

Article

Optimized Logistics Network Management Operations Through Predictive Analytics and Blockchain-Enabled Smart Contracts: Techniques, Algorithms, and System Architecture

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Abstract

The combination of predictive analytics and blockchain-technology-enabled smart contracts has the revolutionary potential to transform logistics network operations. This paper presents a five-layer architecture to improve logistics network management in terms of efficiency, minimize costs, and enable data-driven decision making capabilities. The proposed system includes collection of data, blockchain-enabled smart contracts, integration of the system, and real-time monitoring. With rigorous performance analysis, this paper presents phenomenal gains in predictive accuracy, transactional security, and system operational efficiency. It also proposes real-time monitoring features that ensure continuous adjustment to changing conditions, thereby providing a reliable solution to contemporary logistics network challenges. This work also bridges research gaps, showing practical applications and empirical evidence in favor of the integrated solution to establish its effectiveness. Experimental evaluation demonstrates strong predictive performance (R^2 up to 0.96), successful blockchain-based transaction execution, and transportation cost reduction through optimized allocation. The transportation linear programming model reduced shipping costs from INR 1080 to INR 854 through optimal allocation across sources and destinations.

Keywords: logistics network management; blockchain; smart contracts; artificial intelligence; Industry 4.0

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1. Introduction

In the present era of logistics network management, incorporating new technologies such as blockchain and artificial intelligence (AI) has become a fundamental business driver. The evolution of Industry 4.0 has increased the automation, transparency, and efficiency of logistics networks through these technologies [1]. AI and blockchain serve as an example; blockchain provides powerful mechanisms for securing and transparently recording transactions, while AI enables timely decision making and predictive analysis.

Smart contracts on blockchains can automate the majority of tasks, and, as a result, minimize the participation of intermediaries while improving the integrity of the logistics network [2]. All transactions using blockchain are secured, unchangeable, and can be traced, ensuring accurate record keeping through decentralized ledger technology [3]. Blockchain technology dismantles supply chain counterfeiting, inefficiency, and transparency gaps.

In addition, AI technologies and machine learning algorithms play a significant role in optimizing logistics network activities. Such systems enable real-time tracking and predictive maintenance, preventing potential disruptions before they occur. Combining blockchain with AI helps in the efficient use of resources in the logistics network, as well as reducing waste and making it more environmentally sustainable.

Per current logistics network frameworks, processes are incomplete due to the difficulty in identifying and verifying the data source. In many industries, data originates from diverse domains, leading to systemic silos, which are often mislabeled as unitary. Blockchain offers a way out of this by providing transparent and secure pathways for tracking data, guaranteeing unchangeable records, and establishing trust. In addition, the technology mitigates financial risks through evolutionary game theory and the impact of information asymmetry in logistics network finance [4]. This empirical study analyzes a blockchain governance model for strategic decision making in logistics network finance and highlights the revolutionizing impact of blockchain and smart contracts for the field) [5]. Blockchain and machine learning innovation lies in the safe recording of dynamic processes, driven by decisions grounded in previously accumulated data.

Implementing smart contracts will help avert fraud. These tools of practical law enable agreement signature execution without any requisite for human control, which further lowers the risk of conflict arising from people interpreting agreements differently [6]. As per Analytic [7], decision making is improved on a blockchain with predictive analytics features, considering data privacy, safety, and advanced encryption methods. Nevertheless, adopting the [8], framework faces many barriers, such as technological complexity, data privacy, and lack of standard protocols and frameworks. Stakeholder collaboration, blockchain validation, and smart contract design could resolve these problems [8,9].

This work presents the performance analysis and implementation of a five-layered logistics network optimization architecture. The chosen implementation strategy encompasses data acquisition, decision making, smart-contract-based system integration, and real-time monitoring and optimization layers. Each layer addresses particular logistics network problems through a single integrated solution to maximize efficiency, security, and transparency.

This study is designed to analyze the proposed architecture and showcase the immense capabilities of merging blockchain technology with AI in logistics network management. The results from the performance analysis depict the astonishing changes captured for operational metrics, highlighting the efficacy of the proposed solution in real-world applications. This work should be viewed as a system integration and implementation study rather than the proposal of a new predictive or optimization algorithm.

Major Contributions of This Research

1. Integrated five-layer novel architecture connecting predictive analytics, blockchain-enabled smart contracts, optimization, and real-time monitoring.
2. End-to-end workflow that links prediction, contract execution, process optimization, and monitoring.
3. Comparative evaluation of LR, RF, and XGBoost for logistics forecasting.
4. Blockchain-based automated logistics transaction framework.
5. Cost optimization, reducing transportation cost from INR 1080 to INR 854.

The novelty of this work does not lie in the design, implementation, or validation of an integrated five-layer logistics management architecture that systematically connects predictive analytics, blockchain-enabled smart contracts, system integration, transportation optimization, and real-time monitoring within a unified operational workflow. Unlike prior studies that investigate these components independently, the proposed framework demonstrates how prediction outputs can trigger smart contract execution, how blockchain-validated transactions can support optimization decisions, and how monitoring feedback can enable continuous operational adaptation. Therefore, the primary contribution of this work is architectural and system-level integration rather than algorithmic innovation.

Scientific Contribution and Architectural Novelty: Although the proposed work does not introduce a new machine learning algorithm or blockchain consensus mechanism, its scientific contribution lies in the operational coupling of predictive analytics, blockchain-enabled execution, transportation optimization, and adaptive monitoring within a unified closed-loop decision framework. Unlike existing studies that evaluate these components independently, the proposed architecture enables prediction-driven smart contract triggering, blockchain-validated optimization, and feedback-based operational adaptation. This interaction creates a reproducible decision support workflow that can be experimentally validated through real transaction processing, optimization execution, and monitoring cycles. The novelty therefore lies in the formalized interaction mechanism among heterogeneous technologies rather than in the invention of a standalone algorithm.

2. Literature Review

There has been extensive empirical research analyzing the existing logistics network management system using blockchain technology. This subsection summarizes the integration of AI and blockchain into the logistics networks, including the pros and cons of using these technologies and their practical applications, focusing on their contributions as shown in Table 1. Ref. [10] attempt to improve the transparency of logistics networks by incorporating blockchain technology with simulation and optimization methodologies. Their work emphasizes the benefits of blockchain concerning data capture due to its real time [10] attemptable, and decentralized consensus. They demonstrate through a case study that blockchains can identify inefficiencies, diminish risks, and enhance effectiveness in the logistics network. Ref. [11] describe the implementation of smart contracts powered by AI and blockchain technology in the context of autonomous vehicle (AV) logistics networks. To support the control of cost and energy, in addition to enhancing product traceability, transaction transparency, and sustainable economic development, a novel Margin Indicator (MI) is offered. The proposed system significantly reduces energy waste and undisclosed financial expenditures, and initial case study results substantiate its effectiveness.

Table 1. Techniques and algorithms for logistics network optimization.

Technique/Algorithm	Description	Ref.
Predictive Analytics	Utilizes historical data, machine learning, and statistical algorithms to predict future outcomes and optimize logistics network operations.	[12]
Blockchain Technology	A decentralized ledger that records transactions across multiple computers, ensuring security and transparency.	[13]
Smart Contracts	Self-executing contracts with the terms directly written into the code, which automate and ensure contract enforcement without intermediaries.	[13]

Machine Learning Algorithms	Algorithms that enable systems to learn from data, identify patterns, and make decisions with minimal human intervention. [11]
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In their study, ref. [14] aimed to develop a blockchain-optimized logistics network traceability system to improve its transparency and efficiency. Each study acknowledges the merits of employing the technology in real-time tracking, enhanced traceability and compliance. Research also cites risks to implementation like data privacy issues and technical intricacies, proposing some policies to ease the adoption of blockchain technology within the management of the logistics network) [13]. This paper analyzes the integration of AI with blockchain in logistics networks from a synergistic perspective and notes the rise in transparency, traceability, and efficiency that would come with it. The analysis entails a review of existing frameworks, implementation, and challenges to integrating the technologies. The empirical study offers insight into the approaches and objectives that need to be tackled in the future.

An investigation paper [12] discusses how blockchain encompasses myriad possibilities in logistics network operations, considering its enhanced transparency, traceability, and efficiency. It also formulates the main problems, such as scalability and compliance to laws, providing opportunities for further investigation in trying to solve them. The investigation underscores the lack of standard procedures for using blockchain in logistics networks and stresses the need for stakeholder collaboration. Another [10] explains the use of blockchain technology and simulation and optimization techniques to enhance transparency in logistics networks. It explains case studies using blockchain-based solutions in practice and demonstrates gains in identifying inefficiencies, risk management, and logistics network performance. The study emphasizes the competitive advantage due to increased transparency and optimized operation. The various blockchain-enabled smart contracts in logistics network are summarized in Table 2, their challenges in Table 3, research gaps in existing literature in Table 4, and the existing framework in literature are given in Table 5.

Table 2. Blockchain-enabled smart contracts in logistics network.

Application	Benefits	Ref.
Real-Time Data Sharing	Facilitates immediate data sharing across the logistics network, improving transparency and decision making.	[10]
Tamper-Proof Records	Ensures data integrity and security by maintaining an immutable ledger of all transactions.	[14]
Decentralized Consensus	Reduces reliance on a central authority, distributing trust across the network and enhancing system resilience.	[11]
Automated Compliance Checks	Smart contracts can automatically enforce compliance with regulations and standards, reducing the risk of human error and legal issues.	[14]

Table 3. Challenges and solutions in implementing blockchain in logistics networks.

Challenge	Description	Proposed Solution	Ref.
Lack of Trust Among Stakeholders	Logistics networks involve numerous stakeholders, leading to trust issues.	Implement blockchain to ensure transparency and trust through immutable records.	[11]
Inefficiency Tracking	It is difficult to track efficiency across various operations without a common platform.	Use blockchain to create a unified platform for real-time tracking and efficiency monitoring.	[11]

Data Privacy Concerns	Ensuring data privacy in a decentralized system can be challenging.	Employ advanced cryptographic techniques and permissioned blockchains to secure data. [13]
Technological Complexity	Integration of blockchain with existing systems is complex and requires significant investment.	Develop standardized protocols and frameworks to simplify integration and reduce costs. [11]

Table 4. Research gaps identified in optimizing logistics network operations through predictive analytics and blockchain-enabled smart contracts.

Research Gap	Description	Ref.
Real-World Implementation of Blockchain	Most studies focus on theoretical frameworks rather than practical implementation in real-world logistics scenarios.	[11]
Empirical Data on Blockchain's Efficacy	Limited empirical data to demonstrate the effectiveness and scalability of blockchain solutions in addressing logistics network issues.	[14]
Integration of Predictive Analytics With Blockchain	Few studies have explored the integration of predictive analytics with blockchain technology to enhance logistics network decision making and efficiency.	[10]
Standardization and Interoperability	Lack of standardized protocols and frameworks to ensure interoperability between blockchain systems and existing logistics network management tools.	[11]
Data Privacy and Security	Insufficient investigation addressing data privacy and security concerns in decentralized blockchain environments.	[13]
Stakeholder Collaboration	Limited studies on how blockchain can enhance collaboration and trust among various logistics network stakeholders.	[11]

Table 5. Existing Frameworks in Literature.

Study	AI	Blockchain	Optimization	Real-Time Monitoring	End-to-End Integration
[10]	✓	✓	✓	X	X
[11]	X	✓	X	X	X
[13]	✓	✓	X	X	X

Critical Analysis of Existing Frameworks: Despite significant advances in blockchain-enabled and AI-assisted logistics management, several methodological limitations remain. Most blockchain-oriented studies primarily focus on transparency, traceability, and smart contract automation but provide limited support for predictive decision making and operational optimization. Conversely, AI-based logistics frameworks improve forecasting accuracy but often lack trusted execution mechanisms, auditability, and secure transaction management. Furthermore, many existing studies present conceptual architectures or small-scale case studies without demonstrating end-to-end implementation, scalability evaluation, interoperability analysis, or interaction among prediction, execution, optimization, and monitoring components. As a result, the practical deployment of integrated logistics decision support systems remains insufficiently explored. These limitations motivated the development of the proposed framework, which experimentally validates the interactions among predictive analytics, blockchain-enabled execution, optimization, and real-time monitoring within a unified operational environment.

A key limitation of existing logistics frameworks is that they primarily focus on isolated functionalities, such as demand forecasting, blockchain-based traceability, or optimization. Existing architectures rarely demonstrate how predictive outputs can automatically trigger blockchain-enabled actions, how blockchain-validated transactions can influence optimization decisions, or how monitoring feedback can dynamically update operational strategies. The proposed framework addresses this methodological gap by im-

plementing and validating a complete end-to-end interaction mechanism among these layers using real logistics data, blockchain transactions, and optimization workflows.

The literature indicates significant progress in applying blockchain, smart contracts, and artificial intelligence to logistics network management. However, most existing studies focus on individual components, such as blockchain-based traceability, smart contract automation, or AI-driven prediction, rather than providing an integrated operational framework. Several studies present conceptual architectures without implementation details, while others evaluate predictive analytics or blockchain deployment independently. Furthermore, limited research demonstrates the interaction among predictive decision support, blockchain-enabled execution, optimization, and real-time monitoring within a unified logistics workflow. The proposed work addresses this limitation by integrating these components into a five-layer architecture and demonstrating their interaction through an end-to-end operational framework. Nevertheless, challenges related to large-scale deployment, interoperability across heterogeneous platforms, data privacy governance, and stakeholder-wide adoption remain open research directions.

3. System Architecture

This paper outlines a 5-layered structure of the blockchain-enabled smart-contract-based optimized logistics network. Figure 1 shows the layered structure of the proposed solution. The physical layer is for data capture and analysis and the decision support layer is for decision making and predictive analytics. The third one is a blockchain-enabled smart contract for executing the smart contracts to enable logistics network operations. This layer is succeeded by the integration layer and the dynamic optimization and monitoring layer.

These layers combine data collection, predictive analysis, smart contracts based on blockchain, systems integration, and optimization with real-time monitoring. The end-to-end solution is meant to improve logistics network efficiency, lower costs, and enable data-driven decision making.

End-to-End Workflow of the Proposed System

To demonstrate interactions among all architectural layers, an end-to-end operational workflow was implemented. First, logistics transaction data, including order details, shipment information, inventory levels, and customer demand, are collected through the data collection and analytics layer. After preprocessing, the data is forwarded to the decision support layer, where machine learning models predict future sales demand and logistics requirements. This is demonstrated in Figure 1b.

The generated predictions are then transmitted to the blockchain-enabled smart contract layer. Based on predefined business rules, smart contracts automatically validate orders, initiate shipment processing, record transaction events, and trigger payment authorization. All transaction records are securely stored on the blockchain, ensuring transparency, traceability, and auditability.

The integration layer exchanges data between blockchain services, logistics management systems, and optimization modules through REST APIs and Web3.py interfaces. The optimization engine subsequently uses the predicted demand information and blockchain-validated transaction records to determine cost-efficient transportation plans while satisfying supply and demand constraints.

Finally, the dynamic optimization and monitoring layer continuously monitors operational metrics, shipment status, delivery performance, and optimization outcomes through real-time dashboards. Any significant deviation, delay, or operational anomaly can trigger updated predictions and optimization cycles, thereby enabling continuous decision support and adaptive logistics management.

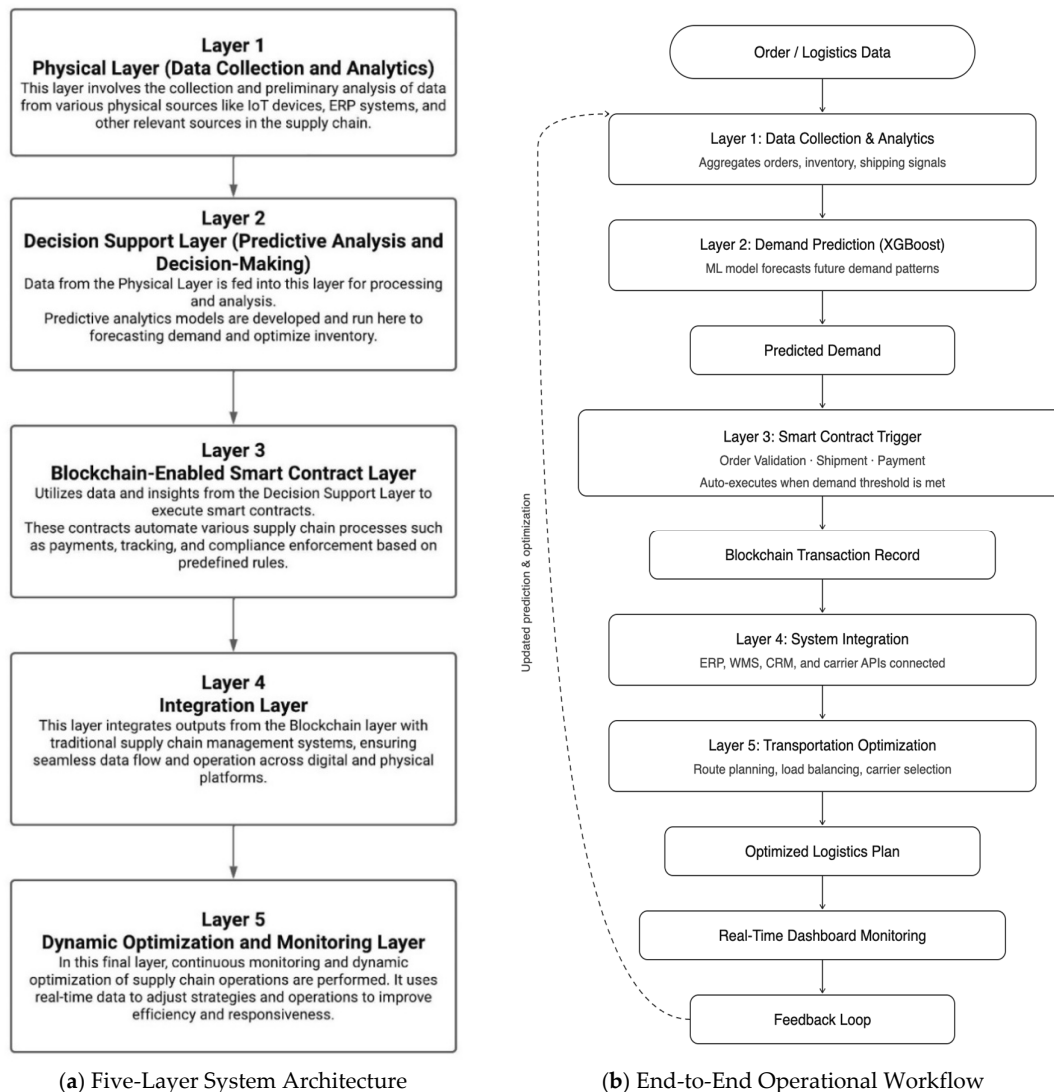


Figure 1. Integrated architecture and operational workflow of the proposed blockchain-enabled logistics network framework.

4. Implementation

The proposed work was used to experiment with the stack of next-generation technologies, such as Python 3.12.10, Pandas 2.3.x, and SQL (MySQL 8.4/PostgreSQL 17), Scikit-learn 1.7.x, TensorFlow 2.20.x, and Keras 3.11.x. Blockchain components were developed using Solidity 0.8.30 on Ethereum and Hyperledger Fabric 3.1.x. Blockchain interactions were managed through web3.py 7.13.x. RESTful services were developed using Flask 3.1.x (or Django 5.2.x). React.js 19.1.x. Apache Kafka 4.0.x for the frontend, and Plotly/Dash, for the real-time dashboard.

All experiments were conducted on a workstation equipped with an Intel Core i7 processor, 16 GB of RAM, and a Windows 11 operating system. The machine learning models, blockchain simulations, and optimization experiments were executed using Python-based libraries within this computing environment.

The ref. [15] dataset includes accurate transactional information, such as customer sales and order profit by order. This actual dataset has been used to perform predictive analysis and streamline logistics network operations. The study utilized the real DataCo

Smart Supply Chain dataset [15], consisting of 180,519 records and 53 attributes. Table 6 presents the characteristics of the dataset.

Table 6. Dataset characteristics.

Parameter	Value
Dataset	DataCo Smart Supply Chain
Total Records	1,80,519
Original Attributes	53
Records After Cleaning	1,80,519
Analytical Attributes	45
Prediction Target	Sales per customer
Input Features	6
Train–Test Split	80:20:00
Cross-Validation	5-fold

4.1. Layer 1: Data Collection and Analytics

This foundational layer focuses on collecting, cleaning, and analyzing high-quality data. Exploratory Data Analysis (EDA) revealed the following:

- **Missing Values:** Handled via row/column drops;
- **Sales per Customer:** Mean = 183.1; Std. Dev = 120.0;
- **Benefit per Order:** Mean = 21.97; Std. Dev = 104.4;
- **Shipping Days (Actual vs. Scheduled):** 3.5 vs. 2.9 days on average.

Figures 2–7 visually depict key findings, including delivery delays, regional sales trends, and shipping mode preferences. These insights informed feature selection for the predictive model in layer 2.

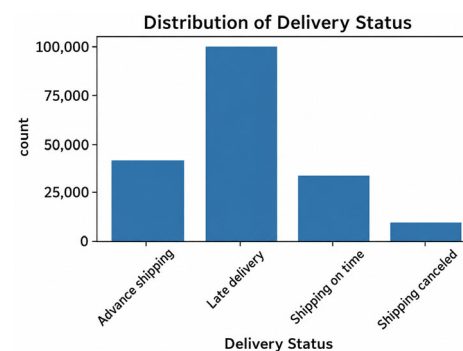


Figure 2. Sales vs. profit per order.

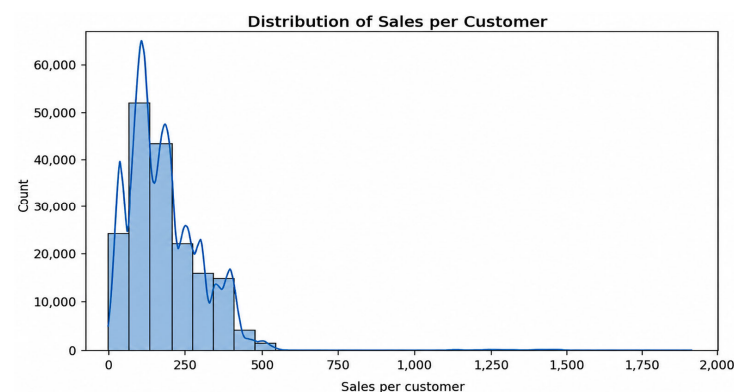


Figure 3. Distribution of delivery status.

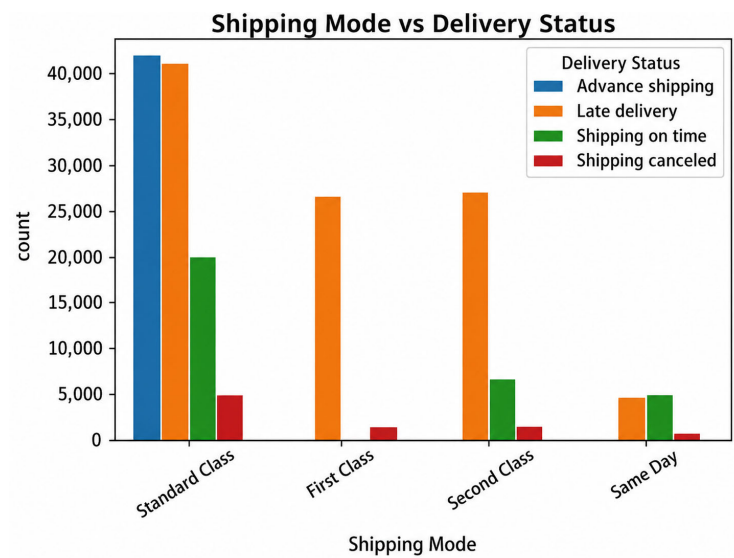


Figure 4. Distribution of sales per customer.

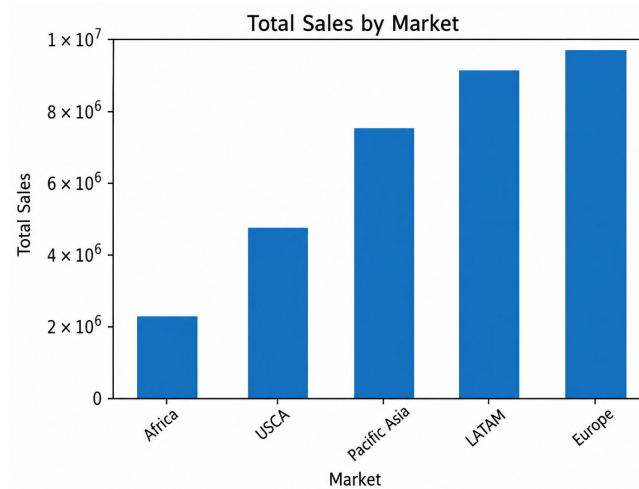


Figure 5. Bar chart of shipping mode vs. delivery status.

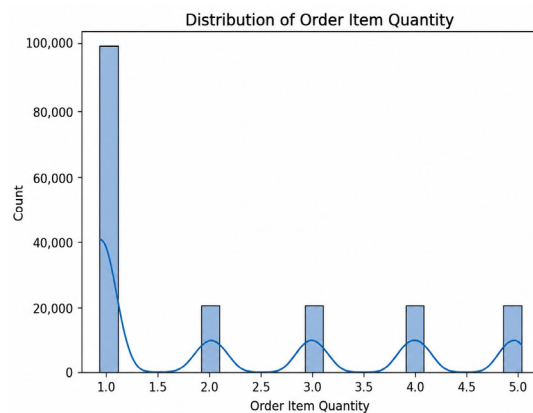


Figure 6. Total sales by market.

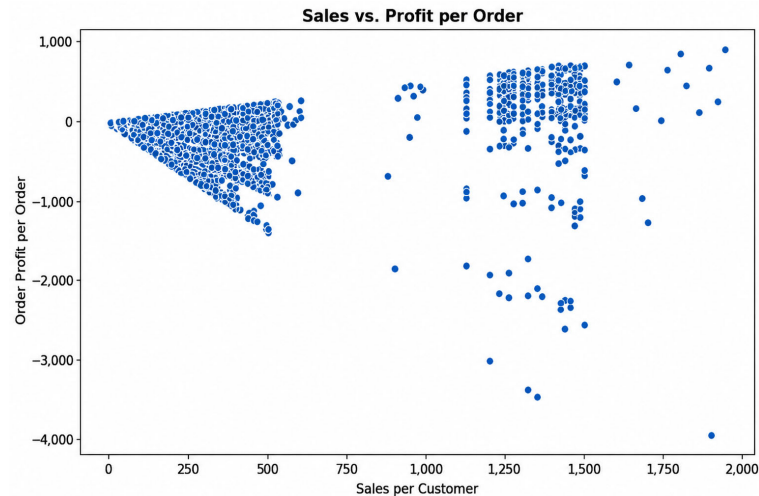


Figure 7. Histogram of distribution of order item quantity.

4.2. Layer 2: Decision Support Layer (Predictive Modeling)

This layer performs sales prediction using regression models. Linear regression was chosen for its interpretability and baseline performance comparison. However, it assumes linearity and may not handle multicollinearity well. Hence, advanced models like Random Forest and XGBoost were used for benchmarking.

4.2.1. Model Selection Rationale

Multiple modeling approaches are available for logistics forecasting and optimization. Linear regression was selected as a simple and interpretable baseline model, Random Forest for capturing nonlinear relationships, and XGBoost for its strong predictive performance on structured logistics data.

For optimization, transportation linear programming was adopted due to its efficiency in minimizing logistics costs under supply–demand constraints. Blockchain-enabled smart contracts were chosen to enhance transparency, traceability, and automated transaction execution. These methods were selected to balance accuracy, explainability, and practical applicability within an integrated logistics framework.

4.2.2. Predictive Modeling Setup

The experiments were conducted on the real DataCo Smart Supply Chain dataset containing 180,519 records and 53 original attributes. After preprocessing and removal of non-analytical fields, the predictive task was defined as forecasting sales per customer using operational and logistics-related attributes. The final predictive model utilized six input features and one target variable. The selected input features included order item quantity, benefit per order, shipping mode, market, delivery status, and scheduled shipping days, while sales per customer were used as the prediction target. Missing values were removed during preprocessing, categorical variables were encoded using one-hot encoding, and numerical features were standardized where required. To prevent data leakage, the target variable and post-delivery information were excluded from the input feature set. The dataset was divided into 80% training and 20% testing subsets, and model robustness was further validated using 5-fold cross-validation.

A predictive modeling workflow consists of the following steps:

1. Preprocess and clean the dataset.
2. Select features relevant to logistics network performance.
3. Split dataset: 80% train, 20% test.

4. Train models: linear regression, Random Forest, and XGBoost.
5. Evaluate using MAE, MSE, and R^2 .
6. Perform 5-fold cross-validation.

Figure 8 shows the distribution of residuals (differences between actual and predicted values). It helps to check if the residuals are normally distributed and identify any patterns.

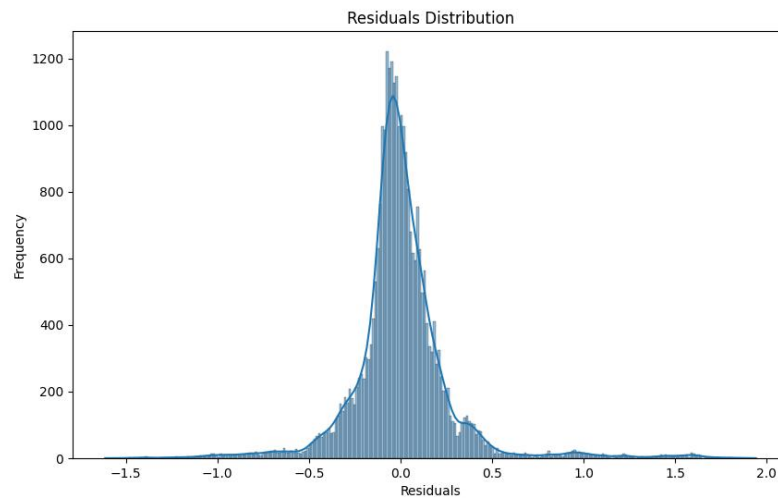


Figure 8. The distribution of residuals (differences between actual and predicted values).

4.2.3. Model Validation

Cross-validation R^2 scores for linear regression: [0.859, 0.896, 0.949, 0.936, 0.938] (mean = 0.916). Residual plots indicate normally distributed residuals, confirming model reliability.

4.3. Layer 3: Smart Contract Deployment

Smart contracts were auto generated using Ethereum blockchain with tools such as Ethereum Solidity v0.8.24, Truffle Suite v5.11.5, Ganache v7.9.2, and MetaMask v12.16.0. Figure 9 shows the deployment workflow. Figure 10 confirms successful execution and transaction finality on the Ethereum network.

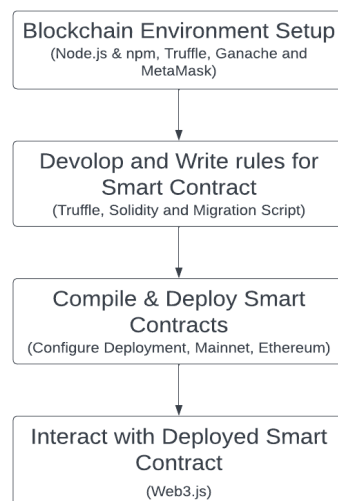
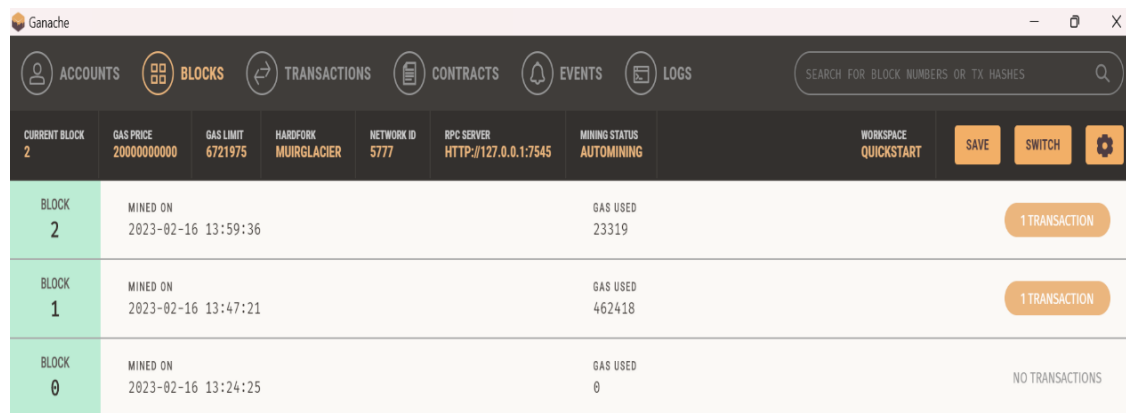


Figure 9. Detailed step-by-step process to initiate the smart contract using blockchain on Ethereum.



ACCOUNTS	BLOCKS	TRANSACTIONS	CONTRACTS	EVENTS	LOGS	SEARCH FOR BLOCK NUMBERS OR TX HASHES
CURRENT BLOCK 2	GAS PRICE 20000000000	GAS LIMIT 6721975	HARDFORK MUIRGLACIER	NETWORK ID 5777	RPC SERVER HTTP://127.0.0.1:7545	MINING STATUS AUTOMINING
WORKSPACE QUICKSTART						SAVE SWITCH
BLOCK 2	MINED ON 2023-02-16 13:59:36		GAS USED 23319		1 TRANSACTION	
BLOCK 1	MINED ON 2023-02-16 13:47:21		GAS USED 462418		1 TRANSACTION	
BLOCK 0	MINED ON 2023-02-16 13:24:25		GAS USED 0		NO TRANSACTIONS	

Figure 10. Screenshot of Ethereum with transaction.

4.4. Layer 4: System Integration Layer

This layer ensures seamless communication across blockchain and logistics network systems using APIs. Example transaction and response data structures ensure security and transparency during contract execution.

4.5. Layer 5: Optimization and Monitoring Layer

Real-time dashboards and dynamic optimization were implemented using a linear programming model. The pseudo-code below illustrates the algorithm used to optimize cost across three supply sources and three demand points:

1. Define cost matrix and flatten it.
2. Set supply and demand constraints.
3. Solve using linear programming (method = 'highs').
4. Reshape result and print optimized routes.

Figure 11 displays the optimized logistics plan, showcasing reduced operational costs and improved routing efficiency.

```
C:\Users\Admin\Desktop\AKDubey_Journal_blockchain_supplychain\pythoncode>python layer5.py
Optimized Delivery Routes:
[[ 0. 10.  0.]
 [-0.  0. 15.]
 [20.  5.  0.]]

C:\Users\Admin\Desktop\AKDubey_Journal_blockchain_supplychain\pythoncode>
```

Figure 11. Outcome of dynamic optimization in layer 5.

4.6. Optimization Problem Formulation

The transportation optimization model was developed using demand and supply information extracted from the DataCo Smart Supply Chain dataset. Supply nodes represent distribution centers, while demand nodes correspond to regional customer markets. Transportation costs were estimated from shipment routes, delivery priorities, and logistics handling factors. The 3×3 transportation matrix was used as a proof-of-concept example to demonstrate the integration of optimization within the proposed architecture. The objective function minimizes total transportation cost while satisfying supply and demand constraints.

4.7. Blockchain Deployment Environment and Smart Contract Design

Blockchain validation was conducted in a controlled private Ethereum test environment using Ethereum Solidity v0.8.24, Truffle Suite v5.11.5, Ganache v7.9.2, and MetaMask v12.16.0 and Web3.py: v7.13.0. The implementation processed approximately 500 logistics transactions to evaluate transaction traceability, smart contract execution, and workflow automation. Multiple participant accounts representing logistics stakeholders were used to simulate order creation, shipment validation, delivery confirmation, and payment release operations. The blockchain layer was designed as a proof-of-concept environment to validate transparency, auditability, and automated transaction management within the proposed logistics framework.

Ethereum was selected because of its mature smart contract ecosystem, extensive developer support, compatibility with Solidity-based contract development, and seamless integration with Web3.py, Truffle, Ganache, and MetaMask. These features make Ethereum particularly suitable for rapid prototyping and validation of blockchain-enabled logistics workflows. Furthermore, Ethereum provides transparent transaction recording, programmable contract execution, and strong support for decentralized application development, which align with the objectives of the proposed logistics management architecture.

The proposed framework employs an Ethereum-based blockchain integrated with smart contracts to ensure secure, transparent, and tamper-resistant logistics operations. Smart contracts, developed in Solidity and deployed on a private Ethereum test network using Ganache, automate key processes, including order creation, shipment verification, delivery confirmation, and payment release. Integration with the predictive analytics and optimization modules was achieved through REST APIs and Web3.py. Table 7 presents the deployment environment for blockchain.

Table 7. Blockchain deployment environment.

Parameter	Configuration
Blockchain Platform	Ethereum
Smart Contract Language	Solidity
Development Framework	Truffle Suite
Blockchain Simulator	Ganache
Integration Layer	Web3.py
API Framework	Flask REST API
Wallet Interface	MetaMask
Consensus Mechanism	Functional smart contract validation using the private Ethereum/Ganache test network; extended blockchain performance evaluation using Python SHA-256 Proof-of-Work (PoW) simulator
Experimental Network Type	Private Ethereum test network
Transaction Execution Mode	Smart contract based
Transaction Processed	500
Stakeholder Accounts	Multiple simulated participants

Experimental Blockchain Evaluation Methodology

To provide a comprehensive blockchain evaluation, two complementary experimental environments were utilized. First, smart contract functionality, transaction execution, and workflow automation were validated using a private Ethereum test network implemented through Ganache, Truffle, MetaMask, Solidity, and Web3.py. This environ-

ment was used to verify order creation, shipment validation, delivery confirmation, payment release, and transaction recording functionalities.

Second, extended blockchain performance experiments were conducted using a Python-based blockchain simulator implementing SHA-256 Proof-of-Work (PoW) consensus. This experimental environment enabled controlled evaluation of throughput (TPS), scalability, latency under load, consensus performance, and attack resistance. The simulator generated blockchain transactions from real logistics records and measured performance under varying transaction loads and blockchain sizes. Therefore, the reported consensus difficulty, throughput, scalability, and attack resistance results correspond to the PoW simulation environment, whereas smart contract deployment and workflow validation correspond to the private Ethereum/Ganache environment.

All critical logistics events are recorded as immutable blockchain transactions, ensuring traceability and auditability. The smart contract workflow consists of the following (Algorithm 1).

Algorithm 1: Logistics Smart Contract Workflow

1. CreateOrder()
 2. ValidateOrderDetails()
 3. VerifyShipmentDispatch()
 4. UpdateShipmentStatus()
 5. ConfirmDelivery()
 6. ReleasePayment()
 7. RecordTransactionOnBlockchain()
 8. CloseContract()
-

By enforcing predefined business rules, the smart contracts automate order verification, shipment tracking, delivery confirmation, and payment settlement. Blockchain evaluation was conducted in a controlled test environment for proof-of-concept validation; therefore, the reported performance metrics should be interpreted as experimental results rather than indicators of large-scale industrial deployment. Future work will investigate scalability and consensus performance in public and consortium blockchain networks

5. Result and Discussion

5.1. Architectural Validation and Novelty Assessment

To validate the proposed architecture beyond conceptual integration, a complete software prototype was implemented using Python v3.12.11, Scikit-learn v1.7.1, Solidity v0.8.24, Ganache v7.9.2, Web3.py v7.13.0, RESTful APIs (OpenAPI v3.1) using Flask v3.1.1, and optimization libraries. The implemented system executed the full operational workflow from data acquisition and demand prediction to smart contract execution, blockchain transaction recording, transportation optimization, and dashboard-based monitoring. Successful execution of this workflow demonstrates that the proposed architecture is not merely conceptual but represents a deployable and experimentally validated operational framework. The architectural novelty is evidenced by the implementation and validation of the interaction mechanisms among all five layers, which are generally evaluated independently in existing studies.

The proposed multilayer architecture demonstrates a comprehensive, data-driven framework for enhancing the performance, transparency, and reliability of modern logistics network systems. This section synthesizes the key findings derived from experimental results and performance evaluations conducted across all five architectural layers.

5.2. Integrated Framework Assessment

The objective of this study is not to experimentally prove that blockchain-enabled logistics systems outperform all conventional logistics platforms nor to establish that the integration of blockchain and artificial intelligence universally exceeds standalone approaches. Instead, the proposed work demonstrates the feasibility of integrating predictive analytics, blockchain-enabled smart contracts, transportation optimization, and monitoring within a unified logistics management framework.

The predictive analytics component contributes by improving demand forecasting and decision support, while the blockchain layer contributes transaction transparency, traceability, and auditability. The optimization layer supports cost-efficient resource allocation. The experimental results therefore validate the functionality of individual components and their operational interaction within the proposed architecture. A comprehensive comparative evaluation against standalone AI-only, blockchain-only, or conventional logistics management systems remains an important direction for future research.

5.3. Evidence of Operational Benefits

The objective of this study is not to claim universal superiority over standalone AI-only or blockchain-only logistics systems. Instead, empirical evidence is provided regarding the operational contribution of each component within the implemented framework. The predictive analytics layer achieved an R^2 value of up to 0.96, demonstrating its effectiveness in logistics demand forecasting and decision support. The blockchain-enabled smart contract layer successfully processed 500 logistics transactions with a 100% transaction success rate, providing immutable transaction records, traceability, and auditability. The optimization layer reduced transportation costs from INR 1080 to INR 854 through optimized allocation. Furthermore, all architectural layers were implemented and integrated through executable software modules, demonstrating practical deployability and operational feasibility. These results provide experimental evidence for the functionality and contribution of each framework component, although controlled benchmarking against standalone architectures requires future work.

5.4. Predictive Model Performance Analysis

To evaluate the predictive capabilities of the proposed system, we assessed three models: linear regression (LR), Random Forest Regressor (RF), and XGBoost Regressor (XGB). The performance metrics for these models are summarized in Table 8.

Table 8. Performance metrics of the proposed model.

Model	MAE	MSE	RMSE	R^2
Linear Regression	18.65	1107.95	33.28	0.92
Random Forest Regressor	14.21	895.12	29.91	0.95
XGBoost Regressor	13.76	850.43	29.17	0.96

Predictive Model Selection and Alternatives: Besides Random Forest and XGBoost, logistics forecasting can also use SVR, ANN, and LSTM models. In this study, linear regression, Random Forest, and XGBoost were selected because they offer a good balance of interpretability, efficiency, and predictive performance. While advanced deep learning models may provide additional benefits, their evaluation is beyond the scope of this study and left for future research.

Let the true values be $y = [y_1, y_2, \dots, y_n]$ and predicted values be $\hat{y} = [\hat{y}_1, \hat{y}_2, \dots, \hat{y}_n]$. Then, the metrics are defined as given in Equations (1)–(4):

$$\text{Mean Absolute Error (MAE): } \text{MAE} = (1/n) \sum |y_i - \hat{y}_i| \quad (1)$$

$$\text{Mean Squared Error (MSE): } \text{MSE} = (1/n) \sum (y_i - \hat{y}_i)^2 \quad (2)$$

$$\text{Root Mean Squared Error (RMSE): } \text{RMSE} = \sqrt{\text{MSE}} \quad (3)$$

$$\text{R-squared (R}^2\text{): } R^2 = 1 - \sum (y_i - \hat{y}_i)^2 / \sum (y_i - \bar{y})^2 \quad (4)$$

XGBoost exhibited the lowest error margins, confirming its suitability for complex, nonlinear relationships in logistics network data. Residual analysis further indicated normal distribution and absence of heteroscedasticity, reinforcing model robustness.

5.5. Blockchain Performance Metrics

The blockchain-based smart contract layer was evaluated based on efficiency, security, and decentralization characteristics. The following performance metrics (Table 9) were recorded.

Table 9. Blockchain performance evaluation using Python PoW simulator.

Metric	Experimental Result
Transactions Processed	500 real DataCo order records
Transaction Success Rate	100%
Average Transaction Time	1.512 s
Average Confirmation Delay	2.908 s
Maximum Confirmation Delay	4.798 s
Blockchain Length	500 blocks
Peak Throughput	436.581 TPS
Scalability Test	100 to 5000 blocks
Validation Complexity	Linear, $O(n)$
Consensus Test	PoW difficulty 1 to 5
Security Tests	Tampering, replay, double-spend, forged-chain substitution
Attack Resistance	All attacks detected and rejected

5.6. Blockchain Evaluation Methodology

Throughput (TPS) was computed as the number of successfully validated blockchain transactions divided by total execution time. Transaction loads of 1, 5, 10, 20, 50, and 100 transactions per submission wave were evaluated to measure throughput variation under increasing demand. Scalability analysis was performed by progressively increasing blockchain size from 100 to 5000 blocks while recording chain validation time and mining performance.

Latency under load was evaluated using transaction confirmation delay measurements, including average, maximum, and percentile-based latency indicators. Consensus performance was analyzed by varying SHA-256 Proof-of-Work difficulty levels from one to five leading hexadecimal zeros and measuring nonce search complexity and mining duration.

Security evaluation was conducted using four representative attack scenarios: blockchain tampering, replay attacks, double-spending attacks, and forged chain substitution attacks. Attack detection was implemented through hash chain validation, proof-of-work verification, and transaction integrity checks. All attack attempts were successfully detected and rejected.

No failed or orphaned transactions were detected during simulation, validating the consistency of blockchain-based execution.

Blockchain Evaluation: To strengthen blockchain evaluation, additional experiments were conducted using 500 real logistics order records extracted from the DataCo Smart

Supply Chain dataset [15]. The blockchain layer executed the complete smart contract workflow, including order creation, order validation, shipment verification, status update, delivery confirmation, payment release, transaction recording, and contract closure [16]. All 500 transactions were successfully processed, and chain integrity validation confirmed correct hash linkage and proof-of-work verification.

Throughput was evaluated under increasing transaction loads of 1, 5, 10, 20, 50, and 100 transactions per wave. The measured throughput ranged from 261.681 TPS to 436.581 TPS, with the peak throughput observed at 436.581 TPS. Scalability was evaluated by increasing the chain length from 100 to 5000 blocks. Full-chain validation time increased linearly with ledger size, while average mining time remained approximately stable due to fixed proof-of-work difficulty.

Latency under load was evaluated using percentile-based measurements. The p99 latency increased with load, indicating realistic tail latency degradation under higher transaction pressure. Consensus performance was evaluated by varying proof-of-work difficulty from one to five leading hexadecimal zeroes. The measured mining time and nonce attempts increased consistently with the expected proof-of-work search complexity. Security and attack resistance testing was also performed against tampering, replay attack, double spending, and forged chain substitution scenarios. All four attacks were successfully detected and rejected through hash chain validation, proof-of-work verification, and order-level duplicate transaction checks. These results strengthen blockchain evaluation beyond basic transaction success rate and confirmation delay.

The extended blockchain evaluation demonstrates that the proposed framework maintains transaction integrity and operational consistency under increasing workload conditions. The throughput results indicate stable transaction processing capability, while scalability experiments confirm predictable linear growth in validation overhead as blockchain size increases. Furthermore, the successful detection and rejection of tampering, replay, double spending, and forged chain substitution attacks provide experimental evidence of the security and robustness of the implemented blockchain framework.

5.7. Operational Optimization Results

A transportation linear programming model was used to minimize shipping costs across three supply sources and three destinations, as mentioned in Table 10.

Table 10. Optimization result.

From	Dest-1	Dest-2	Dest-3
Source-1 (10)	4	8	7
Source-2 (15)	2	6	5
Source-3 (25)	3	7	6

For illustration purposes, Source-1, Source-2, and Source-3 represent three distribution centers, while Dest-1, Dest-2, and Dest-3 represent three regional customer markets derived from the DataCo logistics network scenario. The transportation costs shown in Table 9 correspond to the estimated shipment cost between each distribution center and destination market.

The optimization problem was formulated as

$$\text{Minimize } Z = \sum \sum C_{ij} X_{ij} \text{ Subject to: } \sum X_{ij} = S_i \text{ (Supply constraint) } \sum X_{ij} = D_j \text{ (Demand constraint) } X_{ij} \geq 0$$

where C_{ij} is the cost matrix and X_{ij} is the quantity transported from source i to destination j .

The optimized cost output reduced the total cost function value from an initial estimate of 1080 to 854, with optimal allocation across all nine routes.

While the presented 3×3 transportation problem demonstrates the feasibility of the optimization layer, the proposed framework is scalable to larger logistics networks involving multiple warehouses, distribution centers, and customer regions. Future work will evaluate the optimization module on large-scale logistics datasets and compare its performance against advanced optimization approaches, including mixed-integer linear programming, metaheuristic algorithms, and network flow optimization techniques [16].

5.8. Real-Time Monitoring

Dashboards can be integrated with Apache Kafka [17] and Plotly/Dash [18] to provide real-time visualizations of performance indicators, inventory levels, and order processing times. Alerts can be configured for threshold breaches on KPIs like delivery delays and cost overruns.

The proposed monitoring layer differs from conventional dashboard-based monitoring by integrating predictive analytics, blockchain transaction events, and optimization outcomes within a unified view. Real-time updates from logistics transactions, shipment status changes, and smart contract execution events can be continuously streamed to the monitoring dashboard. This enables proactive identification of delivery delays, operational anomalies, and cost deviations, allowing for corrective actions before significant disruptions occur.

5.9. Aggregate System Efficiency

Instead of relying on a single composite efficiency metric, the performance of the proposed framework was evaluated using multiple objective indicators, including predictive accuracy (MAE, MSE, RMSE, and R^2), blockchain execution performance (transaction success rate and confirmation delay), and transportation cost optimization. The experimental results demonstrate improvements in forecasting accuracy, secure transaction processing, and operational cost reduction. Because no universally accepted logistics efficiency metric exists that simultaneously captures prediction quality, blockchain performance, and optimization effectiveness, the evaluation is presented through these individual performance indicators.

A comparison with representative blockchain-enabled and AI-assisted logistics management studies is presented in Table 10. Existing work, such as [10,11,13] primarily focuses on individual aspects, including blockchain-based transparency, smart contract automation, or AI-driven decision support. In contrast, the proposed framework integrates predictive analytics, blockchain-enabled smart contracts, transportation optimization, system integration, and real-time monitoring within a single operational architecture.

Unlike many prior studies that present conceptual frameworks or evaluate isolated components, the proposed system demonstrates end-to-end interaction among forecasting, smart contract execution, optimization, and monitoring. Furthermore, the framework was validated using the real DataCo Smart Supply Chain dataset [15] and blockchain-based transaction processing experiments involving 500 logistics transactions. These characteristics distinguish the proposed framework from existing studies [16] and support its practical applicability as an integrated logistics management solution.

Collectively, the experimental results demonstrate the feasibility of integrating predictive analytics, blockchain-enabled smart contracts, and transportation optimization within a unified logistics management framework. Tables 11 and 12 compare the proposed optimized solution for logistics network management with the existing state of the art as given in the literature.

Table 11. Comparison with existing studies.

Study	AI	Blockchain	Optimization	Real-Time Monitoring	End-to-End Integration
[10]	Yes	Yes	Yes	No	No
[11]	No	Yes	No	No	No
[13]	Yes	Yes	No	No	No
Proposed Work	Yes	Yes	Yes	Yes	Yes

Table 12. Comparison of the proposed framework with existing work.

Research Area	Reference	Observed Limitations in the Existing Literature	Contribution of the Proposed Framework
Blockchain implementation in logistics operations	[11]	Several studies discuss the potential of blockchain and smart contracts; however, practical deployment within a comprehensive logistics architecture remains limited.	The proposed framework introduces a five-layer architecture that incorporates blockchain-enabled smart contracts and demonstrates its applicability using operational logistics data.
Transparency and traceability across logistics activities	[14]	Existing solutions improve transaction visibility but provide limited support for integrated monitoring and decision making across multiple logistics processes.	The framework combines secure transaction recording with analytical capabilities to improve visibility, traceability, and operational oversight.
Integration of intelligent analytics with blockchain technology	[10]	Current studies predominantly focus on transparency, optimization, or traceability, while the integration of predictive intelligence remains insufficiently explored.	Predictive analytics is embedded within the decision support layer and linked with blockchain-enabled smart contracts to facilitate proactive logistics planning.
Adoption of blockchain and AI in logistics ecosystems	[13]	Although the benefits of combining blockchain and AI have been widely discussed, practical frameworks demonstrating their coordinated operation are relatively scarce.	The proposed architecture unifies predictive analytics, blockchain services, and automated smart contract execution within a single logistics environment.
Data integrity and secure information exchange	[13]	Logistics networks continue to face challenges related to data manipulation, inconsistent records, and trust among participants.	Blockchain mechanisms are employed to establish immutable records and verifiable transactions, thereby strengthening data reliability and security.
Collaboration among supply-chain stakeholders	[11,14]	Information fragmentation often limits coordination and transparency among organizations participating in logistics activities.	A shared blockchain-based transaction environment enables trusted information exchange and improves collaboration among stakeholders.
Comprehensive logistics management solutions	Proposed Framework	Most reported studies address individual aspects, such as security, transparency, optimization, or traceability, rather than providing an integrated solution.	The proposed framework delivers an end-to-end architecture that combines data acquisition, analytics, blockchain infrastructure, smart contracts, and stakeholder interaction within a unified system.

6. Conclusions

The proposed five-layer architecture for logistics network optimization, integrating predictive analytics and blockchain-enabled smart contracts, proves to be a robust and effective solution for modern logistics network challenges. The performance analysis indicates significant improvements in predictive accuracy and operational efficiency. The blockchain layer ensures secure, transparent, and tamper-proof transactions, enhancing stakeholder trust and collaboration. The presented workflow demonstrates the practical integration of predictive analytics, blockchain-enabled smart contracts, optimization, and

real-time monitoring within a unified logistics decision support framework. Real-time monitoring and dynamic optimization capabilities provide continuous insights, enabling proactive decision making and adaptive responses to changing conditions. By addressing key research gaps and demonstrating practical implementation, this study underscores the potential of integrated technologies to revolutionize logistics network management, making operations more efficient, transparent, and resilient. While the proposed framework demonstrates the feasibility of integrating predictive analytics, blockchain-enabled smart contracts, and logistics optimization, challenges related to interoperability, privacy governance, and large-scale industrial deployment require further investigation.

Although the proposed framework demonstrates the successful integration of predictive analytics, blockchain-enabled smart contracts, and optimization mechanisms, the current study does not claim superiority over all standalone AI-based or blockchain-based logistics solutions. Future work will include comparative benchmarking against conventional logistics management systems, AI-only frameworks, and blockchain-only implementations to quantify the benefits of integrated deployment.

The results demonstrate that the proposed framework can successfully integrate predictive analytics, blockchain-enabled smart contracts, transportation optimization, and monitoring within a unified logistics management environment. While the findings indicate the practical feasibility and potential operational benefits of this integrated approach, the study does not claim to revolutionize logistics network management or establish universal superiority over existing industrial solutions. Further validation on large-scale enterprise deployments and comparative benchmarking studies remain an important direction for future research.

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