Yugoslav Journal of Operations Research
35 (2025), Number 3, 483-500
DOI: https://doi.org/10.2298/YJOR231115026M

Research Article

ENHANCING SUPPLY CHAIN EFFICIENCY THROUGH BLOCKCHAIN TECHNOLOGY: A CENTRALIZED MULTI-DISTRIBUTOR AND MULTI-RETAILER APPROACH

Ritu MOTLA
Department of Mathematics, Meerut College, Meerut, India
ritumotla121@gmail.com

Neha SAXENA
Department of Mathematics, Swami Vivekanand Subharti University, Meerut, India
nancineha.saxena@gmail.com, ORCID: 0000-0001-7946-9845

Ashok KUMAR
Department of Mathematics, Meerut College, Meerut, India
drashokkumar@meerutcollege.org

Shib Sankar SANA*
Kishore Bharati Bhagini Nivedita College(Co-Ed), Behala, Kolkata-700060, India.
shib_sankar@yahoo.com, ORCID: 0000-0002-7834-8969

Received: November 2023 / Accepted: April 2024

Abstract: Blockchain technology has emerged as a transformative solution for supply chain management, offering a myriad of benefits to the industry. This paper explores the potential benefits of incorporating blockchain technology into supply chain management to enhance security and trustworthiness. We present a centralized supply chain system comprising a single manufacturer, multiple distributors, and multiple retailers. Geographical divisions have been assumed among distributors, each catering to a specific area with its own set of retailers. Mathematical expressions are developed to determine the optimal replenishment policies for the manufacturer, distributors, and retailers. Numerical examples are provided to illustrate the results, and sensitivity analysis is conducted to assess the model's responsiveness to parameter variations. Finally, managerial insights are discussed, shedding light on the implications and advantages of the proposed blockchain-based supply chain management system.

* Corresponding author

Keywords: Inventory modelling, block chain, supply chain, multi retailer, multi distributer.

MSC: 90B05.

1. INTRODUCTION

Blockchain technology plays a pivotal role in enhancing inventory control throughout the supply chain, presenting numerous advantages that contribute to increased efficiency and accuracy. One of its primary benefits in inventory management lies in the real-time visibility it affords. Through a shared and immutable ledger, all participants in the supply chain can access current information on inventory levels, product movements, and demand fluctuations. This transparency serves as a preventive measure against both overstocking and stockouts, ultimately optimizing inventory levels and reducing carrying costs.

In addition to real-time visibility, blockchain's end-to-end traceability is crucial for effective inventory control. Every transaction and movement of goods is meticulously recorded in the blockchain, establishing an unbroken chain of custody. This feature empowers supply chain managers to precisely track the location and status of products at any given moment. Consequently, identifying inefficiencies, anticipating delays, and addressing potential bottlenecks become more straightforward, facilitating informed decision-making and timely corrective actions. Furthermore, the secure and tamper-resistant nature of blockchain ensures data integrity, minimizing the risk of errors and discrepancies in inventory records. This heightened accuracy creates a more reliable inventory control system, reducing the likelihood of mismanagement and fraud. Blockchain-based smart contracts further contribute to inventory control by automating processes, such as triggering replenishment orders based on predetermined thresholds. This streamlines the ordering process, diminishes manual intervention, and optimizes inventory turnover, collectively leading to a more cost-effective and efficient inventory management system within the supply chain.

Consider the application of blockchain technology in the supply chain management of the pharmaceutical industry. In this real-life example, a pharmaceutical company can implement blockchain to enhance transparency, traceability, and efficiency across its supply chain. By utilizing blockchain, each transaction, from the manufacturing of raw materials to the distribution of final products, can be securely recorded in an unalterable and decentralized ledger. This implementation ensures the authenticity of the pharmaceuticals, mitigates the risk of counterfeit drugs, and facilitates rapid traceability in case of recalls or regulatory audits. The pharmaceutical sector, which relies on a complex network of manufacturers, distributors, and retailers, stands to benefit significantly from the increased security, transparency, and efficiency brought about by blockchain technology in ensuring the integrity and safety of its products throughout the supply chain.

The paper explores the integration of blockchain technology into supply chain management, emphasizing its potential to enhance security, transparency, and trustworthiness. It presents a centralized supply chain system involving a single manufacturer, multiple distributors, and multiple retailers, with geographical divisions among distributors. Mathematical models are developed to determine optimal replenishment policies for each stage of the supply chain, with numerical examples and sensitivity analysis illustrating the results. Assumptions include a constant production rate for the manufacturer and specific configurations of distributors and retailers. Blockchain technology is integrated into the system to ensure transparency and traceability, enhancing data integrity and trust among supply chain participants. The paper sheds light on the implications and advantages of this blockchain-based approach, offering managerial insights for improving supply chain efficiency.

1.1. Objective

The objective of this paper is to investigate the optimal replenishment policies for the inventory control by integrating blockchain technology into supply chain management, specifically focusing on enhancing the traceability in the supply chain, where multiple distributer and retailers are included. The study aims to develop a centralized supply chain system encompassing a single manufacturer, multiple distributors, and multiple retailers, with geographical divisions among distributors. Mathematical expressions are formulated to derive optimal replenishment policies for each entity in the supply chain. By addressing the critical aspect of inventory control, the paper aims to contribute to the existing literature, which has predominantly focused on traceability and relationships within the supply chain.

1.2. Contribution

The main contribution of this paper lies in the development of a novel blockchain-based inventory control system for supply chain management. By addressing the gap in existing literature, the study shifts the focus from traceability to the critical domain of inventory control. The inclusion of multiple distributors, retailers, and geographical divisions enriches the model's complexity and practical relevance. Through mathematical expressions, the paper contributes by offering insights into optimal replenishment policies, considering economic efficiency. The incorporation of blockchain ensures transparency and traceability, fostering trust and accountability among supply chain participants. The use of hashing and transaction fees further enhances the security and reliability of the proposed blockchain-based system. The managerial insights provided aim to guide industry practitioners in understanding the implications and advantages of adopting such a system, ultimately contributing to the advancement of inventory control and supply chain management practices.

2. LITERATURE REVIEW

2.1. Blockchain in Inventory Control

Blockchain technology is making substantial contributions to inventory management across various industries. Researchers have delved into different aspects of blockchain's application, including traceability, information sharing, trust resolution, sustainability, and quality maintenance during shipment. These investigations collectively highlight the transformative impact of blockchain on inventory control. Dong and Xu (2002) delved into a supply chain model of vendor-managed inventory. Explored how blockchain integration can enhance transparency and coordination in inventory management. Aung and Chang (2014) Investigated traceability in the food supply chain, emphasizing safety and quality perspectives. They emphasized the role of blockchain in ensuring transparent records for product safety. Azzi et al. (2019) explored the comprehensive impact of blockchain in the supply chain, highlighting its potential to revolutionize inventory management for improved efficiency. Chen et al. (2017) proposed a blockchain-based supply chain quality management framework, ensuring the integrity of quality-related data across the supply chain. Majumder et al. (2018) presented a multi-retailer supply chain model emphasizing volume flexibility and allowable shortages, likely aiming to optimize inventory allocation across retailers. Min (2019) explored the incorporation of blockchain technology in supply chain management, addressing uncertainties and investigating its role in enhancing supply chain resilience. Queiroz et al. (2019) conducted a systematic literature review on blockchain in the supply chain, providing a comprehensive overview of existing research and applications. Mondol (2021) examined the impact of blockchain and smart inventory systems on supply chain performance in the retail industry, emphasizing positive effects on overall efficiency. In the aviation sector, Ho et al. (2021) present a blockchain-based system that enhances traceability and trackability of aircraft parts, improving inventory management efficiency. Similarly, in the retail industry, Kurdi et al. (2022) investigate the impact of blockchain and smart inventory systems on supply chain performance, emphasizing the positive effects on overall efficiency. Govindasamy and Antonidoss (2022) focus on hybrid meta-heuristic approaches for inventory management in the cloud sector, aiming to enhance responsiveness. Additionally, Li (2023) explores the use of blockchain to improve information sharing and collaboration in inventory management, while Singh and Adhikari (2023) highlight the role of blockchain and AI in reducing inventory fraud and errors. Wong et al. (2024) conducted a comprehensive review on enhancing supply chain traceability through Blockchain and IoT integration, likely providing insights into improved traceability. Purwaningsih et al. (2024) utilized blockchain technology to enhance supply chain efficiency and export performance in construction projects, exploring implications on SMEs' financial performance. Basheer et al. (2024) introduced a decentralized material management system for construction projects using blockchain, contributing to transparent and efficient material tracking. Liu et al. (2024) introduced a blockchain-enabled integrated model for the production-inventory-delivery problem, focusing on enhancing efficiency in inventory management through secure and transparent transactions.

2.2 Blockchain in Supply Chain Management

The integration of blockchain technology in supply chain management (SCM) has the potential to revolutionize inventory control and address significant industry challenges. SCM is tasked with efficiently coordinating the flow of inventory among various stakeholders, spanning from raw materials to finished products. Traditional SCM systems often encounter issues related to transparency, data integrity, and traceability, leading to inefficiencies and increased costs. Kelepouris et al. (2007) | Focused on RFID-enabled traceability in the food supply chain, likely exploring how blockchain, when integrated with RFID technology, enhances traceability and transparency in food supply chain management. Wang et al. (2011) optimized inventory policy for products with time-sensitive deteriorating rates in a multi-echelon supply chain, exploring how blockchain can optimize inventory decisions. Zhang (2013) developed an integrated production and inventory model for a manufacturing supply chain involving reverse logistics, likely addressing how blockchain can enhance transparency and traceability in reverse logistics, affecting inventory control positively. Zhang (2013) incorporated blockchain for traceability in the food supply chain, aiming to improve transparency and trace the journey of food products from farm to table. Likely contributes to understanding blockchain and IoT integration in enhancing supply chain traceability. Francisco and Swanson (2018) integrated blockchain into the supply chain to increase transparency, likely focusing on how blockchain's transparency enhances supply chain visibility and accountability. Schmidt and Wagner (2019) utilized the transaction cost theory to understand how blockchain could influence supply chain relations and explored its potential impact on transaction costs and efficiency. Azzi et al. (2019) analyzed the application of blockchain to maintain the quality of sensitive goods during shipment, demonstrating how blockchain ensures the integrity and security of valuable products. Wang et al. (2020) focused on resolving traceability and information sharing issues within the supply chain, exploring how blockchain, along with IoT integration, can improve data sharing and trust among participants. Manupati et al. (2020) proposed a multi-layer blockchain-based supply chain system, considering sustainability issues and exploring how blockchain contributes to sustainable supply chain practices. Cai et al. (2020) studied a platform-supported supply chain with blockchain, likely investigating the role of blockchain in enhancing collaboration and information sharing among supply chain stakeholders. Chod et al. (2020) explored the financing benefits of supply chain transparency and blockchain adoption, likely delving into how blockchain adoption enhances financial aspects related to inventory management. Ho et al. (2021) presented a blockchain-based system to enhance traceability and trackability of aircraft parts, improving inventory management efficiency in the aviation sector. Govindasamy and Antonidoss (2022) focused on hybrid meta-heuristic approaches for inventory management in the cloud sector, aiming to enhance responsiveness in inventory control using blockchain technology. Govindasamy et al. (2022) delved into cost optimization for inventory management in blockchain and cloud environments, likely providing insights into how blockchain can contribute to cost-efficient inventory practices. Kurdi et al. (2022) empirically studied the effect of blockchain and smart inventory systems on supply chain performance in the retail industry, providing practical evidence of how blockchain influences inventory management in the retail sector. While several studies explore different assumptions, such as incorporating sustainability issues (Manupati at el., 2020) or addressing uncertainties (Min, 2019), a critical aspect appears to be missing: a blockchain-based inventory control problem, which was addressed by Saxena and Sarkar (2023). Basheer et al. (2024) developed a blockchain-based decentralized material management system for construction projects, contributing to understanding how blockchain can decentralize material management, impacting inventory control in construction. Sankar and Bhaskaran (2024) investigated the impact of inventory management techniques on service quality measures in the service sector, likely providing insights into how blockchain can contribute to improving service quality within supply chain processes.

2.3 Research Gap

The research in blockchain's application in inventory control and supply chain management has made significant strides, emphasizing its potential in enhancing transparency, traceability, and overall efficiency. However, a notable research gap exists in the limited exploration of the mathematical modeling of the inventory control in supply chain using blockchain. While existing studies showcase the theoretical advantages and positive outcomes, there is a scarcity of empirical research addressing real-world challenges, regulatory complexities, and the integration hurdles faced by organizations when implementing blockchain-based inventory control and supply chain management solutions. Bridging this gap would not only contribute valuable insights to academia but also provide actionable guidance to industry practitioners seeking to leverage blockchain effectively in optimizing their inventory and supply chain operations. Inventory flow and information sharing among supply chain members are given in Figure 1.

3. ASSUMPTIONS AND NOTATION

3.1 Assumptions

In this paper, we use following assumptions:

2 The supply chain system is designed for a centralized structure, comprising a single manufacturer, multiple distributors, and multiple retailers.

3 The production rate of the manufacturer is considered to be constant and remains unchanged during the analysis.

4 The supply chain involves m distributors, and each i^{th} distributor serves p_i retailers. The number of distributors and retailers can vary, but for the purpose of this paper, specific values are assumed.

5 To meet the demand, the manufacturer supplies the i^{th} distributor in n_i shipments, and in turn, the i^{th} distributor fulfils the demand of the j^{th} retailer in n_{ij} shipments. Here, j varies from 1 to p_i, representing each retailer, and i varies from 1 to m, representing each distributor.

6 Blockchain technology has been incorporated into the supply chain system to ensure transparency and traceability among all members involved in the process. The use of blockchain enhances data integrity and trust within the supply chain.

3.2 Notation

The following notation has been used throughout the paper.

P	Replenishment rate
D_i	Demand of the i^{th} distributer
R_{ij}	j^{th}Retailer of i^{th} distributer
$\emptyset_{ij}$	Demand of the j^{th} retailer of i^{th} distributer
q_{D_i}	Ordering quantity of the i^{th} distributer
$q_{R_{ij}}$	Ordering quantity of the j^{th} retailer of i^{th} distributer
n_i	number of shipments for i^{th} distributer
n_{ij}	number of shipments for j^{th} retailer of i^{th}distributer
T_{D_i}	cycle length of i^{th}distributer
$T_{R_{ij}}$	cycle length of j^{th} retailer of the i^{th} distributer
O_{D_i}	ordering cost of the i^{th} distributer
$O_{R_{ij}}$	ordering cost of j^{th} retailer of the i^{th} distributer
h	holding cost
T_1	Production period
T_2	total replenishment period

4. MATHEMATICAL MODELLING

The supply chain system in this paper is designed with a centralized structure, consisting of a single manufacturer, multiple distributors, and multiple retailers. It is assumed that the production rate of the manufacturer remains constant throughout the analysis. The supply chain involves several distributors, with each distributor serving a certain number of retailers. While the number of distributors and retailers can vary, specific values have been assumed for the purpose of this study. To fulfill the demand, the manufacturer supplies each distributor in a specific number of shipments, and in turn, each distributor fulfils the demand of individual retailers with a certain number of shipments. Blockchain technology has been integrated into the supply chain system to ensure transparency and traceability among all participants. By leveraging blockchain, the supply chain gains enhanced data integrity and foster a greater level of trust among all parties involved in the process. Inventory flow and information sharing among supply chain members are given in Figure 1.

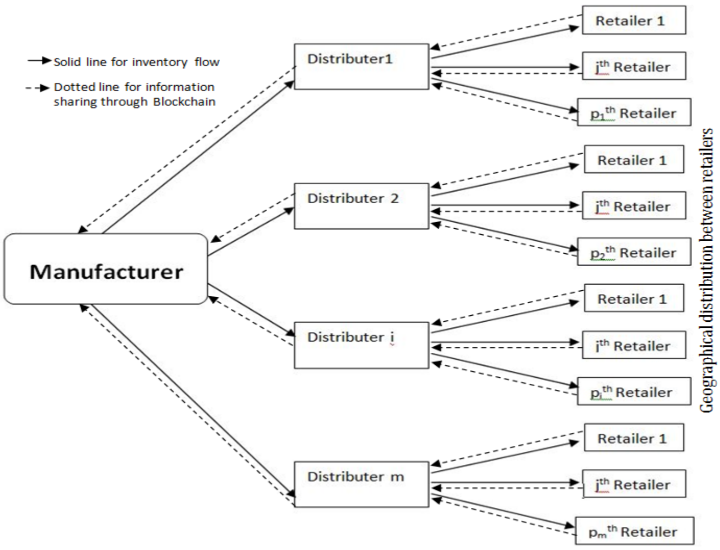

Figure 1: Inventory flow and information sharing between supply chain members.

The inventory depletion is governed by following differential equations:

$$\frac{dI_m(t)}{dt} = P - \sum_{i=1}^{m} D_i \text{ with } I_m(T_1) = 0, \forall\, t \in [0, T_1] \;; \tag{1}$$

$$\frac{dI_m(t)}{dt} = -\sum_{i=1}^{m} D_i \text{ with } I_m(T_2) = 0, \forall\, t \in [T_1, T_2] \;; \tag{2}$$

$$\frac{dI_{D_i}(t)}{dt} = -\sum_{j=1}^{p_i} R_{ij} \text{ with } I_{D_i}\left(T_{D_i}\right) = 0, \forall\, t \in [0, T_{D_i}] \;; \tag{3}$$

$$\frac{dI_{R_{ij}}(t)}{dt} = -\phi_{ij} \text{ with } I_{R_{ij}}\left(T_{R_{ij}}\right) = 0, \forall\, t \in [0, T_{R_{ij}}] \tag{4}$$

The solutions of the above equations are as follows:

$$I_m(t) = (P - \sum_{i=1}^{m} D_i)t \;; \tag{5}$$

$$I_m(t) = \sum_{i=1}^{m} D_i\,(T_2 - t); \tag{6}$$

$$I_{D_i}(t) = \left(\sum_{j=1}^{p_i} R_{ij}\right)\left(T_{D_i} - t\right); \tag{7}$$

$$I_{R_{ij}}(t) = \phi_{ij}\left(T_{R_{ij}} - t\right) \tag{8}$$

By using the above equations, one can find the ordering quantities for distributers and retailers as follows:

$$q_{D_i} = \sum_{j=1}^{p_i} n_{ij} q_{R_{ij}} = T_{D_i} \sum_{j=1}^{p_i} R_{ij} \ ,$$

$$q_{R_{ij}} = \phi_{ij} T_{R_{ij}}$$

4.1. Cost Components

When considering inventory control in the context of the Blockchain-Based Centralized Supply Chain Inventory System with Multi-Distributor and Multi-Retailer, there are cost components related to the implementation and maintenance of the inventory control system using blockchain technology. These cost components include:

4.1.1. Cost of Blockchain Integration

Incorporating blockchain technology into the supply chain requires financial investment. Each time a member executes a transaction, a hash is generated to form a transaction block, and a transaction fee is applied to ensure the completion of the transaction. The transaction fee is calculated based on the gas used during the transaction process. In this context, "gas" refers to the cost associated with each operation executed to perform the transaction, and the amount of gas utilized depends on the data storage requirements within the system.

Therefore, the total transaction cost C can be calculated as:

$$C = G \times p$$

Where G is the amount of gas and p is the price of the transaction per unit gas.

4.1.2. Holding cost of the Manufacturer

Holding cost, also known as carrying cost, is the cost incurred by a manufacturer to store and maintain inventory over a specific period. It represents the expenses associated with holding raw materials, work-in-progress, or finished goods in a warehouse or production facility until they are used in the manufacturing process or sold to customers. It can be calculated as

$$HC_m = \frac{h}{2}(P - \sum_{i=1}^{m} D_i) T_1 T_2$$

4.1.3. Ordering cost of the Manufacturer

Ordering cost is the expense incurred by a business each time they initiate an order to replenish the raw material by the manufacturer. This cost includes expenses related to purchase order processing, supplier communication, transportation, receiving, and supplier management. Efficiently managing ordering costs is essential for optimizing inventory levels and improving overall supply chain efficiency. It can be calculated as

$$OC_m = S_m$$

4.1.4. Holding cost of the Distributer

It is the cost incurred by a distributor to store and maintain inventory over a specific period. As a distributor, holding cost is a critical factor in managing inventory effectively and optimizing supply chain operations. It can be calculated as

$$HC_D = \frac{h}{2}\left(\sum_{i=1}^{m} n_i\, q_{D_i}\right)T_{D_i}$$

4.1.5. Ordering cost of the Distributer

It is the expense incurred by a distributor each time they place an order to replenish their inventory from suppliers or manufacturers. As a distributor, efficiently managing ordering cost is crucial for optimizing inventory levels and ensuring timely product availability to meet customer demand. It can be calculated as

$$OC_D = \sum_{i=1}^{m} n_i\, O_{D_i}$$

4.1.6. Holding cost of the Retailer

It is the cost incurred by a retailer to store and maintain inventory over a specific period. It represents the expenses associated with holding stock in a warehouse or on store shelves until it is sold or used. Holding cost is an important component in inventory management as it directly impacts the overall cost of carrying inventory. It can be calculated as follows.

$$HC_R = \frac{h}{2}\left(\sum_{i=1}^{m}\sum_{j=1}^{p_i} n_{ij} q_{R_{ij}} T_{R_{ij}}\right)$$

4.1.7. Ordering cost of the Retailer

It refers to the expenses incurred by a business or organization each time they place an order to replenish their inventory. The ordering cost is incurred to initiate the process of acquiring new stock when the inventory level reaches a specified reorder quantity. It can be calculated as follows.

$$OC_R = \sum_{i=1}^{m}\sum_{j=1}^{p_i} n_{ij} O_{R_{ij}}$$

Overall, implementing a blockchain-based centralized supply chain inventory system with multi-distributor and multi-retailer capabilities can introduce significant benefits in terms of transparency, traceability, and efficiency, but it also comes with initial and ongoing costs that need to be carefully considered and justified based on the potential advantages for the organization.
Hence the total cost is

$$TC = \frac{1}{T_2}\left(C + HC_m + OC_m + HC_D + OC_D + HC_R + OC_R\right)$$

$$= \frac{1}{T_2}\Big(G \times p + \frac{h}{2}\left(P - \sum_{i=1}^{m} D_i\right)T_1 T_2 + S_m + \frac{h}{2}\left(\sum_{i=1}^{m} n_i\, q_{D_i}\right)T_{D_i} + \sum_{i=1}^{m} n_i\, O_{D_i} + \frac{h}{2}\left(\sum_{i=1}^{m}\sum_{j=1}^{p_i} n_{ij} q_{R_{ij}} T_{R_{ij}}\right) + \sum_{i=1}^{m}\sum_{j=1}^{p_i} n_{ij} O_{R_{ij}}\Big) \quad (9)$$

Now using the given boundary values and other conditions, the following results have been derived.

$(P - \sum_{i=1}^{m} D_i)T_1 = \sum_{i=1}^{m} D_i (T_2 - T_1)$; $n_i T_{D_i} = T_2$; $n_{ij} T_{R_{ij}} = T_{D_i}$;

$q_{D_i} = \sum_{j=1}^{p_i} n_{ij} q_{R_{ij}} = T_{D_i} \sum_{j=1}^{p_i} R_{ij}$; $\sum_{i=1}^{m} D_i T_2 = \sum_{i=1}^{m} \sum_{j=1}^{p_i} \phi_{ij} T_{R_{ij}} n_{ij}$.

By using the above relations one can find the value of $T_2, T_{D_i}, T_{R_{ij}}, q_{R_{ij}}, q_{D_i}, n_i$ and n_{ij} in the terms of T_1, as follows

$$T_2 = \frac{[(P-\sum_{i=1}^{m} D_i)+(\sum_{i=1}^{m} D_i)]}{\sum_{i=1}^{m} D_i} T_1 \tag{10}$$

$$T_{D_i} = \frac{[(P-\sum_{i=1}^{m} D_i)+(\sum_{i=1}^{m} D_i)]}{(\sum_{i=1}^{m} D_i) n_i} T_1 \tag{11}$$

$$T_{R_{ij}} = \frac{[(P-\sum_{i=1}^{m} D_i)+(\sum_{i=1}^{m} D_i)]}{(\sum_{i=1}^{m} D_i) n_i n_{ij}} T_1 \tag{12}$$

$$q_{D_i} = [(P - \sum_{i=1}^{m} D_i) + (\sum_{i=1}^{m} D_i)] T_1 \sum_{j=1}^{p_i} R_{ij} \tag{13}$$

$$\sum_{i=1}^{m} D_i\, n_i = \sum_{i=1}^{m} \sum_{j=1}^{p_i} \phi_{ij} \tag{14}$$

Now our objective is to minimize the objective function (9) with the help of equations (10)-(14).

5. CASE STUDY

TechCom Electronics Inc. operates in the consumer electronics industry, specializing in the production and distribution of electronic gadgets. To streamline its supply chain operations and enhance efficiency, TechCom is exploring the integration of blockchain technology. This case study examines the implications of implementing blockchain in a centralized multi-distributor and multi-retailer supply chain model. The parametric values of the system has been taken from the industry (Table 1).

Table 1: The values of the parameters

P (Replenishment rate) = 2000 units per month	
D_i (Demand of the ith distributor):	
	• D_1 = 450 units per month
	• D_2 = 550 units per month
	• D_3 = 450 units per month
	• D_4 = 350 units per month
R_{ij} (Demand of the jth Retailer of ith distributor):	
	• R_{11} = 150 units per month
	• R_{12} = 250 units per month
	• R_{21} = 200 units per month
	• R_{22} = 150 units per month
	• R_{23} = 120 units per month
	• R_{31} = 150 units per month
	• R_{32} = 180 units per month
	• R_{41} = 150 units per month
	• R_{42} = 100 units per month
q_i (Ordering quantity of the ith Distributer):	
	• q_1 = 350 units per order

- q_2 = 400 units per order
- q_3 = 350 units per order
- q_4 = 300 units per order

q_{ij} (Ordering quantity of the j[th] Retailer of i[th] distributor):

- q_{11} = 200 units per order
- q_{12} = 300 units per order
- q_{21} = 250 units per order
- q_{22} = 350 units per order
- q_{23} = 300 units per order
- q_{31} = 250 units per order
- q_{32} = 200 units per order
- q_{41} = 300 units per order
- q_{42} = 350 units per order

n_i (Number of shipments for i[th] distributor):

- n_1 = 4 shipments per month
- n_2 = 5 shipments per month
- n_3 = 4 shipments per month
- n_4 = 3 shipments per month

n_{ij} (Number of shipments for j[th] Retailer of i[th] distributor):

- n_{11} = 3 shipments per month
- n_{12} = 2 shipments per month
- n_{21} = 4 shipments per month
- n_{22} = 6 shipments per month
- n_{23} = 3 shipments per month
- n_{31} = 2 shipments per month
- n_{32} = 3 shipments per month
- n_{41} = 5 shipments per month
- n_{42} = 4 shipments per month

p (price of the transaction)=0.1Rs per unit

O_{Di} (Ordering cost of the i[th] distributor):

- O_{D1} = $150 per order
- O_{D2} = $200 per order
- O_{D3} = $180 per order
- O_{D4} = $250 per order

O_{Rij} (Ordering cost of j[th] Retailer of i[th] distributor):

- O_{R11} = $180 per order
- O_{R12} = $220 per order
- O_{R21} = $200 per order
- O_{R22} = $150 per order
- O_{R23} = $180 per order
- O_{R31} = $220 per order
- O_{R32} = $190 per order
- O_{R41} = $170 per order
- O_{R42} = $200 per order

h (Holding cost) = $0.60 per unit per month

By using these parametric values for the mathematical expressions, we got the following results which are given in Table 2.

Table 2: Optimal values of the variables

T_1 (Production period) = 3 months
T_2 (Total replenishment period) = 2.5 months
T_{Di} (Cycle length of ith distributor): • T_{D1} = 2 months • T_{D2} = 1.5 months • T_{D3} = 2 months • T_{D4} = 2.5 months
T_{Rij} (Cycle length of j^{th} Retailer of i^{th} distributor): • T_{R11} = 2 weeks • T_{R12} = 3 weeks • T_{R21} = 2 weeks • T_{R22} = 1 week • T_{R23} = 2 weeks • T_{R31} = 3 weeks • T_{R32} = 2 weeks • T_{R41} = 1 week • T_{R42} = 2 weeks
q_i (Ordering quantity of the i^{th} Distributer): • q_1 = 350 units per order • q_2 = 400 units per order • q_3 = 350 units per order • q_4 = 300 units per order
q_{ij} (Ordering quantity of the j^{th} Retailer of i^{th} distributor): • q_{11} = 200 units per order • q_{12} = 300 units per order • q_{21} = 250 units per order • q_{22} = 350 units per order • q_{23} = 300 units per order • q_{31} = 250 units per order • q_{32} = 200 units per order • q_{41} = 300 units per order • q_{42} = 350 units per order
Average cost TC = $25631 per month

5.1. Discussion

Through numerical analysis, TechCom Electronics Inc. gains insights into optimizing inventory management strategies within its centralized supply chain. The integration of blockchain technology enhances transparency and trust, contributing to more efficient operations. However, careful management of associated costs is essential to ensure overall cost-effectiveness and competitiveness in the market.

5.2. Managerial Implications

For TechCom Electronics Inc., understanding the implications of blockchain integration and optimizing inventory control strategies is crucial for maintaining a competitive edge. The findings from this case study provide valuable insights for supply chain managers in balancing efficiency and costs. Moreover, exploring emerging technologies like quantum computing could further enhance supply chain efficiency and drive innovation in the electronics industry.

6. CONCLUSION

In conclusion, TechCom Electronics Inc. recognizes the potential of blockchain technology to optimize its supply chain operations. By leveraging blockchain for transparency and traceability and optimizing inventory management strategies, TechCom can achieve cost savings and operational improvements. Looking ahead, the integration of emerging technologies offers exciting possibilities for revolutionizing supply chain management practices and staying ahead of the competition.

7. NUMERICAL EXAMPLE AND ANALYSIS

A numerical example has been provided to illustrate the mathematical formulation and analytical results of the model. For the numerical illustration of the problem, following parametric values have been considered. These numeric values have been taken from the previous literature but a reasonable estimation has been done for few parameters.

P =2500, D_1=500, $D_2 = 600$, $D_3 = 500$, D_4=400, $p_1 = 2, p_2 = 3, p_3 = 2, p_4 = 2, S_m = 800, G = 1000$, $p = 0.2$, $O_{D_1} = 200, O_{D_2} = 300, O_{D_3} = 250, O_{D_4} = 320$, $O_{R_{11}}$= 200, $O_{R_{12}}$= 300,$O_{R_{21}}$ = 250, $O_{R_{22}}$=320,$O_{R_{23}}$=300,$O_{R_{31}}$= 250,$O_{R_{32}}$= 200, $O_{R_{41}}$=250,$O_{R_{42}}$=300, $n_1 = 4, n_2 = 5, n_3 = 3, n_4 = 6, \emptyset_{11} = 150, \emptyset_{12} = 250, \emptyset_{21} = 200, \emptyset_{22} = 150, \emptyset_{23} = 120, \emptyset_{31} = 150, \emptyset_{32} = 180, \emptyset_{41} = 150, \emptyset_{42} = 100$, $n_{11} = 3, n_{12} = 2, n_{21} = 4, n_{22} = 6, n_{23} = 3, n_{31} = 2, n_{32} = 3, n_{41} = 5, n_{42} = 4$, h = 0.5

The following optimum values have been derived with the help of computing tool Mathematica

Average cost TC is 3362.77, T_1= 6.91811,$T_2 = 8.64763$, $T_{R_{11}}$=0.720636,$T_{R_{12}}$=1.08095, $T_{R_{21}}$=0.432382, $T_{R_{22}}$=0.288254, $T_{R_{23}}$=0.576509, $T_{R_{31}}$=1.44127, $T_{R_{32}}$=0.960848, $T_{R_{41}}$=0.288254, $T_{R_{42}}$=0.360318 , $T_{D_1} = 2.16191, T_{D_2} = 1.72953, T_{D_3} = 2.88254, T_{D_4} = 1.44127 q_{R_{11}} = 108.095, q_{R_{12}} = 270.239, q_{R_{21}} = 86.4763 q_{R_{22}} = 43.2382, q_{R_{23}} = 69.1811, q_{R_{31}} = 216.191$, $q_{R_{32}} = 172.953, q_{R_{41}} = 43.2382, q_{R_{42}} = 36.0318, q_{D_1} = 864.763, q_{D_2} = 812.877$, $q_{D_3} = 951.24, q_{D_4} = 360.318$

The keen observations of Table 3 are as follows

- Increasing the replenishment rate has a notable impact on the system. As observed in the table, there is a reduction in both T_1 and T_2 (replenishment periods), indicating that a higher rate of replenishment results in a more efficient inventory management process.
- Conversely, the average cost experiences an increase with the increment in the replenishment rate. This suggests that while quicker replenishment might enhance operational efficiency, it comes at the expense of higher overall costs.

- The results highlight a significant sensitivity of decision variables to changes in holding costs. Specifically, the average cost is positively sensitive, meaning that an increase in holding costs results in higher overall expenses. On the other hand, replenishment periods T_1 and T_2 are negatively sensitive, indicating that higher holding costs lead to reduced replenishment periods.
- Optimal results are shown to be moderately positively sensitive to changes in setup costs. This implies that adjustments in setup costs have a moderate impact on achieving optimal outcomes. Businesses should carefully consider and manage setup costs to optimize overall performance.
- The average cost is observed to be moderately negatively sensitive to changes in the distributors' demand rate. This means that an increase in demand rate results in a moderate decrease in the average cost. Efficiently managing inventory in response to changes in demand can contribute to cost savings.
- An interesting observation is that an increment in the demand rate of distributors corresponds to an increase in replenishment periods T_1 and T_2. This suggests that a higher demand rate necessitates more frequent replenishment to meet market needs, potentially impacting overall supply chain dynamics.

Table 3: Sensitivity analysis

	Parametric values	production period	Cycle length	Total cost
P	2500	6.91811	8.64763	3362.77
	2600	6.40351	8.32456	3493.28
	2700	5.96711	8.05559	3609.91
	2800	5.59132	7.82785	3714.94
S_m	1000	6.91811	8.64763	3362.77
	1200	6.96552	8.7069	3385.82
	1400	7.01262	8.76578	3408.71
	1600	7.0594	8.82425	3431.45
h	0.5	6.91811	8.64763	3362.77
	1.0	4.89184	6.1148	4755.68
	1.5	3.99417	4.99271	5824.49
	2.0	3.45905	4.32382	6725.54
D_1	400	6.34764	8.35216	3481.73
	500	6.91811	8.64763	3362.77
	600	7.5827	9.02702	3221.44
	700	8.37757	9.51997	3054.63
D_2	400	5.84758	8.12164	3580.56
	500	6.34764	8.35216	3481.73
	600	6.91811	8.64763	3362.77
	700	7.5827	9.02702	3221.44
D_3	300	5.84758	8.12164	3580.56
	400	6.34764	8.35216	3481.73
	500	6.91811	8.64763	3362.77
	600	7.5827	9.02702	3221.44
D_4	300	6.34764	8.35216	3481.73
	400	6.91811	8.64763	3362.77
	500	7.5827	9.02702	3221.44
	600	8.37757	9.51997	3054.63

7.1. Discussion

The table illustrates a comprehensive exploration of parametric variations in a production system, revealing nuanced relationships between key variables and associated costs. As the production period increases, resulting in more frequent production cycles, there is a corresponding elevation in total costs, emphasizing the delicate balance required to optimize efficiency and expenses. The influence of setup costs is evident, with higher setup expenses correlating positively with increased cycle lengths and total costs, highlighting the imperative for meticulous cost management in production initiation. The observed inverse relationship between holding costs and both cycle length and total cost underscores the strategic trade-off between holding inventory and minimizing production cycles. Additionally, heightened demand scenarios significantly impact cycle lengths and total costs, underscoring the challenges and costs associated with meeting increased consumer demand. These findings collectively offer valuable insights for decision-makers seeking to streamline production processes while navigating the intricate interplay of production parameters and associated costs.

7.2. Managerial Implications

The presented model holds significant managerial implications for optimizing production and inventory management. Managers can leverage the insights gained from the model to determine optimal production periods, strategically manage setup costs, and strike a balance between holding costs and production cycles. By understanding the interplay of these parameters, decision-makers can make informed choices that enhance operational efficiency and minimize overall costs. Additionally, the model facilitates responsive production strategies to meet varying demand scenarios, allowing for adaptive decision-making. Overall, the model equips managers with a comprehensive framework for scenario planning, enabling them to navigate dynamic market conditions and make cost-effective decisions that contribute to the long-term sustainability and competitiveness of their production systems.

8. CONCLUSION AND FUTURE DIRECTION

In conclusion, this article has successfully introduced an integrated model incorporating blockchain technology for managing inventory flow in a system involving a single manufacturer, multiple distributors, and multiple retailers. The model operates under the assumptions of constant production and demand rates for the manufacturer, distributors, and retailers. The manufacturer fulfills distributor demands through small, frequent shipments, while distributors, in turn, satisfy retailer demands through multiple deliveries.

Through the development of a comprehensive mathematical formulation, optimum results have been achieved, shedding light on the intricacies of the system. Notably, the findings offer valuable insights into the complex dynamics of production systems and their associated costs. The observed impacts of varying replenishment rates underscore the trade-offs between operational efficiency and overall expenses, highlighting the need for careful consideration in decision-making. Sensitivity analysis reveals the significant influence of holding costs on total expenses, emphasizing the importance of strategic inventory management. Furthermore, variations in setup costs and distributors' demand rates illustrate the intricate interplay of factors affecting production cycles and costs, emphasizing the need for adaptive strategies. the study highlights the high sensitivity of these optimal outcomes to changes in holding costs. This underscores the importance for practitioners to meticulously calculate holding costs, as even minor inaccuracies can have a significant impact on overall costing.

As a recommendation, future research could extend the model to account for stochastic demand, providing a more realistic representation of market dynamics. The integration of genetic algorithms could be explored as an approach to solving the problem in such scenarios. Additionally, the current model paves the way for further extensions to accommodate quantum computing. These insights provide a foundation for future research directions, particularly in exploring the potential synergies between emerging technologies such as quantum computing and blockchain in revolutionizing supply chain management. Quantum blockchain, with its capabilities in handling complex optimization problems, offers promising avenues for enhancing efficiency and cost-effectiveness in supply chain operations. Future research could delve into leveraging quantum computing to optimize supply chain processes, such as route optimization and inventory management, while integrating blockchain technology to enhance transparency and traceability. By embracing these emerging technologies, supply chain managers can unlock new opportunities for innovation and efficiency, driving sustainable growth and competitiveness in the evolving marketplace.

Funding: This research received no external funding.

REFERENCES

[1] M. M. Aung and Y. S. Chang, "Traceability in a food supply chain: Safety and quality perspectives," *Food Control*, vol. 39, pp. 172–184, May 2014, doi: 10.1016/j.foodcont.2013.11.007.

[2] U. Awan, L. Hannola, A. Tandon, R. K. Goyal, and A. Dhir, "Quantum computing challenges in the software industry: A fuzzy AHP-based approach," *Information and Software Technology*, vol. 147, pp. 106896, Jul. 2022, doi: 10.1016/j.infsof.2022.106896.

[3] R. Azzi, R. K. Chamoun, and M. Sokhn, "The power of a blockchain based supply chain," *Computers & Industrial Engineering*, vol. 135, pp. 582–592, Sep. 2019, doi: 10.1016/j.cie.2019.06.010.

[4] M. Basheer, F. Elghaish, T. Brooks, F. P. Rahimian, and C. Park, "Blockchain-based decentralised material management system for construction projects," *Journal of Building Engineering*, vol. 82, Article 108263, Apr. 2024, doi: 10.1016/j.jobe.2023.108263.

[5] Y. J. Cai, T. M. Choi, and J. Zhang, "Platform supported supply chain operations in the blockchain era: supply contracting and moral hazards," *Decision Sciences*, vol. 52, no. 4, pp. 866–892, Aug. 2021, doi: 10.1111/deci.12457.

[6] S. Chen, R. Shi, Z. Ren, J. Yan, Y. Shi, and J. Zhang, "A blockchain-based supply chain quality management framework," in *Proc. 2017 IEEE 14th Int. Conf. on e-Business Engineering (ICEBE)*, 2017, pp. 172–176, doi: 10.1109/ICEBE.2017.34.

[7] J. Chod, N. Trichakis, G. Tsoukalas, H. Aspegren, and M. Weber, "On the financing benefits of supply chain transparency and blockchain adoption," *Management Science*, vol. 66, no. 10, pp. 4378–4396, Oct. 2020, doi: 10.1287/mnsc.2019.3477.

[8] C. Costa, F. Antonucci, F. Pallottino, J. Aguzzi, D. Sarriá, and P. Menesatti, "A review on agri-food supply chain traceability by means of RFID technology," *Food and Bioprocess Technology*, vol. 6, no. 2, pp. 353–366, Feb. 2013, doi: 10.1007/s11947-012-0958-5.

[9] M. A. Darwish and O. M. Odah, "Vendor managed inventory model for single-vendor multi-retailer supply chains," *European Journal of Operational Research*, vol. 204, no. 3, pp. 473–484, Feb. 2010, doi: 10.1016/j.ejor.2009.11.017.

[10] Y. Dong and K. Xu, "A supply chain model of vendor managed inventory," *Transportation Research Part E: Logistics and Transportation Review*, vol. 38, no. 2, pp. 75–95, Mar. 2002, doi: 10.1016/S1366-5545(01)00017-2.

[11] K. Francisco and D. Swanson, "The supply chain has no clothes: Technology adoption of blockchain for supply chain transparency," *Logistics*, vol. 2, no. 1, pp. 1-13, 2018. doi: 10.3390/logistics2010002

[12] C. Govindasamy and A. Antonidoss, "Hybrid meta-heuristic-based inventory management using blockchain technology in cloud sector," *International Journal of Ad Hoc and Ubiquitous Computing*, vol. 41, no. 3, pp. 147-169, 2022.

[13] C. Govindasamy, A. Antonidoss, and A. Pandiaraj, "Cost optimization for inventory management in blockchain and cloud," in *Artificial Intelligent Techniques for Wireless Communication and Networking*, 2022, pp. 59-74.

[14] G. T. S. Ho, Y. M. Tang, K. Y. Tsang, V. Tang, and K. Y. Chau, "A blockchain-based system to enhance aircraft parts traceability and trackability for inventory management," *Expert Systems with Applications*, vol. 179, Oct. 2021, Art. no. 115101. doi: 10.1016/j.eswa.2021.115101

[15] T. Kelepouris, K. Pramatari, and G. Doukidis, "RFID-enabled traceability in the food supply chain," *Industrial Management & Data Systems*, vol. 107, no. 2, pp. 183-200, 2007. doi: 10.1108/02635570710728121

[16] B. Kurdi, H. Alzoubi, I. Akour, and M. Alshurideh, "The effect of blockchain and smart inventory system on supply chain performance: Empirical evidence from retail industry," *Uncertain Supply Chain Management*, vol. 10, no. 4, pp. 1111-1116, 2022.

[17] X. Li, "Inventory management and information sharing based on blockchain technology," *Computers & Industrial Engineering*, vol. 179, May 2023, Art. no. 109196. doi: 10.1016/j.cie.2023.109196

[18] H. Y. Liu, S. F. Ji, and Y. Y. Ji, "Blockchain-enabled integrated model for production-inventory-delivery problem in physical internet," *Computers & Industrial Engineering*, vol. 187, Jan. 2024, Art. no. 109740. doi: 10.1016/j.cie.2023.109740

[19] A. Majumder, C. K. Jaggi, and B. Sarkar, "A multi-retailer supply chain model with backorder and variable production cost," *RAIRO-Operations Research*, vol. 52, no. 3, pp. 943-954, 2018.

[20] V. K. Manupati, T. Schoenherr, M. Ramkumar, S. M. Wagner, S. K. Pabba, and R. S. R. Inder, "A blockchain-based approach for a multi-echelon sustainable supply chain," *International Journal of Production Research*, vol. 58, no. 7, pp. 2222-2241, 2020. doi: 10.1080/00207543.2019.1651491

[21] H. Min, "Blockchain technology for enhancing supply chain resilience," *Business Horizons*, vol. 62, no. 1, pp. 35-45, 2019. doi: 10.1016/j.bushor.2018.08.005

[22] S. Minner, "Multiple-supplier inventory models in supply chain management: A review," *International Journal of Production Economics*, vol. 81, no. Jan., pp. 265-279, 2003. doi: 10.1016/S0925-5273(02)00306-7

[23] E. P. Mondol, "The impact of block chain and smart inventory system on supply chain performance at retail industry," *International Journal of Computations, Information and Manufacturing*, vol. 1, no. 1, 2021.

[24] E. Purwaningsih, M. Muslikh, S. Suhaeri, and B. Basrowi, "Utilizing blockchain technology in enhancing supply chain efficiency and export performance, and its implications on the financial performance of SMEs," *Uncertain Supply Chain Management*, vol. 12, no. 1, pp. 449-460, 2024.

[25] M. M. Queiroz, R. Telles, and S. H. Bonilla, "Blockchain and supply chain management integration: a systematic review of the literature," *Supply Chain Management: An International Journal*, vol. 25, no. 2, pp. 241-254, 2019. doi: 10.1108/SCM-03-2018-0148

[26] A. Sankar and S. Bhaskaran, "The impact of inventory management techniques on service quality measures with reference to service sector," *Journal of Research Administration*, vol. 6, no. 1, 2024.

[27] C. G. Schmidt and S. M. Wagner, "Blockchain and supply chain relations: A transaction cost theory perspective," *Journal of Purchasing and Supply Management*, vol. 25, no. 4, Art. no. 100552, 2019. doi: 10.1016/j.pursup.2019.100552

[28] N. Singh and D. Adhikari, "Blockchain and AI in reducing inventory fraud and errors," *International Journal for Research in Applied Science and Engineering Technology*, vol. 11, no. 12, pp. 1023-1028, 2023.

[29] F. Tian, "A supply chain traceability system for food safety based on HACCP, blockchain & Internet of things," in *2017 International Conference on Service Systems and Service Management (ICSSSM)*, 2017, pp. 1-6. doi: 10.1109/ICSSSM.2017.7996119

[30] K. J. Wang, Y. S. Lin, and C. P. Jonas, "Optimizing inventory policy for products with time-sensitive deteriorating rates in a multi-echelon supply chain," *International Journal of Production Economics*, vol. 130, no. 1, pp. 66-76, 2011. doi: 10.1016/j.ijpe.2010.11.027

[31] Z. Wang et al., "Blockchain-based framework for improving supply chain traceability and information sharing in precast construction," *Automation in Construction*, vol. 111, Mar. 2020, Art. no. 103063. doi: 10.1016/j.autcon.2019.103063

[32] E. K. S. Wong, H. Y. Ting, and A. F. Atanda, "Enhancing supply chain traceability through blockchain and IoT integration: A comprehensive review," *Green Intelligent Systems and Applications*, vol. 4, no. 1, pp. 11-28, 2024.

[33] D. Z. Zhang, "An integrated production and inventory model for a whole manufacturing supply chain involving reverse logistics with finite horizon period," *Omega*, vol. 41, no. 3, pp. 598-620, 2013. doi: 10.1016/j.omega.2012.11.002