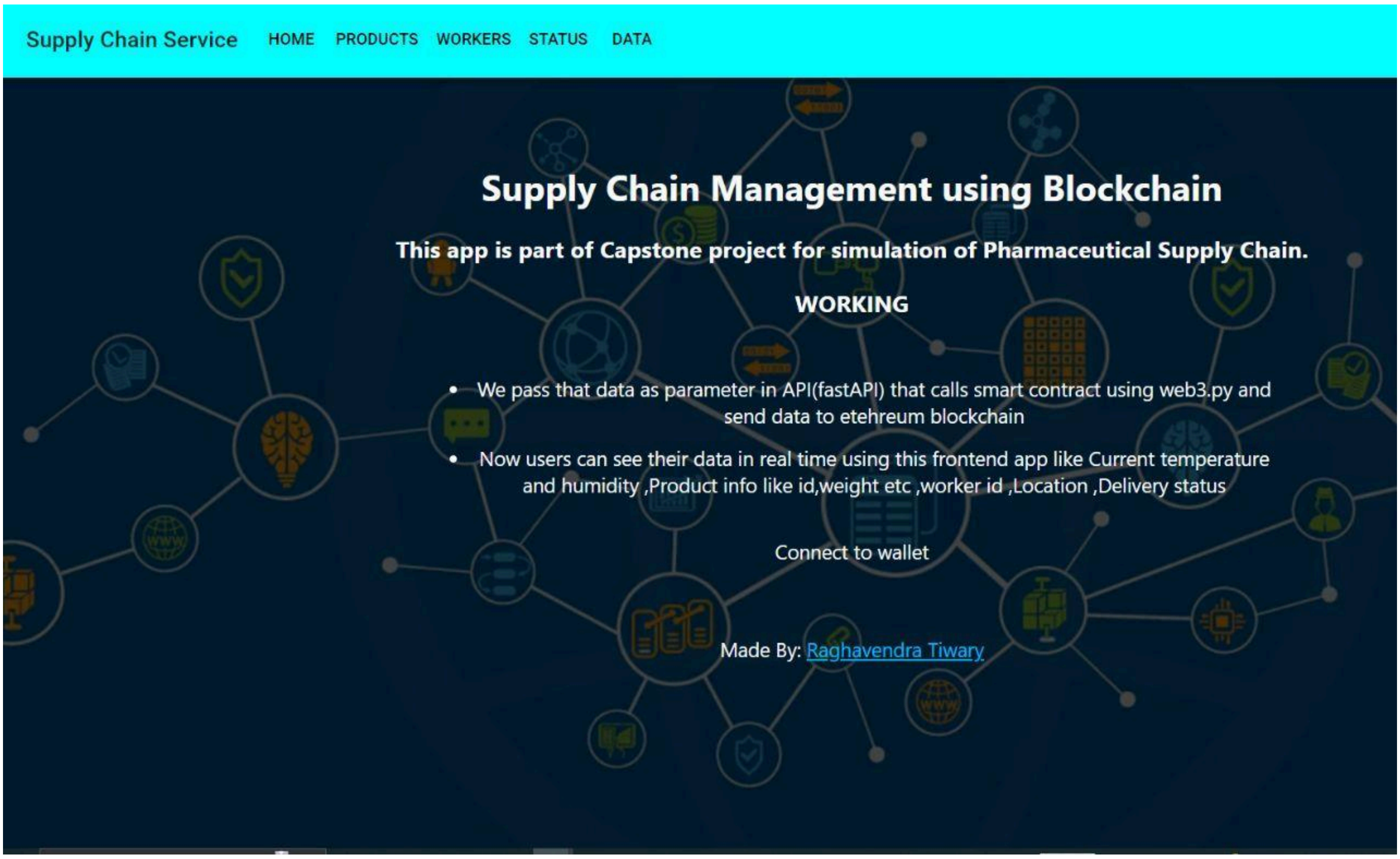

Figure 17. User Interface for Supply Chain.

Discussion

Two possibilities are taken into consideration for this study's purposes in the order listed below.

i) In the first scenario, known as No-IS (No Information Sharing), big-box retailers and wholesalers do not share information about the lead time demand because there is little trust between the parties, or even if information is shared, the companies do not trust one another and the data is assumed to be useless for forecasting and planning.

ii) In the second scenario, each big-box retailer shares information about the lead time demand with a select number of wholesalers at the conclusion of each business day. Wholesalers can use the hash sum of the data stored in the blockchain in this situation, known as B-IS (Blockchain-enabled Information Sharing), to verify the data's authenticity and invariability over time, creating a secure point of trust.

Proposed Conclusion

The effectiveness of companies within a supply chain relies heavily on access to accurate and timely data. However, trust deficits often hinder the willingness of firms to share or utilize such data. Even when data is accessible, concerns persist regarding the possibility of misinformation, whether intentional or accidental, it can undermine collaboration and disrupt supply chain planning.

To address these issues, businesses are increasingly seeking secure solutions that facilitate transparent information exchange while ensuring the verifiability and integrity of data. Blockchain technology emerges as a promising solution by offering a decentralized and immutable ledger that creates a single, tamper-proof source of truth. This capability not only fosters trust among supply chain partners but also discourages unethical practices, such as falsifying or manipulating data.

While blockchain has gained significant traction in the financial sector, its adoption in supply chain management remains nascent. Many firms are still unfamiliar with its practical applications due to limited use cases and empirical studies. Nevertheless, early evidence suggests that blockchain can resolve critical issues of collaboration, trust, and information asymmetry across supply chain divisions.

This study contributes to the growing body of research on blockchain's role in supply chain management by simulating a blockchain-enabled supply chain environment. The findings encourage further exploration of blockchain applications, providing a foundation for future studies aimed at demonstrating the tangible benefits of this technology in real-world supply chain operations.

Future Scope of Work

Blockchain scalability is becoming a difficult problem in large scale systems, along with rising cyber security issues. Also, using a cryptographic technique known as zero-knowledge proof, the privacy preservation concern is addressed. With this method, no information is released during a transaction other than the exchange of a value that is known to both the prover and the verifiers.[20][21][22][23]

Additionally, digital twins, virtual models which replicate physical supply chain processes, are transforming sustainable supply chains through AI and IoT advancements. They enable real-time monitoring, predictive analytics, and optimization, helping minimize waste, improve resource efficiency, and support eco-friendly production. By enhancing transparency and integrating with circular economy practices, they facilitate closed-loop supply chains, reducing carbon footprints and promoting sustainability. [24]

To enhance network security, deploy robust segmentation strategies incorporating router ACLs, stateful packet inspection, firewalls, and DMZ configurations. Utilize VLANs and private VLANs (PVLANs) with or without site-to-site or site-to-client VPNs for refined separation, reinforcing a defense-in-depth approach. Ensure device group isolation through TLS 1.3 as the transport mechanism, leveraging Public Key Infrastructure (PKI)-based certificates rather than self-signed certificates. Permit only essential entries for communication, management, and time synchronization (NTP and PTP). In network security, these processes of validation and verification further uphold the core principles of CIA (Confidentiality, Integrity, and Availability) and AAA (Authentication, Authorization, and Accounting). [25]

Declaration of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The author is an Editorial Board Member/Editor-in-Chief/Associate Editor/Guest Editor for this journal and was not involved in the editorial review or the decision to publish this article.

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Conflicts of Interests

There is no conflict of interest declared by the authors. The manuscript's published version has been read and approved by all authors.

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