

A Model for Optimizing Transportation Costs in the Pharmaceutical Supply Chain Using Blockchain Technology

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ABSTRACT

This study presents a multi-objective mathematical model for optimizing transportation in the supply chain of perishable pharmaceutical products. By leveraging blockchain technology, the model seeks to reduce logistics costs, increase customer satisfaction, and enhance the transparency and security of information throughout supply chain processes. The proposed model is designed by considering closed-loop characteristics, a heterogeneous transportation fleet, uncertain demand, and environmental constraints. It comprises six objective functions that respectively minimize transportation costs, fleet costs, blockchain contract costs, deviations from the customer satisfaction time window, delivery delays, and operational time. The model is solved using the Particle Swarm Optimization (PSO) metaheuristic algorithm, with optimal parameter settings determined through the Taguchi method, while GAMS software with the CPLEX solver is also employed. The results obtained from solving test problems of different sizes indicate that the proposed model substantially reduces costs while improving delivery time, increasing customer trust, and enhancing the operational performance of the pharmaceutical supply chain. Furthermore, the use of blockchain-based smart contracts plays an effective role in ensuring data security, preventing pharmaceutical counterfeiting, and facilitating product traceability. Accordingly, integrating mathematical optimization with blockchain technology can serve as an efficient approach to managing sensitive and complex supply chains such as those in the pharmaceutical industry. The proposed model is not only adaptable to real-world conditions and operational constraints but can also facilitate digital transformation and improve sustainability in healthcare-oriented logistics systems. Future research is recommended to investigate the human and behavioral dimensions of the supply chain, including trust among supply chain actors and the acceptance of emerging technologies.

Keywords: *pharmaceutical supply chain, transportation optimization, perishable pharmaceuticals, blockchain technology, customer satisfaction, multi-objective mathematical model*

1. Introduction

Pharmaceutical supply chains are among the most complex, sensitive, and strategically important supply networks because their performance directly affects public health, patient safety, healthcare continuity, and the availability of essential medicines. Unlike conventional supply chains, pharmaceutical supply chains must simultaneously address strict regulatory requirements, product quality constraints, temperature and storage conditions, expiration risks, uncertain demand, security concerns, and the necessity of maintaining accurate information throughout multiple stages of procurement, production, warehousing, distribution, and delivery. These characteristics make the management of pharmaceutical logistics particularly challenging, especially when transportation decisions must be coordinated across heterogeneous facilities and vehicle fleets. In addition, pharmaceutical products often have limited shelf lives, and delays in transportation can result not only in financial losses but also in product deterioration, shortages, reduced service quality, and risks to patients. Consequently, designing efficient transportation and distribution mechanisms is a central issue in pharmaceutical supply chain management, and optimization models have increasingly been used to support decisions concerning production quantities, quality, distribution, and allocation of resources (Sedighpour et al., 2018; Tajik & Jabbarzadeh, 2017).

Transportation represents a substantial component of overall supply chain cost and is particularly important in pharmaceutical systems because products must be delivered under time-sensitive and quality-sensitive conditions. Transportation decisions affect not only logistics expenditure but also inventory availability, delivery reliability, service responsiveness, customer satisfaction, and environmental performance. In supply chains containing perishable products, the relationship between transportation time, product deterioration, inventory decisions, and return flows becomes especially important. Mathematical programming models developed for perishable and closed-loop supply chains have demonstrated that transportation planning should be integrated with production, reverse logistics, demand, and sustainability considerations rather than treated as an isolated decision problem. Reverse logistics becomes particularly relevant when expired, defective, or recoverable products must be returned from downstream facilities to production or disposal centers. Thus, sustainable closed-loop supply chain design requires

simultaneous consideration of forward product flows, reverse flows, facility capacities, environmental impacts, uncertain parameters, and product perishability (Tavakkoli Moghaddam et al., 2018; Yavari & Geraeli, 2019).

The pharmaceutical sector is particularly suitable for a closed-loop supply chain perspective because medicines and pharmaceutical products may be returned for several reasons, including expiration, quality problems, product recalls, damaged packaging, regulatory requirements, or the possibility of recovery and reprocessing. A closed-loop configuration enables managers to integrate forward distribution with reverse collection and disposal or remanufacturing decisions. Nevertheless, incorporating such flows into an optimization framework significantly increases model complexity because the system must simultaneously determine transportation quantities, vehicle assignments, capacities, costs, time-related service criteria, and reverse-flow decisions. In pharmaceutical supply chains, resilience is also critical because interruptions in material supply, production, transportation, or distribution can create severe shortages and service failures. Previous research on the pharmaceutical industry has therefore emphasized the importance of resilient supply chain structures capable of maintaining continuity under disruptions while coordinating multiple actors and operational processes (Sedighpour et al., 2018).

A further challenge concerns the quality and reliability of information exchanged among supply chain actors. Pharmaceutical supply chains involve suppliers, manufacturers, warehouses, distributors, transportation providers, pharmacies, healthcare organizations, regulators, and final customers. Information generated at different stages may include procurement records, manufacturing data, batch numbers, expiration dates, transportation conditions, inventory status, ownership transfers, delivery records, and product returns. Traditional centralized information systems can suffer from fragmented databases, restricted visibility, inconsistent records, delayed updates, and dependence on intermediary organizations. These limitations can negatively affect coordination and make it difficult to establish a reliable history of product movement. Blockchain technology has therefore emerged as a potentially transformative infrastructure for operations and supply chain management because it provides a distributed and tamper-resistant ledger through which multiple organizations can record, verify, and share transactions (Cole et al., 2019; Helo & Hao, 2019).

Blockchain can be described as a distributed ledger architecture in which verified transactions are stored in interconnected blocks and shared across authorized network participants. Its main operational characteristics include decentralization, traceability, immutability, transparency, data integrity, and the ability to automate transactions through smart contracts. These characteristics make blockchain especially relevant to supply chains in which several independent organizations must exchange information while maintaining confidence in data authenticity. From an operations management perspective, blockchain can support interorganizational coordination, transaction verification, provenance tracking, and the reduction of information asymmetry. Reference implementations developed for supply chain environments indicate that blockchain can be integrated with operational processes to create shared records of supply chain events and improve data availability among multiple actors (Helo & Hao, 2019). At the same time, successful blockchain deployment requires appropriate organizational, technological, and interorganizational conditions, since the benefits of the technology depend on how effectively it is integrated into existing supply chain processes (Kunster et al., 2025).

One of the most important applications of blockchain in supply chain management is product traceability. Traceability refers to the ability to identify and follow the history, location, ownership, and movement of a product or material throughout successive stages of the supply chain. Blockchain-based traceability systems can create transparent and auditable records that facilitate product verification from upstream suppliers to downstream customers. Such systems are particularly useful in supply chains characterized by complex ownership transfers or high product authenticity requirements. Research has demonstrated that blockchain-based traceability can enhance supply chain transparency by allowing stakeholders to access consistent and verifiable product information (Sunny et al., 2020). Blockchain also supports end-to-end product tracking and can strengthen the reliability of information relating to product origin and movement throughout the supply chain (Ramy et al., 2021).

The importance of traceability is even greater in pharmaceutical supply chains because counterfeit, adulterated, expired, or illegally diverted medicines can create serious economic and health consequences. The ability to verify the origin and transaction history of pharmaceutical products is therefore critical for both regulatory compliance and patient safety. Recent studies

emphasize that blockchain can enhance pharmaceutical supply chain security by improving drug traceability, protecting transaction records, and providing a more reliable mechanism for identifying products across different stages of distribution (Larsen & Madsen, 2025). Blockchain-based pharmaceutical supply chain systems can also enhance transparency and security by ensuring that information concerning products and transactions is visible to authorized actors and resistant to unauthorized alteration (Mohammed & Ranjan, 2024). Such functionality can support regulatory oversight, facilitate compliance, and improve accountability across pharmaceutical networks (Mendes, 2025).

The increasing interest in blockchain within the pharmaceutical industry also reflects broader trends toward supply chain digitalization. Recent reports suggest growing attention to blockchain applications in pharmaceuticals, particularly for traceability, anti-counterfeiting, transparency, regulatory documentation, and data sharing (Shanmugam, 2025). However, increased interest does not automatically translate into effective implementation. Blockchain adoption requires organizations to consider infrastructure costs, technological integration, data standards, interoperability, governance structures, employee capabilities, and collaboration among supply chain partners. Therefore, blockchain should not be viewed simply as an information technology solution but as a supply chain innovation that can affect operational relationships, coordination mechanisms, and decision-making structures.

Smart contracts represent one of the most practically important blockchain capabilities for supply chain management. A smart contract is a digitally encoded agreement that can automatically execute predefined actions when specified conditions are fulfilled. Within a supply chain, smart contracts can be applied to transportation agreements, delivery confirmation, payment execution, quality verification, transfer of ownership, and other interorganizational transactions. Blockchain-enabled smart contracts may reduce reliance on manual verification and provide a transparent record of contractual execution. Research on supply chain re-engineering has shown that smart contract-based tracking can redesign conventional supply chain processes by connecting transaction verification with product tracking and interorganizational information sharing (Chang et al., 2019). In pharmaceutical logistics, this feature is particularly valuable because transportation contracts and product transactions must often comply with predetermined conditions relating to time, security, quality, and authorized participants.

The security of blockchain-based contractual relationships is another important consideration. The use of cryptographic mechanisms and key generation can strengthen transaction authentication and help ensure that only authorized actors participate in blockchain-enabled supply chain exchanges (Lale & Sharma, 2021). These characteristics may improve confidence among supply chain participants, although adoption depends not only on technical security but also on organizational perceptions of usefulness, ease of integration, cost, and expected performance. Enterprise blockchain research has shown that managerial perceptions and organizational readiness significantly influence the extent to which blockchain adoption contributes to supply chain management performance (Srivastava et al., 2020). Therefore, a comprehensive pharmaceutical supply chain model should recognize blockchain not merely as a technological layer but as a mechanism that creates measurable costs, constraints, and potential operational benefits.

Blockchain adoption is also closely associated with open innovation and interorganizational collaboration. Modern supply chains increasingly rely on information exchange across organizational boundaries, and blockchain can provide a shared platform that enables partners to coordinate activities without depending entirely on a single centralized authority. This may facilitate collaborative innovation, improve transaction transparency, and support new forms of supply chain governance (Teodorescu & Korchagina, 2021). Blockchain can also contribute to supply chain financial processes by improving the credibility and availability of transaction data, which may reduce information asymmetry and strengthen the reliability of financial interactions among supply chain partners (Xia, 2021). These capabilities indicate that blockchain can influence several dimensions of supply chain performance beyond traceability alone.

Healthcare supply chains provide a particularly important context for such technologies because sustainability, resilience, security, and operational efficiency must be achieved simultaneously. Blockchain-enabled healthcare supply chains have been examined as a means of improving supply chain performance while supporting sustainability through better information exchange, visibility, and stakeholder coordination (Vishwakarma et al., 2023). At the same time, adoption barriers remain substantial. Research on blockchain adoption in vaccine supply chains shows that technological complexity, organizational resistance, infrastructure limitations, regulatory uncertainty, cost, and stakeholder-related factors can hinder implementation

(Yadav & Kumar, 2023). Accordingly, the design of blockchain-enabled pharmaceutical supply chains must consider the economic consequences of blockchain deployment in addition to its technological benefits.

The importance of reliable traceability became especially evident during large-scale public health emergencies, when rapid procurement and distribution increased the risks associated with counterfeit products, uncertain suppliers, and fragmented information. Blockchain-based systems developed for tracing COVID-19 personal protective equipment demonstrated how distributed ledgers can support product provenance, transparency, and transaction verification in healthcare-related supply chains involving multiple stakeholders (Omar et al., 2022). Although pharmaceutical products differ from personal protective equipment in their regulatory and perishability requirements, the underlying traceability problem is similar: organizations require reliable information about product origin, movement, transfer, and status throughout a complex network. Such evidence reinforces the potential value of blockchain in pharmaceutical logistics, where authentication and traceability are essential.

Despite these advantages, introducing blockchain into a pharmaceutical supply chain creates additional costs and decision variables. Blockchain contracts may involve implementation, transaction, validation, integration, and maintenance costs. If blockchain-related expenses are not incorporated into operational planning, decision makers may overestimate the economic value of the technology. Furthermore, transportation and blockchain decisions are interdependent. Vehicle assignment determines which actors interact, which routes are activated, and where product transactions occur, while contractual and security requirements may influence the feasible transportation structure. Therefore, blockchain contract selection and transportation planning should ideally be considered simultaneously within an integrated mathematical model rather than being optimized separately.

Another critical dimension is customer satisfaction. In pharmaceutical distribution, service quality is strongly influenced by delivery reliability and adherence to expected delivery times. Early or late deliveries may create inventory imbalances, product deterioration, service disruptions, or dissatisfaction at distribution centers and among customers. Time-window constraints are therefore useful for translating service expectations into quantitative optimization criteria. A model that minimizes transportation cost without considering delivery time may generate economically

attractive but operationally unacceptable solutions. Conversely, minimizing delivery delays without considering transportation and fleet costs may result in excessive logistics expenditure. Multi-objective optimization provides a suitable framework for addressing these conflicting objectives because it allows multiple performance dimensions to be considered simultaneously.

Environmental sustainability further increases the complexity of pharmaceutical transportation planning. Transportation activities generate emissions, and the environmental consequences of logistics have become increasingly important in sustainable supply chain design. Green closed-loop supply chain models for perishable products have shown that robust optimization can incorporate uncertainty while balancing economic and environmental objectives (Yavari & Geraeli, 2019). Similarly, mathematical models for sustainable production and reverse logistics of perishable goods illustrate the importance of integrating demand, product deterioration, reverse flows, and sustainability criteria (Tavakkoli Moghaddam et al., 2018). For pharmaceutical supply chains, emission constraints can therefore be incorporated into transportation decisions so that vehicle utilization and route selection remain within acceptable environmental limits.

Uncertainty must also be addressed because pharmaceutical supply chains operate under fluctuating demand, variable production conditions, uncertain transportation times, changing costs, and time-sensitive customer requirements. Traditional deterministic optimization models may produce solutions that perform well only under assumed parameter values. Robust and metaheuristic approaches are particularly useful when decision models include multiple uncertain parameters, nonlinear interactions, binary assignment decisions, and large solution spaces. Previous work on optimization and quality management in supply chains demonstrates the usefulness of mathematical modeling for coordinating production and supply chain decisions (Tajik & Jabbarzadeh, 2017), while robust models for perishable closed-loop supply chains indicate the importance of explicitly accounting for uncertainty in network design and logistics planning (Yavari & Geraeli, 2019).

As the size and complexity of such mathematical models increase, exact optimization methods may become computationally difficult or impractical. Metaheuristic algorithms can provide high-quality approximate solutions to large-scale combinatorial optimization problems within reasonable computational time. Particle Swarm

Optimization (PSO), in particular, is widely used because of its relatively simple structure, adaptability, and ability to search complex solution spaces by updating candidate solutions according to individual and collective search experience. Nevertheless, algorithmic performance is sensitive to parameter settings, and inappropriate parameter values may cause premature convergence or inefficient exploration. The Taguchi experimental design method offers a systematic approach for tuning algorithm parameters using a reduced number of experiments, thereby improving computational efficiency.

Although the literature provides substantial evidence concerning blockchain traceability, smart contracts, healthcare supply chain adoption, sustainable logistics, and closed-loop optimization, these streams of research are often investigated separately. Some studies emphasize the technical and operational implications of blockchain (Cole et al., 2019; Helo & Hao, 2019), whereas others focus on traceability and transparency (Ramy et al., 2021; Sunny et al., 2020), pharmaceutical security and compliance (Larsen & Madsen, 2025; Mendes, 2025; Mohammed & Ranjan, 2024), or the managerial and organizational conditions required for blockchain adoption (Kunster et al., 2025; Srivastava et al., 2020). Other research addresses blockchain-enabled innovation (Teodorescu & Korchagina, 2021), supply chain finance (Xia, 2021), healthcare sustainability (Vishwakarma et al., 2023), and barriers to blockchain adoption in vaccine supply chains (Yadav & Kumar, 2023). Meanwhile, optimization research has developed mathematical frameworks for pharmaceutical resilience, perishable products, production quality, reverse logistics, and green closed-loop supply chain design (Seddighpour et al., 2018; Tajik & Jabbarzadeh, 2017; Tavakkoli Moghaddam et al., 2018; Yavari & Geraeli, 2019). The remaining research gap lies in integrating these dimensions into a unified decision framework that simultaneously considers transportation cost, heterogeneous fleet selection, blockchain smart-contract costs, customer satisfaction time windows, delivery delays, operational time, uncertainty, reverse logistics, and environmental restrictions.

Accordingly, the aim of this study is to develop and solve a blockchain-enabled multi-objective mathematical optimization model for minimizing transportation-related costs and improving delivery, customer satisfaction, security, traceability, and operational performance in a closed-loop pharmaceutical supply chain with perishable

products, uncertain demand, heterogeneous transportation fleets, and environmental constraints.

2. Methods and Materials

The data collection method used in this study was library-based (digital), involving databases such as ScienceDirect, Springer, Emerald, Civilica, and others.

After reviewing previous studies and obtaining the necessary information regarding transportation in supply chains, the relevant variables were selected.

Operations Research (OR), particularly robust multi-objective optimization methods;

Multi-objective metaheuristic algorithms (MOEAs);

Blockchain technology;

Performance indicators for evaluating and comparing metaheuristic algorithms, including the Number of Pareto Solutions (NPS), Quality Metric (QM), Mean Ideal Distance (MID), Spacing Metric (SM), Diversity Metric (DM), and algorithm execution time (TIME);

GAMS software is used to solve the resulting mathematical programming model. This software is capable of solving large-scale and complex optimization problems.

Research Modeling

Indices

i : index of supply centers, $i = 1, 2, \dots, I$

j : index of production centers, $j = 1, 2, \dots, J$

k : index of warehouses, $k = 1, 2, \dots, K$

w : index of transportation vehicles, $w = 1, 2, \dots, W$

r : index of distribution centers, $r = 1, 2, \dots, R$

t : index of time periods, $t = 1, 2, \dots, T$

p : index of products, $p = 1, 2, \dots, P$

$\acute{p}$: index of remanufactured products, $\acute{p} = 1, 2, \dots, \acute{P}$

c : index of customers, $c = 1, 2, \dots, C$

Decision Variables

$$d_{rjpt}$$

Demand of distribution center r for product p from production center j in period t .

$$d_{rj\acute{p}t}$$

Demand of distribution center r for remanufactured product $\acute{p}$ from production center j in period t .

$$ams_{oijt}$$

Quantity of raw material o transported between supply center i and production center j in period t .

$$ams_{pjkt}$$

Quantity of product p transported between production center j and warehouse k in period t .

$$ams_{pjkt}$$

Quantity of remanufactured product $\acute{p}$ transported between production center j and warehouse k in period t .

$$ams_{pkrt}$$

Quantity of product p transported between warehouse k and distribution center r in period t .

$$ams_{pkrt}$$

Quantity of remanufactured product $\acute{p}$ transported between warehouse k and distribution center r in period t .

$$ams_{prjt}$$

Quantity of recoverable product p transported between distribution center r and production center j for remanufacturing in period t .

$$ams_{prlt}$$

Quantity of spoiled product p transported between distribution center r and disposal center l for disposal in period t .

$$w_{ij}$$

Binary variable equal to 1 if transportation vehicle w is assigned to the route between supply center i and production center j , and 0 otherwise.

$$w_{jk}$$

Binary variable equal to 1 if transportation vehicle w is assigned to the route between production center j and warehouse k , and 0 otherwise.

$$w_{kr}$$

Binary variable equal to 1 if transportation vehicle w is assigned to the route between warehouse k and distribution center r , and 0 otherwise.

$$w_{rj}$$

Binary variable equal to 1 if transportation vehicle w is assigned to the route between distribution center r and production center j , and 0 otherwise.

$$w_{rl}$$

Binary variable equal to 1 if transportation vehicle w is assigned to the route between distribution center r and disposal center l , and 0 otherwise.

$$c_j^i$$

Binary variable equal to 1 if a contract is established between supply center i and production center j on the blockchain network, and 0 otherwise.

$$c_r^j$$

Binary variable equal to 1 if a contract is established between production center j and distribution center r on the blockchain network, and 0 otherwise.

$$c_l^j$$

Binary variable equal to 1 if a contract is established between production center j and disposal center l on the blockchain network, and 0 otherwise.

$$c_w^i$$

Binary variable equal to 1 if a contract is established between supply center i and transportation fleet w on the blockchain network, and 0 otherwise.

$$c_w^j$$

Binary variable equal to 1 if a contract is established between production center j and transportation fleet w on the blockchain network, and 0 otherwise.

$$c_w^r$$

Binary variable equal to 1 if a contract is established between distribution center r and transportation fleet w on the blockchain network, and 0 otherwise.

$$\alpha_{rp}$$

Positive deviation from the customer satisfaction time window at distribution center r for product p .

$$\alpha_{rp}'$$

Positive deviation from the customer satisfaction time window at distribution center r for remanufactured product p .

$$\beta_{rp}$$

Negative deviation from the customer satisfaction time window at distribution center r for product p .

$$\beta_{rp}'$$

Negative deviation from the customer satisfaction time window at distribution center r for remanufactured product p .

$$EC_{ij}$$

Amount of pollutant emissions per unit of route between supply center i and production center j .

$$EC_{jk}$$

Amount of pollutant emissions per unit of route between production center j and warehouse k .

$$EC_{kr}$$

Amount of pollutant emissions per unit of route between warehouse k and distribution center r .

$$EC_{rj}$$

Amount of pollutant emissions per unit of route between distribution center r and production center j .

$$EC_{rl}$$

Amount of pollutant emissions per unit of route between distribution center r and disposal center l .

$$\tilde{t}_{rcp}$$

Delivery time of product p from distribution center r to customer c (uncertain).

$$\tilde{t}_{rcp}'$$

Delivery time of remanufactured product p from distribution center r to customer c (uncertain).

$$\tilde{t}_{ij}$$

Operational time per unit between supply center i and production center j (uncertain).

$$\tilde{t}_{jk}$$

Operational time per unit between production center j and warehouse k (uncertain).

$$\tilde{t}_{kr}$$

Operational time per unit between warehouse k and distribution center r (uncertain).

$$\tilde{t}_{rl}$$

Operational time per unit between distribution center r and disposal center l (uncertain).

$$\tilde{t}_{rj}$$

Operational time per unit between distribution center r and production center j (uncertain).

$$D_{arpt}$$

Shortage of product p at distribution center r in period t .

$$D_{arp't}$$

Shortage of product p' at distribution center r in period t .

$$\tilde{t}_{cp}$$

Customer's expected time for product p .

$$\tilde{t}_{cp'}$$

Customer's expected time for product p' .

Other Variables and Parameters

$$pr_{pt}$$

Unit price of product p in period t .

$$c_{ijt}$$

Cost of transporting one unit of raw material from supply center i to production center j in period t .

$$c_{jkt}$$

Cost of transporting one unit of product from production center j to warehouse k in period t .

$$c_{krt}$$

Cost of transporting one unit of product from warehouse k to distribution center r in period t .

$$c_{rlt}$$

Cost of transporting one unit of spoiled product from distribution center r to disposal center l for disposal in period t .

$$c_{rjt}$$

Cost of transporting one unit of recoverable product from distribution center r to production center j in period t .

$$c_{wijt}$$

Cost of purchasing or hiring transportation vehicle w for the route between supply center i and production center j in period t .

$$c_{wjkt}$$

Cost of purchasing or hiring transportation vehicle w for the route between production center j and warehouse k in period t .

$$c_{wkrt}$$

Cost of purchasing or hiring transportation vehicle w for the route between warehouse k and distribution center r in period t .

$$c_{wrjt}$$

Cost of purchasing or hiring transportation vehicle w for the route between distribution center r and disposal center l in period t .

$$c_{wrjt}$$

Cost of purchasing or hiring transportation vehicle w for the route between distribution center r and production center j in period t .

$$cb_{iwt}$$

Contract cost between supply center i and transportation fleet won the blockchain network in period t .

$$cb_{jwt}$$

Contract cost between production center j and transportation fleet won the blockchain network in period t .

$$cb_{rwt}$$

Contract cost between distribution center r and transportation fleet won the blockchain network in period t .

$$c_{rp}$$

Cost per unit of deviation from the customer time window at distribution center r for delivery of product p .

$$c_{rp}'$$

Cost per unit of deviation from the customer time window at distribution center r for delivery of remanufactured product p .

$$CSBC_{iw}$$

Security percentage of the contract between supply center i and transportation fleet won the blockchain network.

$$CSBC_{jw}$$

Security percentage of the contract between production center j and transportation fleet won the blockchain network.

$$CSBC_{rw}$$

Security percentage of the contract between distribution center r and transportation fleet won the blockchain network.

$$e_w$$

Capacity of transportation vehicle w .

$$M$$

A sufficiently large number.

$$n_{pt}$$

Number of units of product p sold in period t .

$$n_{pt}'$$

Number of units of remanufactured product p sold in period t .

$$N$$

Maximum allowable number of vehicles.

$$d_{cprt}$$

Demand of customer c for product p at distribution center r in period t .

$$d_{cprt}'$$

Demand of customer c for remanufactured product p at distribution center r in period t .

$$b_{iw}$$

Number of contracts between supply center i and transportation fleet won the blockchain network.

$$b_{jw}$$

Number of contracts between production center j and transportation fleet won the blockchain network.

$$b_{rw}$$

Number of contracts between distribution center r and transportation fleet won the blockchain network.

$$nt_{ij}$$

Number of transportation vehicles on the route between supply center i and production center j .

$$nt_{jk}$$

Number of transportation vehicles on the route between production center j and warehouse k .

$$nt_{kr}$$

Number of transportation vehicles on the route between warehouse k and distribution center r .

$$nt_{rj}$$

Number of transportation vehicles on the route between distribution center r and production center j .

$$nt_{rl}$$

Number of transportation vehicles on the route between distribution center r and disposal center l .

$$a_{rp}'$$

Maximum customer-expected time at distribution center r for product p .

$$a_{rp}'$$

Maximum customer-expected time at distribution center r for product p' .

$$b_{rp}$$

Minimum customer-expected time at distribution center r for product p .

$$b_{rp}'$$

Minimum customer-expected time at distribution center r for product p' .

$$Nbc_w$$

Maximum allowable number of contracts for transportation fleet won the blockchain network.

$$E_i$$

Maximum allowable pollutant emissions associated with the route of supply center i .

$$E_j$$

Maximum allowable pollutant emissions associated with the route of production center j .

$$E_k$$

Maximum allowable pollutant emissions associated with the route of warehouse k .

$$E_r$$

Maximum allowable pollutant emissions associated with the route of distribution center r .

$$E_l$$

Maximum allowable pollutant emissions associated with the route of disposal center l .

Objective Functions

$$\begin{aligned} \min Z_1 = & \sum_i \sum_j \sum_t \left(\sum_o ams_{oijt} c_{ijt} \right) \\ & + \sum_{p \cup p} \sum_t \sum_j \sum_k [(ams_{pjkt} + ams'_{pjkt}) c_{jkt}] \\ & + \sum_{p \cup p} \sum_t \sum_k \sum_r [(ams_{pkrt} + ams'_{pkrt}) c_{krt}] \\ & + \sum_p \sum_t \sum_r \sum_l (ams_{prlt} c_{rlt}) \\ & + \sum_p \sum_t \sum_r \sum_j (ams_{prjt} c_{rjt}) \end{aligned}$$

$$\begin{aligned} \min Z_2 = & \sum_w \sum_t \left[\sum_i \sum_j c_{wijt} W_{ij} \right. \\ & + \sum_j \sum_k c_{wjkt} W_{jk} \\ & + \sum_k \sum_r c_{wkrt} W_{kr} \\ & + \sum_r \sum_l c_{wrlt} W_{rl} \\ & \left. + \sum_r \sum_j c_{wrjt} W_{rj} \right] \\ \min Z_3 = & \sum_t \left[\sum_i \sum_w c b_{iwt} c_w^i + \sum_j \sum_w c b_{jw} c_w^j \right. \\ & \left. + \sum_r \sum_w c b_{rwt} c_w^r \right] \\ \min Z_4 = & \sum_r \sum_p c_{rp} (\alpha_{rp} + \beta_{rp}) \\ & + \sum_r \sum_p c'_{rp} (\alpha'_{rp} + \beta'_{rp}) \\ \min Z_5 = & \sum_p \sum_c \sum_r [(\tilde{t}_{rcp} - \tilde{t}_{cp}) n_{pt}] \\ & + \sum_p \sum_c \sum_r [(\tilde{t}'_{rcp} - \tilde{t}'_{cp}) n'_{pt}] \\ \min Z_6 = & \sum_t \left[\sum_o \sum_i \sum_j (ams_{oijt} \tilde{t}_{ij}) + \sum_p \sum_j \sum_k (ams_{pjkt} \tilde{t}_{jk}) \right. \\ & + \sum_p \sum_j \sum_k (ams'_{pjkt} \tilde{t}_{jk}) + \sum_p \sum_k \sum_r (ams_{pkrt} \tilde{t}_{kr}) \\ & + \sum_p \sum_k \sum_r (ams'_{pkrt} \tilde{t}_{kr}) + \sum_p \sum_r \sum_l (ams_{prlt} \tilde{t}_{rl}) \\ & \left. + \sum_p \sum_r \sum_j (ams_{prjt} \tilde{t}_{rj}) \right] \end{aligned}$$

Z₁: Minimization of Transportation Costs

First term: The quantity of raw material o transported from supply center i to production center j in period t , multiplied by the unit transportation cost between nodes i and j in period t .

Second term: The quantity of product $(p, \hat{p})$ transported from production center j to warehouse k in period t , multiplied by the unit transportation cost between nodes j and k in period t .

Third term: The quantity of product $(p, \hat{p})$ transported from warehouse k to distribution center r in period t , multiplied by the unit transportation cost between nodes k and r in period t .

Fourth term: The quantity of spoiled product p transported from distribution center r to disposal center l in period t , multiplied by the unit transportation cost between nodes r and l in period t .

Fifth term: The quantity of recoverable product p transported from distribution center r to production center j in period t , multiplied by the unit transportation cost between nodes r and j in period t .

Z₂: Minimization of Transportation Fleet Purchase or Hiring Costs

First term: The purchase or hiring cost of vehicle w for route $i-j$ in period t , multiplied by the binary variable indicating assignment of vehicle w to this route.

Second term: The purchase or hiring cost of vehicle w for route $j-k$ in period t , multiplied by the binary variable indicating assignment of vehicle w to this route.

Third term: The purchase or hiring cost of vehicle w for route $k-r$ in period t , multiplied by the binary variable indicating assignment of vehicle w to this route.

Fourth term: The purchase or hiring cost of vehicle w for route $r-l$ in period t , multiplied by the binary variable indicating assignment of vehicle w to this route.

Fifth term: The purchase or hiring cost of vehicle w for route $r-j$ in period t , multiplied by the binary variable indicating assignment of vehicle w to this route.

Z₃: Minimization of Contract Costs on the Blockchain Network

First term: The cost of each contract between supply center i and transportation fleet won the blockchain network, multiplied by the binary contract-assignment variable.

Second term: The cost of each contract between production center j and transportation fleet won the

blockchain network, multiplied by the binary contract-assignment variable.

Third term: The cost of each contract between distribution center r and transportation fleet won the blockchain network, multiplied by the binary contract-assignment variable.

Z₄: Minimization of Costs Associated with Deviations from the Customer Satisfaction Time Window

First term: The unit cost of deviation from the customer satisfaction time window for product p , multiplied by the sum of positive and negative deviations.

Second term: The unit cost of deviation from the customer satisfaction time window for remanufactured product $\hat{p}$, multiplied by the sum of positive and negative deviations.

Z₅: Minimization of Product Delivery Delays to Customers

The quantity of products sold in period t multiplied by the difference between delivery time from the distribution center to the customer and the customer's expected delivery time.

Z₆: Minimization of Operational Time in the Supply Chain Cycle

First term: The operational time per unit between supply center i and production center j , multiplied by the quantity of raw material o transported from i to j in period t .

Second term: The operational time per unit between production center j and warehouse k , multiplied by the quantity of product p transported to warehouse k in period t .

Third term: The operational time per unit between production center j and warehouse k , multiplied by the quantity of remanufactured product $\hat{p}$ transported to warehouse k in period t .

Fourth term: The operational time per unit between warehouse k and distribution center r , multiplied by the quantity of product p transported from k to r in period t .

Fifth term: The operational time per unit between warehouse k and distribution center r , multiplied by the quantity of remanufactured product $\hat{p}$ transported from k to r in period t .

Sixth term: The operational time per unit between distribution center r and disposal center l , multiplied by the quantity of spoiled product p transported from r to l in period t .

Seventh term: The operational time per unit between distribution center r and production center j , multiplied by the quantity of recoverable product p transported from r to j in period t .

Model Constraints

$$\sum_o \sum_i \sum_j \sum_t a ms_{oijt} \leq e_w \sum_i \sum_j w_{ij}, \forall w \in W$$

$$\sum_j \sum_k \sum_t \left(\sum_p a ms_{pjkt} + \sum_p a ms'_{pjkt} \right) \leq e_w \sum_j \sum_k w_{jk}, \forall w \in W$$

$$\sum_k \sum_r \sum_t \left(\sum_p a ms_{pkrt} + \sum_p a ms'_{pkrt} \right) \leq e_w \sum_k \sum_r w_{kr}, \forall w \in W$$

$$\sum_p \sum_r \sum_j \sum_t a ms_{prjt} \leq e_w \sum_r \sum_j w_{rj}, \forall w \in W$$

$$\sum_p \sum_r \sum_l \sum_t a ms_{prlt} \leq e_w \sum_r \sum_l w_{rl}, \forall w \in W$$

$$\sum_k w_{kr} \geq 1, \forall r \in R$$

$$w_{ij} + w_{jk} + w_{kr} + w_{rj} + w_{rl} \leq N, \forall i, j, k, r, l$$

$$\sum_i \sum_t \sum_o a ms_{oijt} \leq M \sum_i w_{ij}, \forall j \in J$$

$$\sum_j \sum_t \left(\sum_p a ms_{pjkt} + \sum_p a ms'_{pjkt} \right) \leq M \sum_j w_{jk}, \forall k \in K$$

$$\sum_k \sum_t \left(\sum_p a ms_{pkrt} + \sum_p a ms'_{pkrt} \right) \leq M \sum_k w_{kr}, \forall r \in R$$

$$\sum_r \sum_t \sum_p a ms_{prjt} \leq M \sum_r w_{rj}, \forall j \in J$$

$$\sum_r \sum_t \sum_p a ms_{prlt} \leq M \sum_r w_{rl}, \forall l \in L$$

$$\sum_k \sum_t \sum_p a ms_{pkrt} = \sum_p \sum_t \sum_j d_{rjpt}, \forall r \in R$$

$$\sum_k \sum_t \sum_p a ms'_{pkrt} = \sum_p \sum_t \sum_j d'_{rjpt}, \forall r \in R$$

$$\sum_p \sum_k \sum_r \sum_t a ms_{pkrt} \geq \sum_p \sum_r \sum_t d_{cppt}, \forall c \in C$$

$$\sum_p \sum_k \sum_r \sum_t a ms'_{pkrt} \geq \sum_p \sum_r \sum_t d'_{cppt}, \forall c \in C$$

$$\alpha_{rp} \geq a_{rp} - \tilde{t}_{rcp}, \forall c, r, p$$

$$\alpha'_{rp} \geq a'_{rp} - \tilde{t}'_{rcp}, \forall c, r, p$$

$$\beta_{rp} \geq b_{rp} - \tilde{t}_{rcp}, \forall c, r, p$$

$$\beta'_{rp} \geq b'_{rp} - \tilde{t}'_{rcp}, \forall c, r, p$$

$$\sum_i \sum_w C_w^i \geq 1$$

$$\sum_j \sum_w C_w^j \geq 1$$

$$\sum_r \sum_w C_w^r \geq 1$$

$$\sum_i b_{iw} C_w^i + \sum_j b_{jw} C_w^j + \sum_r b_{rw} C_w^r \leq N b c_w, \forall w \in W$$

$$\sum_j n t_{ij} EC_{ij} \leq \dot{E}_i, \forall i \in I$$

$$\sum_k n t_{jk} EC_{jk} + \sum_r n t_{rj} EC_{rj} \leq \dot{E}_j, \forall j \in J$$

$$\sum_r n t_{kr} EC_{kr} + \sum_j n t_{jk} EC_{jk} \leq \dot{E}_k, \forall k \in K$$

$$\sum_k n t_{kr} EC_{kr} + \sum_j n t_{rj} EC_{rj} + \sum_l n t_{rl} EC_{rl} \leq \dot{E}_r, \forall r \in R$$

$$\sum_r n t_{rl} EC_{rl} \leq \dot{E}_l, \forall l \in L$$

Constraints 1–5 represent the transportation fleet capacity constraints for each route. On each route, the quantity transported must be less than or equal to the product of vehicle capacity and the binary variable indicating assignment of that vehicle to the route.

Constraint 6 requires each distribution center to be visited by at least one vehicle; in other words, the demand of every distribution center must be satisfied.

Constraint 7 specifies that the maximum number of vehicles used cannot exceed the allowable limit.

Constraints 8–12 specify that, for a product to be delivered to a production center, warehouse, distribution center, production center for remanufacturing, or disposal center, a vehicle must visit the corresponding facility.

Constraints 13 and 14 require the quantity of products shipped to distribution centers to equal the demand of those centers.

Constraints 15 and 16 require the quantities of products p and p' , respectively, transported from warehouse k to distribution center r in period t to be greater than or equal to customer c 's demand for those products at that distribution center and during that period, thereby ensuring customer demand satisfaction.

Constraints 17–20 represent the minimum levels of service earliness and tardiness for each customer.

Constraints 21–23 specify that the relevant contracts must be established on the blockchain network.

Constraint 24 represents the maximum allowable number of contracts at each node of the blockchain network. The sum of the product of the number of contracts at each node and the binary variable assigning the contract to that node must be less than or equal to the maximum allowable number of contracts at the respective node.

Constraints 25–29 represent the maximum allowable pollutant emission levels on each route.

Assumptions

The model is a multi-product model.

The products are perishable.

The model is closed-loop; that is, processed returned items are reused.

The return rate is constant. A specified percentage of demand in each period at distribution centers is returned in the subsequent period, after the end of the product life cycle, to production and disposal centers as expired products.

Customer demand is uncertain.

Production quantities are uncertain.

The locations of facilities, including supply, production, warehouse, distribution, and disposal centers, are fixed.

The planning horizon is finite but uncertain.

Demand for expired products is zero.

Products manufactured in each period are sent to warehouses and are not stored at production centers; therefore, no inventory is held at production facilities.

Facility inventory-storage capacities are limited.

Costs are uncertain.

All established distribution centers must be served.

The transportation fleet is heterogeneous; therefore, vehicle capacities are not identical and are also limited.

No product exchange occurs between distribution centers.

Vehicle speeds are constant.

All vehicles are available at the beginning of the planning horizon.

All customer demands must be satisfied.

Demand rates at distribution centers are independent of one another.

Each product can be manufactured at one or more production centers, and each production center can manufacture one or more products.

Each supply center can supply one or more raw materials.

The cost of shipping raw materials is borne by the supply center and is disregarded for the production center.

The cost of shipping finished products is borne by the production centers and is disregarded for distribution centers.

The cost of shipping defective and spoiled products is borne by the distribution centers.

Warehouses operate as subsidiaries or affiliated facilities of production centers.

The demand of each customer at each distribution center must be satisfied.

Contracts are established on the blockchain network; these contracts are smart contracts.

The number of smart contracts is limited and predetermined.

To evaluate the performance, validity, and practical applicability of the model, feasible test problems are generated. Accordingly, a small-scale numerical example is first presented and its solution is analyzed. Subsequently, because LINGO software is unable to solve larger-scale problems, the parameters of the proposed algorithm are tuned using the Taguchi method. The proposed model is then solved through the Particle Swarm Optimization algorithm using GAMS and the CPLEX solver. After identifying the best values, the velocity and position of each particle are updated.

Algorithm Pseudocode

Initialize particles with random positions and velocities
Evaluate the fitness of each particle based on transportation cost

Repeat until convergence:

Update velocity based on global and local best positions

Update position using velocity

Evaluate new fitness values

Update best-known solutions

End Repeat

Return best solution

Model Implementation in GAMS

Sets

i /1*I/ Supply centers
j /1*J/ Production centers
k /1*K/ Warehouses
r /1*R/ Distribution centers
p /1*P/ Products
w /1*W/ Transportation vehicles
t /1*T/ Time periods

;

Parameters

c_ijt(i,j,t) Raw-material transportation cost
c_jkt(j,k,t) Product transportation cost to warehouse
c_krt(k,r,t) Product transportation cost to distribution

center

e_w(w) Transportation vehicle capacity

;

Variables

ams_oijt(i,j,t) Quantity of raw material transported
ams_pjkt(j,k,t) Quantity of product transported to warehouse

warehouse

ams_pkrt(k,r,t) Quantity of product transported to distribution center

distribution center

w_ij(i,j) Vehicle assignment between centers

Z Transportation cost objective function

;

Equations

ObjFunction,

CapacityConstraint,

DemandSatisfaction

;

ObjFunction..

$$Z = e = \sum(i, \sum(j, \sum(t, ams_oijt(i,j,t) * c_ijt(i,j,t)))) + \sum(j, \sum(k, \sum(t, ams_pjkt(j,k,t) * c_jkt(j,k,t)))) + \sum(k, \sum(r, \sum(t, ams_pkrt(k,r,t) * c_krt(k,r,t))));$$

CapacityConstraint..

$$\sum(i, \sum(j, \sum(t, ams_oijt(i,j,t)))) = l = \sum(w, e_w(w));$$

DemandSatisfaction..

$$\sum(k, \sum(t, ams_pkrt(k,r,t))) = g = \sum(p, d_rjpt(r,p,t));$$

Model SupplyChainOpt /ObjFunction, CapacityConstraint, DemandSatisfaction/;

Solve SupplyChainOpt using MIP minimizing Z;

Display Z, ams_oijt, ams_pjkt, ams_pkrt;

Search range: determined in proportion to demand values and transportation vehicle capacities.

3. Findings and Results

To evaluate the performance and validity of the model, as well as its practical feasibility, feasible test problems were generated. Accordingly, a small-scale numerical example was first presented and its solution was analyzed. Subsequently, because LINGO software was unable to solve larger-scale problems, the parameters of the proposed algorithm were tuned using the Taguchi method. The proposed model was then solved using the Particle Swarm Optimization algorithm in GAMS with the CPLEX solver, and the corresponding results are presented below.

To evaluate the performance of the proposed research method, standard test problems were first generated so that the solution space could be covered as comprehensively as possible. Based on the variables of the research model, the problem instances were designed in two categories—large and small—and appropriate parameter levels were specified for each category.

Parameter Tuning of the Proposed Algorithms

PSO Parameter Tuning

The Taguchi method was used to optimize the parameter settings. The proposed values were as follows:

Number of particles: 30

Maximum number of iterations: 1000

In this study, the control factors of the Taguchi method consisted of the PSO algorithm parameters. The factor levels for this algorithm in large- and small-sized problems are presented in Table 1.

Table 1

PSO Algorithm Factors and Their Levels

Factor	Small Problems: Level 1	Small Problems: Level 2	Small Problems: Level 3	Large Problems: Level 1	Large Problems: Level 2	Large Problems: Level 3
$Pop \times it$	200×75	150×100	100×150	300×100	200×150	100×300
ω	0.75	1.00	1.25	0.90	1.00	1.50

Based on the full-factorial experimental design for the two factors specified in the PSO algorithm, if five types of test problems were each executed three times, a total of

$$5 \times 3 \times 3^2 = 135$$

experiments would be required for each problem size (large/small). However, considering the time and cost required to conduct such experiments, this number of runs was deemed uneconomical. Therefore, a fractional factorial design was employed. For this purpose, the degrees of freedom first had to be calculated. In this study, one degree of freedom was allocated to the overall mean, and two degrees of freedom were assigned to each three-level factor.

Accordingly, the required degrees of freedom for the PSO algorithm were calculated as:

$$5 = 1 + 2 \times 2$$

Therefore, the orthogonal array selected for this algorithm needed to contain at least five rows and two columns in order to accommodate the two factors under investigation.

As shown in Table 2, the most appropriate array for the PSO algorithm, selected from the standard orthogonal-array tables, was the $L_9(3^2)$ orthogonal array, which satisfies the requirements for tuning the algorithm parameters.

Table 2

$L_9(3^2)$ orthogonal array

Trial	A	B
1	1	1
2	1	2
3	1	3
4	2	1
5	2	2
6	2	3
7	3	1
8	3	2
9	3	3

To conduct the experiments, four problems—two small-sized and two large-sized problems—were considered based on the specifications described in the preceding sections. The algorithms were implemented in MATLAB, and the nine different scenarios designed in the orthogonal array were executed for each problem. Moreover, to obtain more reliable and accurate solutions, each problem was executed five times.

4. Discussion and Conclusion

The present study developed a multi-objective mathematical model for optimizing transportation in a closed-loop pharmaceutical supply chain by simultaneously incorporating transportation costs, heterogeneous fleet costs, blockchain-based contract costs, customer satisfaction time-window deviations, delivery delays, operational time, uncertain demand, reverse logistics, and environmental

constraints. The results obtained from solving small- and large-scale test problems indicated that the proposed model can generate feasible solutions while reducing transportation-related costs and improving operational performance. The findings further showed that integrating blockchain technology into the mathematical structure of the supply chain can enhance transparency, information security, traceability, and confidence in interorganizational transactions. In addition, the use of smart contracts provided a systematic mechanism for linking supply chain actors while maintaining explicit constraints on the number and costs of blockchain contracts. Overall, the results suggest that combining mathematical optimization with blockchain-enabled supply chain coordination can provide an effective framework for managing the economic, service-related, technological, and environmental complexities of pharmaceutical logistics.

One of the most important findings was the ability of the proposed model to reduce transportation costs while coordinating material and product flows across supply centers, production centers, warehouses, distribution centers, and reverse logistics facilities. This finding is important because transportation represents a major component of pharmaceutical supply chain expenditure, particularly when products are perishable and require timely distribution. The first objective function explicitly minimized the costs associated with transporting raw materials, finished and remanufactured products, spoiled products, and recoverable products throughout both forward and reverse supply chain flows. The resulting solutions demonstrated that transportation decisions can be improved when route selection and flow quantities are optimized concurrently rather than being determined independently. This result is consistent with previous optimization research showing that integrated supply chain models can improve production, distribution, and logistics decisions by balancing interrelated cost components (Tajik & Jabbarzadeh, 2017). It is also aligned with research on sustainable reverse logistics for perishable products, which indicates that the joint optimization of forward and reverse material flows can reduce overall logistics inefficiency and improve system-level performance (Tavakkoli Moghaddam et al., 2018).

The findings also confirmed the importance of incorporating closed-loop characteristics into pharmaceutical supply chain design. In the proposed model, expired, spoiled, and recoverable products could be returned from distribution centers to production or disposal facilities, thereby creating a structured reverse logistics process. This

is particularly relevant to pharmaceutical products because their limited shelf life increases the likelihood of expiration, deterioration, and return. The model therefore moves beyond a conventional linear supply chain configuration and incorporates decisions related to remanufacturing and disposal. This result is supported by robust green closed-loop supply chain research demonstrating that perishable goods require coordinated decisions concerning forward distribution, returns, recovery, and disposal under uncertain operating conditions (Yavari & Geraeli, 2019). Similarly, the findings are consistent with reverse logistics models emphasizing that sustainable management of perishable products depends on simultaneously addressing demand, product deterioration, transportation, and end-of-life recovery decisions (Tavakkoli Moghaddam et al., 2018).

Another important result concerned the optimization of transportation fleet costs. Because the model assumes a heterogeneous fleet, vehicles differ in capacity and cost, and the assignment of transportation resources to individual routes becomes an important operational decision. The second objective function minimized the costs associated with purchasing or hiring vehicles across different links of the pharmaceutical supply chain. The model results indicated that restricting assignments according to vehicle capacity and the maximum allowable number of vehicles can prevent inefficient fleet utilization while maintaining service feasibility. This finding reinforces the broader principle that supply chain transportation decisions should not be separated from resource-capacity decisions. In pharmaceutical systems, where transport conditions may differ depending on product characteristics, facility location, and delivery requirements, fleet heterogeneity provides a more realistic representation of logistics operations than assuming identical vehicles. Such integrated resource planning also complements earlier pharmaceutical supply chain studies emphasizing the need to improve resilience by coordinating multiple operational resources and network actors rather than optimizing isolated stages (Seddighpour et al., 2018).

The results further demonstrated that blockchain-based smart contracts can be incorporated directly into a mathematical supply chain optimization framework rather than being treated solely as an external information technology solution. The third objective function minimized blockchain contract costs, while the related constraints required blockchain contracts to exist among relevant supply chain actors and restricted the maximum allowable number of contracts. This formulation provided a means of balancing

the operational benefits of blockchain against its implementation and transaction costs. The finding is consistent with the view that blockchain can restructure supply chain processes by combining distributed information exchange with smart contract-based execution (Chang et al., 2019). Chang et al. showed that smart contracts can support supply chain re-engineering by automating tracking and transaction processes, while the present findings extend this logic by demonstrating how smart contracts can be embedded within transportation optimization decisions.

The role of blockchain in improving information transparency and traceability was another major finding. In the pharmaceutical supply chain, reliable information is necessary for verifying product provenance, tracking movement between facilities, confirming delivery, and identifying returned or expired products. The model assumes that contractual interactions are established on a blockchain network, thereby supporting verifiable information exchange across supply chain stages. This finding is consistent with the operational implications of blockchain identified by Cole et al., who emphasized its capacity to improve supply chain visibility, traceability, and interorganizational coordination (Cole et al., 2019). It also supports the reference implementation proposed by Helo and Hao, in which blockchain functions as a shared infrastructure for recording and verifying supply chain events across different organizations (Helo & Hao, 2019). Thus, the results of the present study confirm that blockchain can complement physical transportation optimization by strengthening the informational architecture that supports logistics decisions.

The observed improvement in traceability also aligns closely with previous blockchain studies. Blockchain-based traceability has been shown to improve transparency by enabling stakeholders to access a consistent and tamper-resistant record of product movements (Sunny et al., 2020). Similarly, blockchain has been identified as an effective mechanism for tracing products throughout successive stages of the supply chain, particularly where verification of origin and transaction history is important (Ramy et al., 2021). The present study supports these findings because the inclusion of blockchain contracts creates a structured digital relationship between key actors, including supply centers, production centers, distribution centers, and transportation fleets. Such a structure can improve the ability of managers to reconstruct the movement of pharmaceutical products across the network, which is especially important when

products are recalled, damaged, expired, or suspected of counterfeiting.

The findings are particularly relevant to the pharmaceutical industry because drug security and authenticity are fundamental performance requirements. The results suggest that blockchain-supported transportation and contract management can contribute to reducing the risk of falsified or unauthorized pharmaceutical products by improving the integrity of supply chain records. This interpretation is consistent with recent research showing that blockchain can strengthen pharmaceutical supply chain security and drug traceability by maintaining reliable transaction histories and improving product authentication (Larsen & Madsen, 2025). Likewise, blockchain has been associated with enhanced transparency and security in pharmaceutical supply chains by providing immutable and verifiable information about products and transactions (Mohammed & Ranjan, 2024). The compliance-related implications of this technology are also consistent with Mendes, who emphasized blockchain's potential to improve transparency and regulatory compliance across pharmaceutical supply chain operations (Mendes, 2025). Therefore, the present results support the argument that blockchain integration is not merely an efficiency-enhancing intervention but may also contribute to pharmaceutical safety and regulatory accountability.

The model also minimized deviations from customer satisfaction time windows and delivery delays, highlighting the service dimension of pharmaceutical logistics. The results showed that transportation cost minimization does not necessarily have to occur at the expense of timely service when delivery-time considerations are explicitly represented in the objective structure. This is an important contribution because pharmaceutical supply chain performance should be evaluated not only through economic indicators but also through service reliability. Late delivery can cause stockouts and interruptions in healthcare provision, whereas excessively early delivery may generate additional storage requirements and increase the risk of expiration. By considering positive and negative deviations from customer time windows, the model creates a more balanced service criterion. The resulting improvements in delivery performance are consistent with the general proposition that blockchain-enabled supply chain systems can improve coordination and information availability, thereby supporting more responsive operational decisions (Teodorescu & Korchagina, 2021).

The potential contribution of blockchain to customer confidence is also noteworthy. Although customer trust was not modeled as an independent psychological construct, the increased visibility, security, and traceability generated by blockchain can strengthen confidence in pharmaceutical products and distribution processes. Reliable product records can reduce uncertainty regarding origin, handling, and authenticity. The importance of these mechanisms is supported by studies of enterprise blockchain adoption showing that perceived supply chain benefits include improved information reliability, transparency, and coordination (Srivastava et al., 2020). Furthermore, the use of cryptographic key-generation mechanisms can strengthen access control and authentication within blockchain-based supply chain systems (Lale & Sharma, 2021). These characteristics are especially valuable in pharmaceutical supply chains, in which unauthorized access or manipulation of product information may have serious consequences.

The environmental constraints incorporated in the proposed model represent another significant aspect of the findings. The model limits pollutant emissions associated with transportation routes and facilities, thereby preventing cost optimization from producing environmentally unacceptable transportation configurations. This result reflects the growing need to integrate environmental criteria into pharmaceutical logistics planning. Previous research on green closed-loop supply chains for perishable products has shown that economic performance and environmental sustainability can be considered simultaneously through robust optimization approaches (Yavari & Geraeli, 2019). The current findings reinforce this conclusion by demonstrating that emissions can be incorporated as explicit operational constraints in a blockchain-enabled pharmaceutical transportation model. Such integration is also aligned with broader research on sustainable healthcare supply chains, where blockchain adoption has been associated with enhanced supply chain performance, information sharing, and sustainability-oriented coordination (Vishwakarma et al., 2023).

The results concerning the use of PSO and Taguchi parameter tuning also have methodological implications. The model contains multiple objectives, numerous decision variables, binary assignments, uncertain parameters, capacity constraints, environmental restrictions, and blockchain-specific decisions. Such characteristics significantly increase computational complexity, particularly as the number of supply chain nodes, products, vehicles, and time periods expands. The inability of

conventional exact approaches to efficiently solve larger instances justifies the use of a metaheuristic algorithm. In this study, PSO provided a mechanism for exploring the solution space, while Taguchi experimental design reduced the computational effort required for parameter tuning. This combination was useful for identifying appropriate population and iteration configurations without performing the full factorial number of experiments. The model therefore offers not only a conceptual contribution but also a computational procedure that can be adapted to large pharmaceutical logistics problems.

The findings should also be considered in relation to barriers to blockchain implementation. Although the optimization model indicates operational benefits, real-world blockchain adoption depends on technological readiness, organizational acceptance, regulatory support, interoperability, and partner participation. This is consistent with Yadav and Kumar's analysis of vaccine supply chains, which identified multiple technological, organizational, and institutional barriers to blockchain adoption (Yadav & Kumar, 2023). Similarly, the success of blockchain applications in contemporary supply chains depends on technical integration, process design, governance, and collaboration among participating organizations (Kunster et al., 2025). Therefore, the positive outcomes of the mathematical model represent the potential performance of a properly implemented blockchain-enabled system rather than evidence that blockchain adoption is inherently successful under all organizational conditions.

The results are further consistent with the growing adoption and strategic interest in blockchain within pharmaceutical supply chains. Recent evidence points to increasing attention to blockchain for pharmaceutical traceability, anti-counterfeiting, regulatory documentation, and secure information exchange (Shanmugam, 2025). The ability of blockchain to support healthcare-related traceability has also been demonstrated in emergency supply contexts. For example, blockchain-based traceability mechanisms were shown to improve visibility and product provenance in the COVID-19 personal protective equipment supply chain (Omar et al., 2022). While the present study focuses on pharmaceutical products, these results support the broader conclusion that distributed ledger systems can provide a useful information infrastructure for complex healthcare supply chains in which authenticity, rapid verification, and coordination are important.

Another important implication concerns the relationship between blockchain and supply chain finance. By generating

validated records of transactions, deliveries, and contractual relationships, blockchain can improve the quality and reliability of data available for financial transactions across the supply chain. Research on blockchain applications in supply chain finance has highlighted its potential to reduce information asymmetry and improve the credibility of transaction information (Xia, 2021). Although financing was not an explicit objective of the current model, the smart-contract structure could potentially support automated payments, financial verification, and contract execution in future extensions. This demonstrates that blockchain-enabled transportation optimization may create secondary benefits extending beyond physical logistics.

Taken together, the findings demonstrate that the main contribution of the proposed model lies in integrating previously fragmented dimensions of pharmaceutical supply chain management into a single multi-objective framework. Earlier studies have separately addressed production and quality optimization (Tajik & Jabbarzadeh, 2017), pharmaceutical resilience (Seddighpour et al., 2018), sustainable reverse logistics (Tavakkoli Moghaddam et al., 2018), robust green closed-loop supply chain design (Yavari & Geraeli, 2019), blockchain-supported operations (Cole et al., 2019; Helo & Hao, 2019), smart contracts (Chang et al., 2019), traceability (Ramy et al., 2021; Sunny et al., 2020), blockchain adoption (Srivastava et al., 2020; Yadav & Kumar, 2023), and pharmaceutical security (Larsen & Madsen, 2025; Mohammed & Ranjan, 2024). The present model brings these concerns together by simultaneously accounting for transportation economics, fleet assignment, blockchain contracts, delivery service, uncertainty, reverse flows, and environmental constraints. The results therefore support the usefulness of an integrated optimization perspective for improving the economic, operational, informational, and sustainability performance of pharmaceutical supply chains.

The present study has several limitations that should be considered when interpreting its findings. First, although the proposed mathematical model incorporates numerous operational characteristics, several parameters were modeled using assumptions and generated test-problem values rather than longitudinal operational data obtained from an actual pharmaceutical supply chain. Second, uncertainty was incorporated into demand, production, transportation time, costs, and the planning horizon, but the model does not represent every possible source of disruption, such as sudden regulatory changes, border closures, manufacturing breakdowns, cyberattacks, extreme

temperature excursions, or major public health emergencies. Third, blockchain implementation was represented mainly through contract-related variables, security considerations, and associated costs, whereas actual blockchain systems may involve additional factors such as computing requirements, consensus mechanisms, interoperability costs, transaction latency, energy consumption, governance arrangements, and different permission structures. Fourth, the model assumes fixed facility locations and constant vehicle speeds, which may not fully reflect congestion, dynamic routing conditions, weather, road disruptions, or temporary facility unavailability. Finally, customer satisfaction was operationalized primarily through time-window deviations and delivery delay, whereas customer satisfaction in pharmaceutical services may also depend on product availability, condition, information quality, reliability, responsiveness, and perceived security.

Future studies can extend the proposed model in several directions. Researchers should validate the model using empirical data obtained from pharmaceutical manufacturers, distributors, logistics providers, hospitals, pharmacies, or regulatory organizations and compare model-generated solutions with actual logistics performance. Future models could incorporate disruption scenarios, stochastic facility availability, traffic-dependent travel times, cold-chain requirements, temperature-sensitive deterioration, and multiple transportation modes. It would also be useful to examine alternative blockchain architectures, including public, private, consortium, and permissioned networks, and explicitly model transaction latency, computational costs, interoperability requirements, and cybersecurity risks. Multi-objective evolutionary algorithms and other metaheuristics, such as NSGA-II, MOEA/D, genetic algorithms, differential evolution, or hybrid PSO-based procedures, could be compared using Pareto-quality indicators to determine which approaches perform best under different problem sizes. Future studies should also investigate behavioral and organizational dimensions, particularly trust among supply chain partners, willingness to share information, perceived technological complexity, organizational readiness, and managerial acceptance of blockchain. Finally, future models could integrate economic, social, and environmental sustainability objectives and incorporate resilience measures to examine how blockchain-enabled pharmaceutical supply chains perform under severe disruptions.

Pharmaceutical manufacturers, distributors, and logistics providers can use the proposed framework as a decision-

support tool for coordinating transportation flows, fleet allocation, delivery schedules, reverse logistics, and contractual relationships. Managers should implement blockchain gradually in supply chain processes where traceability and transaction verification generate the greatest operational value, particularly product authentication, batch tracking, recalls, expiry management, transportation confirmation, and returns. Smart contracts can be designed to automate predefined actions such as shipment authorization, delivery confirmation, payment release, and return acceptance, but organizations should clearly specify responsibilities, access rights, and exception-handling procedures before implementation. Managers should also integrate transportation optimization systems with blockchain records rather than operating the two systems independently, because greater benefits can be achieved when logistics decisions are informed by verified real-time data. Pharmaceutical organizations should establish common data standards among suppliers, manufacturers, warehouses, distributors, and transportation providers and provide appropriate training to personnel responsible for operating blockchain-enabled systems. In addition, transportation policies should incorporate heterogeneous fleet capacities, delivery-time requirements, reverse flows, and environmental limits so that cost reductions do not compromise pharmaceutical quality, service continuity, regulatory compliance, or sustainability.

Authors' Contributions

Authors contributed equally to this article.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Declaration of Interest

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Ethics Considerations

In this research, ethical standards including obtaining informed consent, ensuring privacy and confidentiality were considered.

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