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Blockchain-Enabled FAHP-Based Platform for Third-Party Logistics Evaluation and Selection in Cold Vaccine Supply Chains

Ali Barenji [1,*] and Zhi Li [2]

[1] Department of Mechanical Engineering, New Mexico Tech, Socorro, NM 87801, USA
[2] School of Electromechanical Engineering, Guangdong University of Technology, Guangzhou 510006, China
* Correspondence: ali.barenji@nmt.edu

Abstract

Cold vaccine delivery is often known as a high-cost logistic process, which forces many pharmaceutical manufacturers, particularly small- and medium-sized enterprises (SMEs), to subcontract logistics operations of vaccines to third-party logistics (3PL). It is clear that maintaining the traceability and trackability of vaccines in this dynamic collaborative environment is fundamental for guaranteeing the safety of product. However, the lack of a unified vaccine logistics platform holds back comprehensive supervision and traceability, posing significant challenges to the development of useful cold chain logistics systems. To address these challenges, in this study we propose a blockchain-enabled platform for the evaluation and selection of 3PL providers in vaccine supply chains. We leveraged consortium blockchain technology to guarantee data integrity, transparency, and decentralization, facilitating trust among four main players of vaccine supply chain. We utilized smart contracts as a main part of this platform, which are responsible for automating key operational processes, including 3PL evaluation, contract execution, and monitoring. In this respect, the Fuzzy Analytic Hierarchy Process (FAHP) engine is integrated into the proposed platform to enable a data-driven, multi-criteria decision-making framework for selecting the most suitable 3PL providers. We evaluated the proposed platform through case study and gas consumption analysis; the results of the case study validate high operational accuracy (93.21%), precision (90.23%), recall (94.50%), and an F1-score of 92.32% for the platform, which offers a robust solution to enhance accountability, reliability, and decision-making in vaccine distribution networks.

Keywords: third-party logistics; blockchain; vaccine supply chains; fuzzy analytic hierarchy process; and smart contract

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1. Introduction

In the world, vaccine is one of the most cost-effective and impactful public health interventions for preventing and controlling infectious diseases. According to the report of the World Health Organization (WHO), vaccination can avoid 2 to 3 million deaths every year [1], underscoring its critical role in global health. Over the past century, vaccination programs have prevented an estimated 2–3 million deaths annually, while contributing to the near-eradication of diseases such as smallpox and a >99% reduction in global polio incidence, according to World Health Organization reports [2,3].

Despite these accomplishments, significant challenges continue within vaccine supply chains, especially with cold vaccine supply chain, often leading to disruptions that

compromise both vaccine effectiveness or vaccine safety and public trust in immunization programs. For example, in 2009, adverse events associated with influenza vaccines in Australia resulted in severe reactions in more than 500 children [4]. In 2015, the WHO removed several major Indian vaccine manufacturers from its list of qualified suppliers following incidents of tampered vaccine shelf lives [5]. Similarly, in China, the 2016 illegal vaccine distribution case in Shandong Province prompted significant reforms in the nation's vaccine sales model [6]. In Indonesia, a 2016 incident involving counterfeit vaccines impacted over 5000 children through the supply chain process, eroding public trust in the health sector despite the vaccines being non-harmful [7]. These historical incidents highlight persistent systemic vulnerabilities that re-emerged during the COVID-19 vaccine rollout, including cold chain breaches, counterfeit distribution, and fragmented logistics oversight. Recent studies (2021–2024) emphasize that these challenges remain unresolved in many regions, reinforcing the need for digitally enabled, traceable, and regulation-aware vaccine logistics platforms [2,8,9]. These recent cases highlight the critical need for robust systems to ensure vaccine safety, traceability, and public confidence in supply chains. In addition, unlike other pharmaceutical products, vaccines are highly sensitive to temperature and delivery conditions. The storage and transportation temperatures for most vaccines must be strictly maintained within the range of 2–8 °C [10]. The high sensitivity to temperature changes shows the importance of logistics as a critical component in the vaccine supply chain. Cold chain logistics, a specialized low-temperature logistics process, is fundamental to ensure that vaccines remain within the required temperature range throughout the life cycle. For vaccines, as a unique category of pharmaceutical products, cold chain logistics is required to preserve their efficacy and safety during storage and distribution [11]. A review of the literature on vaccine logistics highlights three major challenges:

(1) High cost of in-house logistics: The cost of establishing, as well as maintaining, an independent or partially dependent cold chain logistics system is often prohibitively expensive for small- and medium-sized pharmaceutical enterprises, especially during crises such as the COVID-19 pandemic. Many SMEs faced limited financial resources and infrastructure to support self-built logistics networks, making them highly dependent on third-party logistics (3PL) providers for vaccine storage and distribution [12,13]. Therefore, pharmaceutical enterprises typically outsource transportation and storage to 3PL; however, selecting a suitable provider requires extensive research and communication, making the process both time-consuming and labor-intensive [10,14]. Furthermore, newly established pharmaceutical manufacturers often have partial awareness of the logistics market, which increases their vulnerability to challenges such as vaccine damage, loss, and inefficiencies in cold chain logistics [15].

(2) Low space truck utilization, which increased logistics costs: Large pharmaceutical companies, such as GlaxoSmithKline, mostly prefer to operate their own logistics networks to manage vaccine distribution. However, a significant portion of the vaccines they produce must still be transported to various locations using their in-house logistics systems. This often results in low space truck utilization on both trips, particularly due to vaccine returns and small-batch orders, directing increased logistics costs and inefficiencies of in-house logistics system [16]. Such inefficiencies not only raise operational expenses but also hinder the long-term sustainability and cost-effectiveness of vaccine distribution, making it imperative to explore optimized logistics solutions [17].

(3) Lack of monitoring through the policy challenges in vaccine logistics: Regulatory policies can significantly impact the demand for 3PL services in the pharmaceutical sector. For example, following the "vaccine event" in 2016, the Chinese government

implemented stricter regulations on vaccine circulation. These regulations require all enterprises producing second-type vaccines, regardless of their size, to distribute vaccines directly to prefecture and county-level Centers for Disease Control and Prevention (CDC) [18]. Due to the vast scale of the distribution endpoints, even large pharmaceutical companies often faced monitoring and tracking of vaccines throughout the delivery process [19,20].

To address these challenges, in this paper we propose a blockchain-based platform for evaluating and selecting logistics providers to enhance coordination in the cold vaccine supply chain. The platform integrates blockchain technology with the Fuzzy Analytic Hierarchy Process (FAHP) to optimize decision-making in 3PL selection. Additionally, by incorporating the Internet of Things (IoT) into vaccine cold chain logistics, the platform enables the collection of real-time, objective data, improving transparency and operational efficiency. Compared with alternative MCDM techniques such as TOPSIS and ELECTRE, FAHP offers additional advantages for regulated vaccine logistics environments. TOPSIS relies on strict normalization procedures and assumes independence among criteria, assumptions that may not be held in cold chain logistics where factors such as temperature control and delivery timeliness are often correlated. ELECTRE focuses on outranking relationships and dominance thresholds, but its complex concordance–discordance structure can limit interpretability and make justification of selection decisions difficult for regulatory authorities. In contrast, FAHP preserves the hierarchical structure of decision-making while enhancing robustness through uncertainty modeling and maintaining transparency in weight derivation. By embedding FAHP within a consortium blockchain architecture, the proposed platform further ensures that evaluation inputs, calculated weights, and final 3PL selection results are traceable, auditable, and tamper resistant. This integration enables uncertainty-aware decision-making while simultaneously satisfying the transparency and accountability requirements of highly regulated cold vaccine supply chains.

Smart contracts deployed on the blockchain network autonomously evaluate vaccine transportation based on temperature data collected. These contracts facilitate automated decision-making, ensuring that only vaccines meeting the required storage and transportation conditions progress through the supply chain. Furthermore, smart contracts continuously assess compliance by analyzing temperature fluctuations and location data throughout the logistics process. Upon delivery to medical institutions, the blockchain framework verifies the authenticity of the vaccines, enhancing traceability and mitigating the risks associated with counterfeit or compromised shipments; developed smart contracts also create supervisory control for FDA, which improve the visibility and safety of vaccines.

In this respect the proposed platform employs encryption to secure data into interconnected blocks. Each block contains essential components, including a hash code, timestamp, and transaction data from the previous block, ensuring immutability and traceability [21]. Each node in the proposed platform maintains a synchronized copy of the transaction ledger, guaranteeing data consistency and transparency across the system. The integrity of recorded data is safeguarded by a consensus mechanism, making them highly resistant to tampering or unauthorized modifications [22]. Given its inherent security, transparency, and decentralized nature, blockchain serves as the foundational technology for ensuring efficient, reliable, and manageable vaccine logistics processes.

The main contributions of this paper are as follows:

1. A novel FAHP–blockchain integrated decision framework for 3PL evaluation and selection, moving beyond traceability-focused blockchain applications toward executable logistics decision support.

2. An on-chain FAHP mechanism that captures uncertainty in logistics performance evaluation while ensuring transparency, immutability, and auditability of selection outcomes.
3. A regulatory-aligned consortium blockchain architecture that enables real-time supervision of cold vaccine logistics without centralized control.
4. A validated case study using one-year industrial data demonstrating the effectiveness, robustness, and practical feasibility of the proposed platform.

The rest of this paper is arranged as follows. Section 2 reviews the relevant literature. The proposed platform is presented in Section 3. Section 4 introduces the core technology of this platform, such as the evaluation of transportation capacity of logistics companies and the selection mechanism of vaccine logistics based on FAHP. The case study is discussed in Section 5. Section 6 provides simulation evaluation techniques to evaluate platform characteristics. Section 7 contains conclusions and future work.

2. Literature Review

This part summarizes the related literature from three aspects: vaccine supply chain, logistics collaboration, and blockchain in supply chain.

2.1. Vaccine Supply Chain

Immunization has been widely recognized as an effective strategy for controlling and eliminating life-threatening infectious diseases. It is estimated that vaccination prevents 2 to 3 million deaths annually, making it one of the most cost-effective public health interventions [23]. As the backbone of immunization efforts, the vaccine supply chain encompasses pharmaceutical manufacturers, logistics providers, medical institutions, and end consumers. Unlike conventional supply chains, vaccine logistics is characterized by high uncertainty in supply and demand, requiring robust and adaptable distribution networks to ensure availability and accessibility [24]. By studying Global Alliance for Vaccines and Immunization (GAVI)'s role in promoting the transformation of vaccine supply chain in various countries, Gemma believes that the policies, national agencies, and collaborative systems related to the vaccine supply chain should establish mutual links to promote the development of vaccine supply chain. At the same time, the vaccine supply chain should be robust enough to deal with emergencies [25]. In vaccine logistics, the integration of 3PL has introduced new productivity and vitality to the vaccine supply chain. Sarley et al. [26] emphasized that logistics serves as a key driver in vaccine supply chain transformation, with 3PL playing a central role in enhancing distribution capabilities. However, to fully leverage the benefits of 3PL integration, stronger national oversight and regulatory frameworks are necessary to ensure the reliability and security of logistics operations. Salari & Sazvar [27] further highlighted that vaccine demand is typically characterized by small quantities, high frequency, and wide geographical distribution. Their research indicates that direct manufacturer or end-user distribution is often costly, whereas outsourcing to 3PL can significantly reduce logistics expenses, enhance service coverage, and improve overall efficiency while maintaining vaccine quality.

The Shandong vaccine case in 2016 prompted significant regulatory changes in China's vaccine distribution system. In response, the government revised the Regulations on the Administration of Vaccine Circulation and Vaccination (referred to as the "Regulations") in the first half of 2016 [28]. These revisions led to a shift in the sales framework for Class II vaccines, transitioning from the traditional "two-vote system" to a "one-vote system," as illustrated in Figure 1.

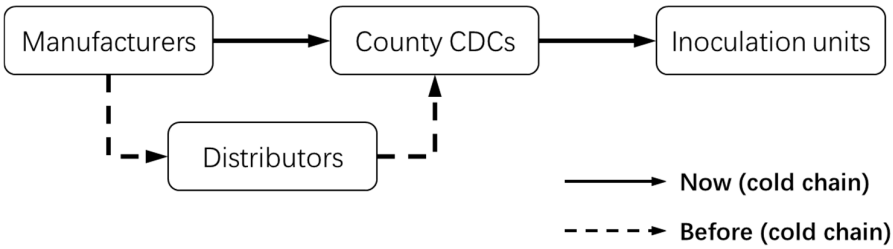


Figure 1. Transformation of vaccine logistics.

Under the revised procurement process, vaccine manufacturers, through provincial CDC bidding platforms, sell and invoice vaccines directly to county-level CDCs based on their demand. Payments for these transactions are processed through provincial public resource trading platforms, ensuring standardized financial procedures. Regarding logistics, the Regulations mandate that vaccine manufacturers must either distribute Class II vaccines directly to county-level disease prevention and control institutions or contract third-party enterprises with specialized cold chain storage and transportation capabilities [29]. This "one-vote system" has significantly restructured the vaccine supply chain by centralizing procurement, enhancing transparency, and streamlining logistics operations to mitigate risks associated with vaccine handling and distribution.

As illustrated in Figure 2, vaccines are uniformly procured by the government and distributed to medical institutions across various levels. Currently, large-scale pharmaceutical manufacturing enterprises often operate their own logistics companies, enabling them to achieve self-sufficiency in logistics services. Medium-sized enterprises typically adopt a hybrid model, combining self-managed logistics with third-party distribution services. In contrast, small-scale enterprises, constrained by limited resources, primarily rely on fully outsourced third-party logistics providers to transport their vaccines.

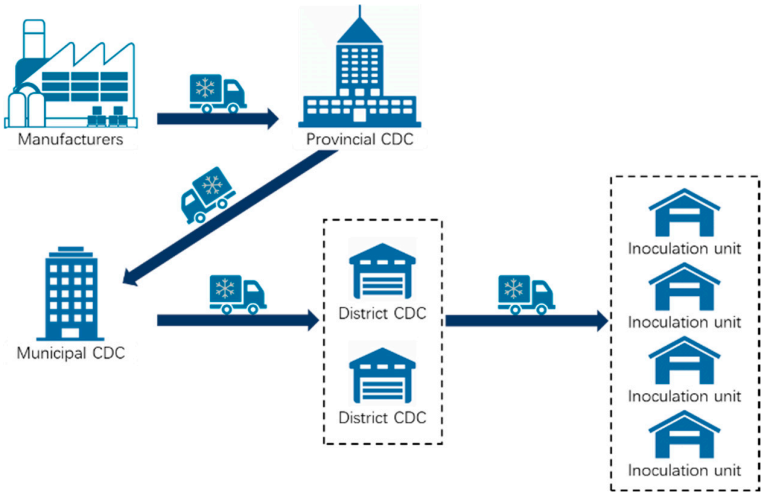


Figure 2. Logistics of one-vote vaccine.

2.2. Logistics Collaboration

Logistics collaboration refers to the strategic coordination of business activities and service provision across networks to enhance profitability and overall supply chain performance. By fostering a collaborative environment, enterprises can efficiently share information and resources, optimize logistics operations, and reduce costs. Logistics collaboration is an advanced development in supply chain management, leveraging the cost advantages of network economies [30]. In the supply chain network, logistics cooperation can be divided into two parts: horizontal and vertical. Horizontal collaboration occurs between entities operating at the same level in the supply chain, such as multiple logistics

providers pooling resources to improve efficiency. Vertical collaboration involves cooperation between upstream and downstream participants, such as manufacturers, suppliers, and distributors, to enhance integration and streamline operations [31]. Research by [32] highlights the benefits of vertical integration, demonstrating how strengthened partnerships between different supply chain tiers improve operational efficiency, responsiveness, and resilience.

In addition, [33] found that a horizontal logistics coordination strategy can promote the frequency of delivery and increase the area covered. In addition, [34] offers a review of the existing research in horizontal collaboration, specifically highlighting efforts focused on the areas of on-demand logistics, freight consolidation, facility sharing, incentives, case studies, and quantitative analyses. Meanwhile, a two-stage-based supply chain for horizontal logistics is proposed by [35]. Above all, logistics collaboration has many advantages, such as improving the efficiency of social logistics distribution, reducing the cost of distribution—saving logistics costs—and improving the quality of distribution services and the operating efficiency of logistics distribution center.

2.3. Blockchain in Supply Chain

Blockchain is essentially a distributed record database. This decentralized digital ledger system uses algorithms and cryptographic keys in linear time periods to create a sequential chain to ensure the verifiability and high level of trust of each block on the chain [36]. Because of its high transparency, low transaction costs, high credibility and digitalization, and data virtualization, many researchers applied blockchain technology to supply chain to take advantage of this technology. For example, [36] proposed a unified five-layer blockchain-based network to provide a decentralized traceability solution in the drug supply chain. Ref. [37] presented a critical review of integrating Artificial Intelligence (AI) and blockchain technologies in vaccine supply chain management during the COVID-19 pandemic. The analysis provided shows the nuanced relationship between vaccine accessibility and manufacturer profitability, emphasizing the sensitivity of manufacturers to vaccine attenuation rates. The findings underscore the need for precise demand forecasting and production planning to maximize the efficacy of AI and blockchain adoption, offering valuable managerial insights into optimizing vaccine supply chain performance. Ref. [38] provided a comprehensive analysis of blockchain adoption barriers in sustainable supply chains, combining advanced methodologies such as machine learning (ML) classifiers, BORUTA feature selection, and the Gray-DEMATEL method. This research demonstrates the ability of machine learning in enhancing analytical precision. Ref. [39] highlights an insightful exploration of the challenges in pharmaceutical supply chains, including drug counterfeiting, and the potential of digital technologies such as blockchain, IoT, and AI to address existing issues. The study proposed that the digitalized supply chain concept integrates advanced technologies to enhance efficiency, traceability, and trust while streamlining communication and processes across the pharmaceutical supply chain.

Blockchain networks are divided into three types: public blockchain, consortium blockchain, and private blockchain [40]. Public blockchain refers to the blockchain that anyone in the world can read and send transactions, and the transactions can be effectively confirmed, and can also participate in the consensus process. Bitcoin is a public blockchain. The consortium blockchain is only for members of a specific group and limited third parties. Multiple preselected nodes are internally designated as bookkeepers. The generation of each block is determined by all preselected nodes. Other access nodes can participate in the transaction, but not in the accounting process. Other third parties can conduct limited queries through the open API of the blockchain. In order to achieve better performance, the consortium blockchain has certain requirements for the configuration of consensus

or verification nodes and network environment. With the access mechanism, transaction performance can be improved more easily, and some problems caused by participants with uneven participation can be avoided [41].

Compared with public blockchain, consortium blockchain has more advantages in efficiency and flexibility: firstly, transaction cost is cheaper; secondly, nodes can be well connected, faults can be quickly repaired through manual intervention, and consensus algorithm is allowed to reduce block time. Thirdly, if the read permission is limited, it can provide better privacy protection. Private blockchain is only open to individual individuals or entities. Compared with the other two blockchains, private blockchain has the fastest transaction speed, the highest privacy protection ability, and the lowest transaction cost.

To clarify the incremental contribution of this study, Table 1 summarizes and compares representative prior works on blockchain-enabled logistics platforms and FAHP-based 3PL selection methods. Existing blockchain-based studies primarily emphasize traceability, tracking, and data integrity in pharmaceutical supply chains, but do not address systematic logistics, provider evaluation, or selection. Conversely, FAHP-based 3PL selection studies are typically implemented as offline, centralized decision-support tools and lack real-time data integration, transparency, and regulatory visibility.

Table 1. Comparison of existing methodologies and tools with key limitations.

Reference	Methodology	Blockchain Used	MCDM Method	Regulatory Role	Key Limitations
[19]	Blockchain-based traceability framework	Yes	No	Implicit	Focuses on tracking and lifecycle data; no logistics provider evaluation or selection
[16,42]	Blockchain architecture for pharmaceutical logistics	Yes	No	Limited	Emphasizes logistics monitoring, not decision-making or 3PL ranking
[43]	3PL provider selection for Industry 4.0	No	Fuzzy AHP + Fuzzy MARCOS	No	Strong MCDM; still centralized and not integrated with real-time IoT/blockchain governance
[44]	Medicine cold chain logistics provider selection (group decision framework)	No	Pythagorean fuzzy DEMATEL–CoCoSo	No	Advanced MCDM but still offline/centralized; lacks blockchain-based trust and traceability

In contrast, the proposed approach uniquely integrates FAHP within a consortium blockchain architecture, enabling uncertainty-aware 3PL evaluation to be executed, recorded, and audited on-chain using real-time IoT data. By explicitly incorporating regulatory authorities as supervisory nodes, the proposed platform advances beyond prior work by aligning logistics provider selection with both operational performance and regulatory compliance requirements.

3. Proposed Platform

3.1. The Conceptual Framework of the Platform

Due to the high sensitivity of the vaccine logistics process, WHO recommends that all aspects of vaccine supply chain management should be directly supervised by national regulatory authorities [45]; traditional centralized tracking systems face issues related to lack of transparency, inefficiencies, and difficulties in ensuring regulatory compliance. The conceptual framework of the proposed platform is shown in Figure 3, follows this recommendation, and it includes four mains primary stakeholders:

- Food and Drug Administration (FDA): The FDA oversees the platform by providing governance, supervising compliance, and issuing vaccine qualification certificates.
- Pharmaceutical manufacturers (PM): Responsible for producing vaccines according to established standards, recording vaccine-related data, and coordinating with logistics providers and FDA.
- 3PL: Handle cold chain transportation, ensuring vaccines are maintained within prescribed temperature and humidity levels and coordinate with PM as well as medical institution directly.
- Medical institutions: Receive and store vaccines, verify their authenticity upon arrival, and assess logistics providers' performance.

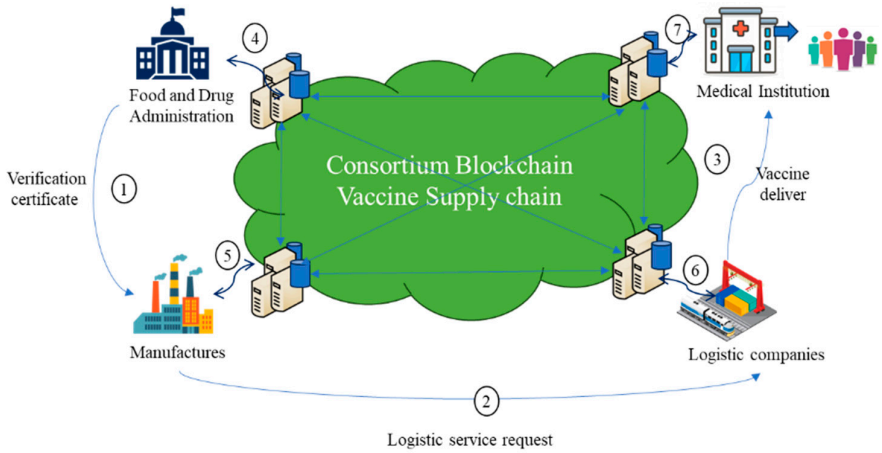


Figure 3. Conceptual framework of the platform.

The consortium blockchain vaccine supply chain network (CBV) provides a secure and trustworthy environment for recording each transaction and process within the vaccine supply chain among stakeholders. The workflow is structured into the following seven key steps, as illustrated in Figure 3.

(1) Regulatory Inspection and Certification:
   a. Before vaccines are approved for distribution by the PM, the FDA conducts strict inspections to verify compliance with safety and quality standards.
   b. If a vaccine meets all required criteria, the FDA issues a digital certification recorded on the CBV.

(2) Logistics Service Request and Vaccine Dispatch:
   a. Medical institutions submit orders to the PM.
   b. Upon receiving an order, PMs request logistics services from 3PL providers within the network.
   c. Only vaccines with FDA-issued certificates are approved for distribution.

(3) Cold Chain Logistics and Vaccine Acceptance:

a. The assigned 3PL provider takes custody of the vaccines and ensures compliance with regulations, including temperature and humidity control.
b. Before storage, medical institutions conduct an acceptance check to ensure temperature stability and package integrity.

(4) Blockchain Integration and Regulatory Oversight:
a. The FDA continuously monitors vaccine distribution through smart contracts, which track vaccine movements and record all transactions.
b. If a logistics provider or manufacturer fails to comply with regulations, the CBV system automatically flags the issue for regulatory review.

(5) Data Upload and Verification:
a. PMs upload key data, including vaccine batch details, production dates, and destination information.
b. The CBV verifies manufacturer qualification certificates before permitting vaccines to leave production facilities.

(6) Real-Time Logistics Monitoring:
a. IoT-enabled sensors track temperature, humidity, and location in real time, ensuring compliance with cold chain protocols.
b. All real-time data is automatically uploaded to the CBV for secure and immutable record-keeping.

(7) Final Acceptance and Performance Evaluation:
a. Upon arrival, medical institutions conduct final inspections to verify vaccine integrity.
b. They then assess and evaluate logistics providers' performance based on key indicators such as delivery timeliness, temperature maintenance, and service quality.
c. This feedback is stored on the CBV, contributing to future 3PL selection decisions.

The proposed consortium blockchain-based vaccine supply chain not only addresses traditional requirements but also enhances the traceability of vaccine orders and logistics process data. This improved traceability facilitates more effective oversight and regulation of the vaccine supply chain by the FDA, ensuring greater transparency and accountability.

3.2. Layer Based Architecture of the Proposed Consortium Blockchain Vaccine Supply Chain Platform

The architecture of the proposed CBV, depicted in Figure 4, is structured into five distinct layers—namely, the source layer, perception layer, analysis layer, application layer, and the blockchain network column. These layers enable seamless vertical and horizontal integration within the different stakeholders in the platform, ensuring efficient data flow, enhanced traceability, and robust system connectivity across all components. The original data is generated at the source layer by various entities, including quality inspectors, machines, logistics vehicles, and other sources. This data is captured in the perception layer through methods such as QR codes, RFID tags, sensors, GPS, and other technologies, making the perception layer a critical step in real-time data acquisition. The collected data is then transmitted to the analytic layer via an intelligent gateway, where it undergoes filtering and preprocessing. The processed, heterogeneous data is subsequently stored in the blockchain network column to ensure secure and immutable record-keeping. In the analytic layer, the FAHP method is employed to evaluate 3PL, with evaluation weights determined by the PM. Finally, at the application layer, key stakeholders including FDA, PM, 3PL, and medical institutions are interconnected to form a comprehensive and cohesive vaccine supply chain system and receive a service from platform. Each layer is explained as follows.

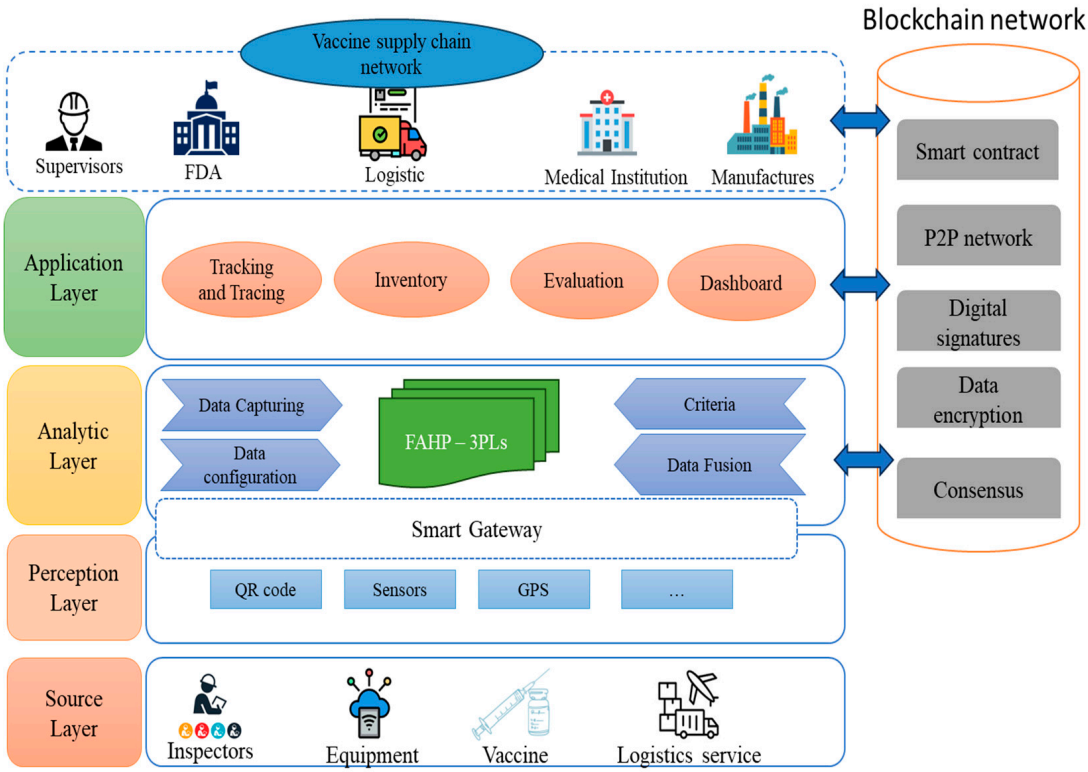


Figure 4. Architecture of the proposed platform.

1. Source layer

The source layer acts as the data origin for all vaccines, PMs, and delivery-related activities. It includes essential entities such as quality inspectors, vaccines ready for shipment, logistics vehicles, and other transport equipment. This layer is the backbone of data generation, capturing essential information about vaccine handling and movement.

2. Perception Layer

The perception layer consists of IoT devices and other sensing technologies responsible for real-time data collection from the source layer. Key devices include handheld PDAs used by quality inspectors, temperature monitoring systems, GPS trackers, and humidity sensors on logistics vehicles. These tools ensure continuous tracking of vaccine conditions such as temperature, humidity, and transportation routes.

3. Analytic layer

Data collected from the source layer via perception layer is transmitted to the analytic layer via smart gateways. This layer processes, filters, and organizes the data for store and use for 3PL evaluation purposes. It ensures the integration of heterogeneous data into a cohesive format, preparing it for storage in the blockchain network. The main part of this layer is the FAHP engine, which is responsible for section right 3PL, this engine explains in Section 4 in detail. Therefore, this layer supports decision-making by providing essential inputs for logistics evaluation and monitoring.

4. Application layer

The application layer connects all stakeholders in the vaccine supply chain, including FDA, PM, 3PL, and medical institutions. It provides an intuitive interface for managing vaccine logistics, monitoring, and evaluating logistics providers. Through this layer, four main stakeholders of cold vaccine supply chain can access real-time monitoring data,

perform vaccine acceptance checks, and ensure seamless collaboration across the supply chain network.

5. Blockchain network

The blockchain network in the platform serves as one of the core technologies; it is responsible for providing a secure and reliable mechanism and execution process for information storing and sharing across the vaccine supply chain. It also acts as the regulator of the consortium blockchain. The FDA defines access principles for PM, 3PL, and medical institutions, ensuring the integrity and trustworthiness of the network.

This blockchain network forms a vertical and horizontal connection between the analytic layer and the broader vaccine supply chain. It comprises a series of technical modules designed to enhance functionality, security, and transparency. In this respect, the smart contracts module automates key processes, such as the verification of vaccine information, scoring of 3PL performance indicators, and evaluation of service providers. This reduces manual intervention, ensuring efficiency and consistency. A peer-to-peer (P2P) network facilitates decentralized data sharing among participants, eliminating single points of failure and enhancing the reliability of the system. A digital signature module is employed to authenticate the accuracy and legitimacy of vaccine though life cycle, ensuring data integrity throughout the whole process. Asymmetric encryption module encrypt data during transmission, safeguarding sensitive information and maintaining confidentiality across the network. The Proof-of-Work (PoW) algorithm is used for transaction authentication and verification within the developed blockchain network. This ensures that all data recorded on the network is accurate, secure, and tamper-proof.

The blockchain network enables all participants in the vaccine supply chain to monitor the process and access evaluations of 3PL. By leveraging this transparent and reliable system, pharmaceutical companies can make informed decisions when selecting logistics providers, ensuring alignment with their specific logistics requirements, and enhancing overall supply chain effectiveness.

4. FAHP Engine in Analytic Layer

FAHP engine in the analytics layer of proposed platform plays an important role by facilitating the evaluation of 3PL. The process behind this engine is explained as follows: Upon the completion of a vaccine logistics order, the platform assess the capability of 3PL providers from the existing poll. This evaluation is essential for ensuring the quality, reliability, and alignment of logistics services with vaccine supply chain requirements. In this study, four key performance indicators (KPIs) have been identified to assess the capability of 3PL, as outlined in Table 2. These indicators provide a structured and objective approach to evaluating each 3PL, thereby enhancing decision-making processes within the platform.

Temperature control ability or S_1: Maintaining the required temperature range is critical for vaccine. This index measures the refrigeration and insulation capability of cold chain vehicles by calculating the ratio of over temperature time to total logistics time [46]. It directly reflects a 3PL's ability to preserve vaccine efficacy during transportation.

On-time delivery rate or S_2: Timeliness in vaccine delivery ensures that vaccines are available at medical institutions when needed. This indicator is evaluated by quality inspectors based on the ratio of on-time deliveries to total delivery orders [47]. It reflects the logistics provider's ability to adhere to agreed delivery schedules.

Package integrity or S_3: The integrity of vaccine packaging during transportation ensures product safety and reliability. This indicator assesses the stability of packaging in the logistics process and is subjectively evaluated by warehouse quality inspectors at medical institutions [48].

Table 2. Indicators of 3PL capability of vaccine logistics.

Indicators	Description
Temperature control ability S_1	Ratio of overtemperature time to total logistics time, reflecting the refrigeration and insulation capacity of cold chain vehicles.
On-time delivery rate S_2	Evaluated subjectively by quality inspectors, measuring the lead-time punctuality of logistics enterprises.
Package integrity S_3	Reflects the stability of vaccine packaging during transportation, assessed subjectively by warehouse quality inspectors.
Service attitude S_4	Reflects the attitude of logistics service personnel, evaluated subjectively by medical institution quality inspectors.

Service attitude S_4: The professionalism and attitude of logistics service personnel significantly impact overall service quality. This indicator reflects the perceived quality of service based on the interactions between logistics staff and medical institutions, evaluated by quality inspectors [49].

4.1. Data Capturing and Process of FAHP Engine

The data capturing and process of FAHP engine is structured into three key phases: 3PL selection, logistics supervision, and warehousing quality inspection. Each phase plays a crucial role in assessing the transportation capabilities of 3PL providers using the FAHP evaluation framework.

- 3PL selection: In this phase, PMs identify and select suitable 3PL based on their historical data and performances. The selection process relies on data collected from indicators S_1, S_2, S_3, and S_4 during both the logistics supervision and warehousing quality inspection stages. This structured approach ensures that selected 3PL providers align with the vaccine supply chain's stringent quality and reliability requirements.
- Logistics supervision: This phase entails continuous monitoring of vaccine transport as they transit from PMs to medical institutions. Critical logistics data, including temperature fluctuations, humidity levels, and adherence to delivery schedules, are recorded to ensure compliance with vaccine storage and transportation regulations. The collected data provides an objective assessment of 3PL performance, particularly concerning S_1 and S_2.
- Warehousing quality inspection: Upon arrival at medical institutions, vaccines undergo a comprehensive quality inspection before being accepted into storage. This step evaluates the packaging integrity (S_3) and the professionalism and service attitude of logistics personnel (S_4). Quality inspectors assess whether vaccines have been transported under appropriate conditions, ensuring compliance with predefined safety and quality standards.

The first half of Figure 5 shows the data exchange mechanism by considering all processes. In this respect the evaluation process includes the real-time upload and analysis of the service status data in the logistics supervision and the evaluation of the three indicators S_2, S_3, and S_4 by the warehousing quality inspector in the warehousing inspection stage.

During the logistics supervision phase, data is continuously collected from sensors integrated within logistics vehicles, including GPS trackers, temperature monitors, and humidity detectors. This data is uploaded to the blockchain network, ensuring transparency, traceability, and compliance with stringent vaccine cold chain requirements. Maintaining a stable temperature between 2 and 8 °C is essential for preserving vaccine efficacy and

meeting regulatory cold chain standards. The integration of sensor data with blockchain technology enables a secure and immutable monitoring framework, ensuring that service providers adhere to the prescribed environmental conditions.

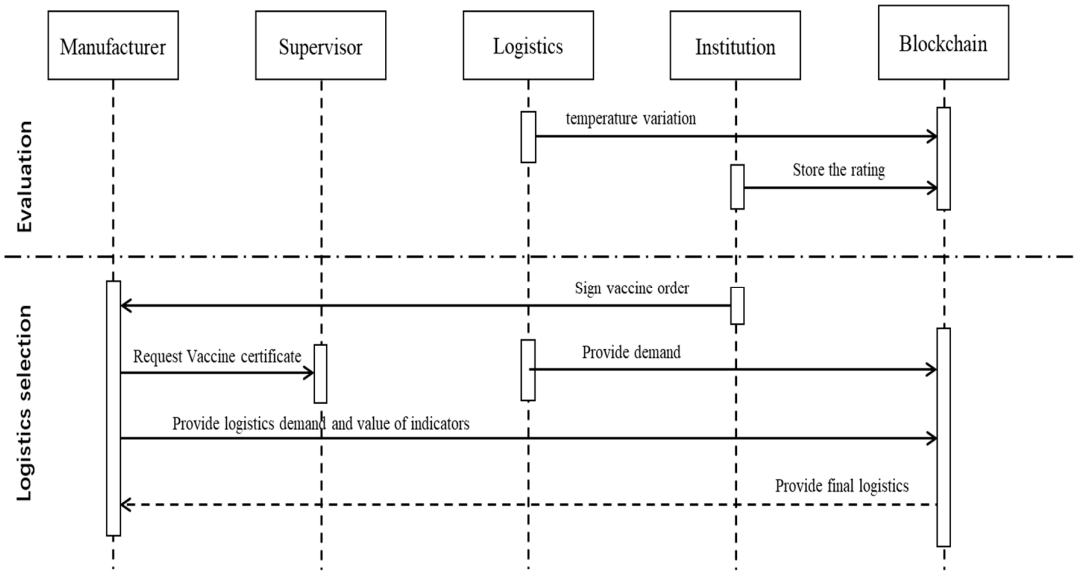


Figure 5. 3PL selection mechanism of the proposed platform.

Given the limitations of cold chain vehicle refrigeration technology, minor temperature fluctuations may occur during transit. To quantify the effectiveness of temperature control (S_1), this study defines the temperature control ability as a function of overtemperature duration relative to the total service time, expressed on a 100-point scale. Specifically, Equation (1):

$$S_1 = 100 - \left(\frac{Total\ overtemperature\ duration}{Total\ logistics\ duration} \times 100 \right) \quad (1)$$

While minor deviations from the prescribed temperature range are occasionally unavoidable, an upper limit for overtemperature duration is necessary to prevent vaccine degradation. However, current regulatory frameworks lack explicit guidelines regarding this threshold. To address this gap, this study introduces a virtual regulatory threshold for overtemperature duration, beyond which the system automatically triggers a return mechanism. Under this protocol, any vaccine shipment exceeding the allowable overtemperature limit must be immediately returned by the 3PL provider to the PM for quality reassessment.

Vaccines that remain within the acceptable temperature range continue through the logistics supervision process and proceed to warehousing quality inspection upon arrival at medical institutions. This structured approach, leveraging blockchain-enabled real-time monitoring, enhances the precision and reliability of vaccine cold chain logistics, ensuring the safety, efficacy, and compliance of vaccine transportation.

Similar to the outbound quality inspection process conducted by PM, the inbound quality inspection at medical institutions is structured into two key steps: Object Identifier (OID) check and batch check.

OID check: Upon arrival at the medical institution, the warehousing quality inspector scans the RFID/QR code on the vaccine box using a Personal Digital Assistant (PDA) device. The system verifies that the OID (Object Identifier) information obtained from the scan matches the corresponding vaccine delivery records. Once the OID verification is successfully completed, the vaccine is authenticated for further processing.

Batch check: This step ensures consistency between the actual received stock batch and the originally dispatched batch from the pharmaceutical enterprise. The verification process is automatically executed by smart contracts, ensuring accuracy and eliminating manual discrepancies. A successful batch check confirms the completion of the warehousing quality inspection process.

Following the quality inspection, the PDA interface prompts the quality inspector to evaluate the three KPIs that influence the transportation performance of the logistics provider, namely S_2, S_3, S_4. Each of these indicators is individually scored by the inspector on a 100-point scale. Once the evaluation is completed, the smart contract autonomously uploads the results to the blockchain network, ensuring immutable and transparent record-keeping. To obtain a comprehensive assessment of the logistics provider, the temperature control ability S_1 recorded during the logistics supervision phase is integrated with the warehousing evaluation scores. The final logistics performance score (E) is calculated as Equation (2):

$$E = S_1 + S_2 + S_3 + S_4 \quad (2)$$

The logistics provider's performance is then classified based on the cumulative score four main groups, "Poor" when $E < 250$, "Average" when $250 \leq E < 300$, "Good" when $300 \leq E < 350$ and "Excellent" when $E \geq 350$. The final evaluation score (E) for each logistic provider is permanently recorded on the blockchain, providing stakeholders with a transparent and data-driven assessment of the logistics provider's performance. This approach enhances accountability, reliability, and decision-making in 3PL selection while ensuring that vaccine logistics meet the highest standards of quality and efficiency.

4.2. FAHP-Based 3PL Selection Mechanism

The lower half of Figure 5 shows the 3PL selection mechanism based on FAHP. This mechanism is initiated immediately after the warehouse quality inspection, once the PM confirms that the vaccines are ready for shipment. The selection process consists of two sequential steps to ensure that the most suitable and efficient logistics provider is chosen and suggested to the PM: the first, preliminary sorting, and the second, FAHP-based selection.

4.2.1. Preliminary Sorting

Following the completion of the outbound quality inspection, PMs upload vaccine shipment details to the platform. Similarly, 3PL submit their transportation availability and capabilities, ensuring that the selection process is based on logistics data. The uploaded information follows a standardized format, as shown in Table 3, to facilitate seamless comparison and evaluation.

Given the geographical dispersion of vaccine demand and the frequent need for vaccine returns, particularly during the COVID-19 pandemic, some 3PL vehicles operate with low-capacity loads. This dynamic encourages 3PL to maximize order fulfillment, increasing their willingness to accept multiple small-batch vaccine shipments. By efficiently balancing available capacity with incoming demand, 3PL can enhance revenue generation while maintaining logistics efficiency. From the pharmaceutical companies' perspective, cost optimization remains a key priority. They seek logistics solutions that minimize transportation costs while ensuring that vaccines reach medical institutions safely and on time. The preliminary selection process serves as a filtering mechanism, eliminating 3PL that do not meet basic eligibility criteria, thereby streamlining the FAHP-based final selection stage.

Preliminary selection of 3PL for specific demand is done by smart contract. The purpose of preliminary screening is to screen out the relatively mismatched logistics companies in a relatively simple way. Algorithm 1 describes shorting mechanism of 3PL.

Algorithm 1 Preliminary Sorting of Logistics Companies

Purpose: To screen out mismatched logistics companies in a simple way.

```
START PreliminarySorting(3PL_List, Pharmaceutical_Requirements)
    FOR each 3PL in 3PL_List DO // Step 1: Exclude 3PL starting from different provinces
        IF 3PL.startingProvince != Pharmaceutical_Requirements.startingProvince THEN
            REMOVE 3PL FROM 3PL_List
        END IF
    END FOR
    FOR each 3PL in 3PL_List DO // Step 2: Exclude 3PL with different provinces as the destination
        IF 3PL.destinationProvince != Pharmaceutical_Requirements.destinationProvince THEN
            REMOVE 3PL FROM 3PL_List
        END IF
    END FOR
    FOR each 3PL in 3PL_List DO // Step 3: Eliminate 3PL whose demand delivery time exceeds that provided
        IF Pharmaceutical_Requirements.deliveryTime > 3PL.providedDeliveryTime THEN
            REMOVE 3PL FROM 3PL_List
        END IF
    END FOR
    FOR each 3PL in 3PL_List DO // Step 4: Eliminate 3PL with insufficient remaining tray space
        IF Pharmaceutical_Requirements.traySpaceDemand > 3PL.remainingTraySpace THEN
            REMOVE 3PL FROM 3PL_List
        END IF
    END FOR
    FOR each 3PL in 3PL_List DO // Step 5: Exclude 3PL with inadequate temperature range
        IF Pharmaceutical_Requirements.temperatureRange > 3PL.providedTemperatureRange THEN
            REMOVE 3PL FROM 3PL_List
        END IF
    END FOR
    RETURN 3PL_List
END PreliminaryScreening
```

Table 3. Example of data provided by 3PL to platform.

Information	Company XX	Company YY
Start	xxx City, xxx Province	xxx City, xxx Province
End	No. xxx, xxx Road, xxx District, xxx City, xxx Province	No. xxx, xxx Road, xxx District, xxx City, xxx Province
Delivery time	Month day, time	Month day, time
Free tray space	xx m^2	xx m^2
Temperature range	x–y °C	x–y °C

Following the preliminary screening via smart contracts, the filtered list of eligible 3PL providers advances to the secondary selection stage, which is based on the FAHP. This stage involves a comprehensive multi-criteria evaluation, ensuring that the most suitable 3PL provider is selected based on key performance indicators (S_1–S_4).

4.2.2. FAHP-Based Selection of 3PL

After the preliminary screening, the shortlisted 3PL providers advance to the final selection stage, where a more comprehensive and structured evaluation is conducted. This phase aims to narrow down the list of potential logistics providers and select the most suitable one based on its ability to meet the primary vaccine delivery requirements. Using the fuzzy importance of the four indicators S_1, S_2, S_3 and S_4 submitted by source layer to the platform, the source layer transmits fuzzy importance values for these indicators to the FAHP engine, which then calculates the relative weights of each KPI, ensuring a balanced and objective assessment. The FAHP model integrates historical evaluation data from previous logistics operations to enhance decision-making accuracy. Using the FAHP-generated scores, the system ranks the shortlisted 3PL based on their overall suitability, ensuring that the final selection aligns with the critical logistics requirements of the vaccine supply chain. This data-driven approach, combined with blockchain-enabled transparency, guarantees that only the most reliable and efficient 3PL provider is selected, minimizing risks, and optimizing cold chain logistics performance. The process consists of the following steps:

***Step 1* Weight Calculation for 3PL Evaluation Indexes**

The FAHP-based selection process begins with the calculation of weight demand for the four key performance indicators (S_1, S_2, S_3, and S_4) as determined by pharmaceutical enterprises. This weighting process ensures that the evaluation aligns with the critical priorities of vaccine logistics, such as temperature control, timely delivery, packaging integrity, and service quality. Table 4 presents the evaluation scale of relative importance among the indicators. The scale ranges from 1 to 9, where 1 represents equal importance, and 9 indicates absolute importance of one criterion over another. Intermediate values (2, 4, 6, 8) represent varying degrees of importance between these extremes. For instance, if S_1 is deemed more important than S_2, with a degree of 5, this importance is expressed as a ratio in the matrix. Also, a_{ij} is used to express the impact ratio of S_i and S_j on customer satisfaction.

Logistics decision-makers construct a positive reciprocal matrix, representing the relative importance of each indicator. The matrix is calculated using Equation (3), where a_{ij} represents the assigned relative importance value between two indicators.

Table 4. Evaluation scale of relative importance among different indicators.

Scale	Implication
1	Equally important
3	Slightly important
5	Important
7	Obviously important
9	Very important
2, 4, 6, and 8 are of intermediate importance, which is the scale value corresponding to the intermediate state	

$$L = \begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{pmatrix} \quad (3)$$

To ensure the consistency and validity of the decision-makers' preferences, the maximum eigenvalue (λ_{max}) of the matrix is determined, and the Saaty consistency index (CI) is computed using Equation (4):

$$CI = (\lambda_{max} - n)/(n - 1) \quad (4)$$

where n is the number of indicators (in our case is 4). To validate the consistency of the matrix, the random consistency index (RI) is then obtained, and the consistency ratio (CR) is calculated using Equation (5):

$$CR = \frac{CI}{RI} \quad (5)$$

If $CR < 0.1$, the consistency test is satisfied, confirming the effectiveness of the fuzzy attention provided by pharmaceutical enterprises. Once consistency is confirmed, the normalized weight vector (W) is computed using Equation (6):

$$W = \begin{bmatrix} w_1 \\ \vdots \\ w_n \end{bmatrix} \quad (6)$$

where W_i represents the final calculated weight for each performance indicator. This weight vector is then applied in the FAHP selection model, enabling a quantitative and structured evaluation of 3PL providers based on their historical performance and real-time logistics data.

***Step 2* Calculate the performance of 3PL**

After determining the weighted importance of each key performance indicator in Step 1, Step 2 involves calculating the performance scores of the shortlisted 3PL providers based on their historical logistics evaluation data. For each 3PL provider (i) that remains in the alternative selection pool, its historical evaluation data is recorded in the following performance matrix (P):

$$S_i = W^T \cdot P_I \quad (7)$$

where

- S_i represents the final FAHP score for the ith logistics provider.

- W is the normalized weight vector from Step 1.
- P_i is the historical performance data of the ith 3PL provider.

The computed FAHP scores (S_i) for all shortlisted 3PL are then presented to pharmaceutical enterprises. The 3PL provider with the highest score is selected for vaccine transportation, ensuring that the logistics provider meets the temperature control, timeliness, packaging integrity, and service quality requirements.

This data-driven selection process, supported by FAHP and blockchain-based evaluation transparency, enhances decision-making accuracy, optimizes logistics provider selection, and ensures the safe and efficient transportation of vaccines.

5. Smart Contract and Its Mechanism

Smart contracts serve as a fundamental component of the blockchain network, enabling multi-user agreements through digital contract execution. They ensure transparency, trust, and automation in the platform, significantly improving traceability, security, and efficiency in vaccine logistics. The smart contracts implemented in this study are developed using Solidity, a widely used programming language for blockchain applications. Four smart contracts have been designed to facilitate drug circulation and logistics management among stakeholders:

- Vaccine ordering smart contract (VOSC): This smart contract is instantiated between medical institutions and PMs, it handles the secure creation of ordering and tracking of vaccines provided by medical institutions to the PMs. VOSC supervisory control by FDA, for traceability purposes.
- PM managing smart contract (PMM): This smart contract is instantiated between the PM and FDA to manage vaccine traceability during manufacturing and inventory, ensuring regulatory compliance and traceability.
- Logistic process managing smart contract (LPM): This smart contract is instantiated between selected 3PL and medical institutes to ensure the tracking and tracing of vaccine condition during transportation.
- 3PL Evaluation smart contract: Implements the FAHP-based selection and evaluation process for logistics providers.

Each smart contract has been mathematically modeled to evaluate its cost-effectiveness and ensure optimized execution. These models provide a structured representation of contract operations, including decision variables, objective functions, constraints, and execution algorithms. Appendix A provides Solidity based smart contracts. Before presenting the mathematical formulation, the notations used are summarized below.

M defined as a set of manufacturers.
I_m defined as a manufacturer inventory.
V defined as a set of vaccines.
O defined as a set of vaccine orders
T defined as a set of transfer orders.
N defined as a set of natural numbers.
$O_t \in N$ is the order ID.
V_o represents the vaccine order details.
S is the starting location.
E is the ending location.
TS is the timestamp.
SP is the required storage space.

LT is the lower temperature limit.
UT is the upper temperature limit.
M_2 is a Boolean indicator (TRUE if the order is processed).
B_2 is a Boolean indicator (TRUE if the order is completed).

5.1. Vaccine Ordering Smart Contract

Designed to manage the vaccine orders by medical institution, the contract enables the creation, evaluation, and status tracking of vaccine orders, ensuring transparency and traceability. It utilizes structured data representations, including *vaccine_order* and *waiting_transfer_order*, to store critical information, such as vaccine name, batch number, transportation conditions, and spatial constraints. This smart contract is divided into five main sections: definition, which provides requested order information, mapping process, which declares orders to FDA and PM, contract initialization, create vaccine order, and set status to tracking. The mathematical model (Table 5) provides the structure of this smart contract and Appendix A provides the Solidity language of the smart contract. Algorithm 2 highlights VOSC in detail.

Algorithm 2 VOSC
Between medical institute and PM supervised by FDA

1. Initialize order_id = 0
2. Receive (N_v, B_v, S, E, TS, SP, LT, UT)
3. Increment order_id
4. Store Order in W(order_id)
    5. If (order is processed) then set M_2 = TRUE
    6. If (order is completed) then set B_2 = TRUE
7. Return order_id

Table 5. Mathematical model for *VOSC*.

Decision Variables	
	$V_o = (N_v,\ B_V)\ \ \forall v \in V$ $T_o = (O_t, V_o, S, E, TS, SP, LT, UT, M_2, B_2)$
Objective Function (if applicable)	$\min \sum_{o \in O}$(Total processing time + logistics cost)
Constraints	
	$O_{count} = O_{count} + 1$ $B_V \geq 0$ $LT \leq Tv \leq UT \qquad \forall v \in V$

5.2. PM Management Smart Contract

PMM smart contract is designed to manage vaccine data during manufacturing and inventory process by storing and retrieving related information and sharing it to FDA and medical institutions. Additionally, it maintains the internal inventory process during manufacturing and provides traceability to the FDA and medical institutions. The contract represents the outbound quality inspection process of vaccines. Table 6 explains the mathematical model behind this smart contract.

Table 6. Mathematical model for PMM.

Manufacturer Structure and Mapping Function
$M_m = (N_m, A_m, I_m)$ $F_m : N_m \rightarrow M_m$
Constraint
$\forall m_i, m_j \in M,\ N_{mi} \neq N_{mj}$
Functional Representation
Insert_Manufacture$(N_m, A_m) \rightarrow M_m$ Get_Manufacture_Inventory$(N_m) \rightarrow I_m$

5.3. Logistic Process Managing Smart Contract

The LPM ensures transparency and traceability of vaccines during the logistics process by 3PL by automatically instantiating connections between the selected 3PL and medical institute. This smart contract is supervised by the FDA and accessible for monitoring by other 3PL and PMs; therefore, it provides global visibility for vaccine as well as performance of 3PL. Algorithm 3 provides a step-by-step execution process of this smart contract by considering outbound quality inspection and monitoring the vaccine during transportation.

Algorithm 3 LPM
Between selected 3PL and medical institute as well as visible for global

1. Initialize logistics_order_id = 0
2. Receive Order Data (S, E, TS_d, P_t, LT, UT)
3. Increment logistics_order_id
4. Store Order in W(logistics_order_id)
5. If Outbound Quality Inspection (QI_o) Fails, then Reject Order
6. If Order is Accepted, set S_t = "Waiting for Shipment"
7. If Shipment is Dispatched, set S_t = "In Transit"
8. Monitor Temperature:
    i. If Tv exceeds limits [LT, UT] for a critical duration, Trigger Alert
9. Upon Arrival, Update Timestamp TS_a
10. If $TS_a > TS_d$, Apply Penalty P_d for Late Delivery
11. Verify Inbound Quality Inspection (QI_d)
    i. If $QI_d = 0$, Apply Penalty P_q and Flag Order for Return
12. If Order Passes All Checks, set S_t = "Delivered"
13. Record Order Data on Blockchain
14. Return logistics_order_id

6. Implementation and Results

To validate the proposed platform for 3PL evaluation and selection in cold vaccine supply chains, two experimental evaluations were conducted: time consumption analysis and simulation-based case study evaluation. These experiments were performed on two different computational environments: one with a 12th Gen Intel Core i7 CPU (2.30 GHz) with 32 GB RAM running Windows 11, and the other with an Intel Core i3 CPU (2.40 GHz) with 6 GB RAM running Windows 11.

In this respect, Visual Studio Code (Version 1.90) is used as the integrated development environment, based on the development method of back-end and front-end separation, to accelerate the development process. The back-end of the platform was deployed on

the Ethereum blockchain, where Ganache was utilized to establish a blockchain network, enabling a controlled and adjustable testing environment. The Itsuku PoW algorithm, a memory-hardened Proof-of-Work (PoW) scheme adapted from MTP-Argon2, was implemented to enhance security while allowing efficient computational performance. The developed back-end integrated smart contracts, which are developed based on Solidity language, which is a contract-oriented, object-oriented programming language and highly adoptable with Ethereum. In the front-end, we use the React.js framework (19.0.0) to develop various interface for users.

6.1. Definition of Performance Metrics for 3PL Selection

To quantitatively evaluate the effectiveness of the proposed blockchain-enabled FAHP platform in selecting appropriate third-party logistics (3PL) providers, standard classification performance metrics—accuracy, precision, recall, and F1-score—are adopted. Although commonly used in classification problems, these metrics are well suited to the 3PL selection context, where the platform produces a discrete decision for each vaccine logistics order.

For each logistics order, the platform recommends one 3PL provider from the available candidate pool. A correct selection is defined as the platform selecting the same 3PL provider as the expert-validated or historically optimal provider, determined based on ground truth industrial records and post-delivery performance validation. Conversely, an incorrect selection occurs when the recommended provider differs from the validated optimal choice. Based on this definition, the following outcomes are identified:

- True Positive (*TP*): The platform correctly selects the optimal 3PL provider.
- False Positive (*FP*): The platform selects a 3PL provider that is not the optimal choice.
- False Negative (*FN*): The platform fails to select the optimal 3PL provider.
- True Negative (*TN*): A non-optimal 3PL provider is correctly not selected.

Using these definitions, the evaluation metrics are computed as follows:

$$\text{Accuracy} = \frac{TP + TN}{TP + TN + FP + FN}$$

Accuracy reflects the overall proportion of correct 3PL selection decisions made by the platform.

$$\text{Precision} = \frac{TP}{TP + FP}$$

Precision measures the reliability of the platform's recommended 3PL providers, indicating how often a selected provider is truly optimal.

$$\text{Recall} = \frac{TP}{TP + FN}$$

Recall evaluates the platform's ability to successfully identify optimal 3PL providers across all logistics orders.

$$\text{F1-score} = \frac{2 \times \text{Precision} \times \text{Recall}}{\text{Precision} + \text{Recall}}$$

The F1-score provides a balanced measure of selection performance by jointly considering precision and recall. This metric is particularly important in vaccine logistics, where failing to select a high-performing 3PL (false negative) may lead to cold chain violations or delivery delays, while selecting an inappropriate provider (false positive) may compromise safety and compliance.

6.2. Case Study

Based on the data provided by our collaborator (1 year data) we designed a real-world simulation scenario where pharmaceutical company A and pharmaceutical company C participated in government-led vaccine procurement in Jiangsu and Guangdong provinces, respectively. The logistics evaluation process was conducted via the platform, ensuring transparent selection based on temperature control capability (S_1), on-time delivery rate (S_2), packaging integrity (S_3), and service attitude (S_4). In order to understand the case study, we provided detailed and example-based explanations as follows:

- Vaccine A ordered by Medical Institution K in Jiangsu Province, scheduled for December 30 at 11:00 AM, with 3 m^2 of required tray space and a 2–8 °C temperature control requirement.
- Vaccine C ordered for 29 December at 10:00 AM in Guangdong Province, with the same 3 m^2 tray space and 2–8 °C temperature control requirement.

The evaluation process used OIDK and OIDJ for digital record verification and considered government regulations that Class II vaccines must be transported directly from pharmaceutical companies to medical institutions without third-party intermediaries. Table 7 shows available 3PL providers (D, E, F, G) in the platform. They submitted their logistics availability to the platform. The smart contract filtered 3PL based on initial feasibility criteria before applying FAHP for final selection.

Table 7. Vaccine order and its information.

Information	Vaccine A	Vaccine C
Start	Chaoyang District, Beijing City	Xinxiang City, Henan Province
End	No. 305, Middle mountain Eastern Road, Xuanwu District, Nanjing City, Jiangsu Province	No. 55, Waihuanxi Road, Panyu District, Guangzhou City, Guangdong Province
Delivery time	30 December, 11 am	29 December, 10 am
Free tray space	3 m^2	3 m^2
Temperature range	2–8 °C	2–8 °C

At the same time, as shown in Table 7, vaccine cold chain logistics companies D, E, F and G have different vaccine cold chain logistics plans, and four companies have different degrees of idle logistics vehicle space. From the perspective of logistics companies, logistics companies are willing to receive as many orders as possible based on the completion of existing orders, so as to improve their own logistics revenue. From the perspective of PMs, they are willing to spend less money to transport vaccines to their destinations safely. Therefore, both PMs and 3PL hope to meet their own needs with the help of the proposed platform. The 3PL uploads the order information as shown in Table 8 to the system, and PMs A and C submit their own vaccine logistics needs as shown in Table 8 to the platform.

Table 8. Indicators of transportation capacity of 3PL.

Information	Company D	Company E	Company F	Company G
Start	Haidian District, Beijing City	Fangshan District, Beijing City	Zhengzhou City, Henan Province	Luohe City, Henan Province
End	No. 155, Hanzhong Road, Qinhuai District, Nanjing City, Jiangsu Province	No. 19, Zhongshanbei Road, Quanshan District, Xuzhou City, Jiangsu Province	No. 1698, Guangzhoudadao-nan Road, Haizhu District, Guangzhou City, Guangdong Province	No. 53, Jidajingle Road, Zhuhai District, Guangzhou City, Guangdong Province
Delivery time	30 December, 15 pm	30 December, 16 pm	29 December, 16 pm	29 December, 15 pm
Free tray space	5 m^2	4 m^2	6 m^2	3 m^2
Temperature range	3–6°C	2–7°C	3–5°C	2–5°C

6.3. Step-by-Step Process of FAHP Engine in the Platform

According to the preliminary selection criteria of logistics in Section 4.2.1, logistics companies D and E are the alternative logistics of pharmaceutical company A; logistics companies F and G are the alternative logistics of pharmaceutical company C.

At the second step, Matrix L_A for PM-A is generated based on the four indexes explained previously then transformed into positive and negative matrix.

$$L_A = \begin{pmatrix} 1 & \frac{1}{5} & 1 & \frac{1}{5} \\ 3 & 1 & 5 & \frac{1}{5} \\ 1 & \frac{1}{5} & 1 & \frac{1}{5} \\ 7 & 5 & 7 & 1 \end{pmatrix} \tag{8}$$

The FAHP engine obtained the maximum eigenvalue of matrix, then the T.L.Saaty consistency index is used to test the consistency of the positive reciprocal matrixaty CI_A. According to Saaty's random consistency index, the RI_A is generated. As it checks the consistency ratio, and if the calculation result is less than 0.1, it also shows that indicators provided by PMs are effective; otherwise, it needs to provide a new value to satisfy this condition. In the final step, the normalized eigenvector (weight vector) is obtained and multiplied by the historical 3PL evaluation information; therefore, transportation capability scores for each PM are calculated and the results compared together; then, the platform suggests the best result to the medical institution.

$$\lambda_A = 4.1578 \tag{9}$$

$$CI_A = (\lambda_A - n)/(n-1) = 0.0526 \tag{10}$$

$$RI_A = 0.90 \tag{11}$$

$$CR_A = CI_A/RI_A = 0.0526/0.9 = 0.0584 < 0.1 \tag{12}$$

$$W_A = \begin{pmatrix} 0.0728 & 0.2144 & 0.0659 & 0.6469 \end{pmatrix} \tag{13}$$

The historical logistics evaluation information of the logistics

$$S_D = \begin{pmatrix} 90 & 95 & 85 & 90 \end{pmatrix}^T \tag{14}$$

$$S_E = \begin{pmatrix} 95 & 85 & 90 & 85 \end{pmatrix}^T \tag{15}$$

$$SS_D = W_A * S_D = \begin{pmatrix} 0.0728 & 0.2144 & 0.0659 & 0.6469 \end{pmatrix} * \begin{pmatrix} 90 & 95 & 85 & 90 \end{pmatrix}^T = 90.74 \quad (16)$$

$$SS_E = W_A * S_E = \begin{pmatrix} 0.0728 & 0.2144 & 0.0659 & 0.6469 \end{pmatrix} * \begin{pmatrix} 95 & 85 & 90 & 85 \end{pmatrix}^T = 86.06 \quad (17)$$

Because of 86.06 < 90.74, pharmaceutical company A chooses logistics company D as its transportation vaccine.

The simulation platform run based on the one-year data sets which are provided by our collaborate and Table 9 show the accuracy evaluation of platform base accuracy of selection (AoS), precision (p), recall (R), and F1-score.

Table 9. Accuracy evaluation of platform for whole year.

Month	Total Orders	Correct Selections	Incorrect Selections	Accuracy (%)	Precision (%)	Recalling (%)	F1-Score (%)
January	80	74	6	92.50%	90.2%	94.8%	92.4%
February	75	70	5	93.33%	89.7%	95.9%	92.7%
March	90	84	6	93.33%	90.5%	94.4%	92.4%
April	85	79	6	92.94%	89.4%	94.0%	91.7%
May	82	76	6	92.68%	89.1%	93.8%	91.4%
June	88	82	6	93.18%	89.7%	94.3%	92.0%
July	93	87	6	93.55%	91.2%	94.6%	92.9%
August	89	83	6	93.26%	90.5%	94.3%	92.4%
September	92	86	6	93.48%	90.7%	94.6%	92.6%
October	87	81	6	93.10%	89.6%	94.2%	91.9%
November	91	85	6	93.41%	90.8%	94.4%	92.6%
December	94	88	6	93.62%	91.4%	94.8%	93.1%
Overall	1046	975	71	93.21%	90.23%	94.50%	92.32%

The proposed platform has demonstrated a high level of accuracy and effectiveness in selecting optimal 3PL for vaccine logistics operations over a one-year period. The average accuracy of selection was 93.21%, demonstrating robust decision-making capabilities. The platform also showcased strong precision (90.23%) and recall (94.50%), reflecting its ability to consistently select top-performing 3PL and efficiently minimize incorrect selections. The overall F1-score of 92.32% confirms the balanced accuracy and reliability of the system. These outcomes validate the practical applicability and effectiveness of the proposed blockchain-enabled FAHP engine, providing significant benefits to vaccine supply chain stakeholders.

6.4. Smart Contract Cost and Time Consumption

We calculate the gas consumption and execution time of proposed platform in order to evaluate the operation cost. Gas represents the essential computational units consumed whenever smart contracts are executed [50]. As expected, operational complexity directly correlates with increased gas usage. Furthermore, gas functions as a token exchangeable on the Ethereum (ETH) network at a specific ratio. For this evaluation, the gas price is established at a fixed rate of 2×10^{10} wei per unit of gas, where wei represents the base denomination of ETH.

Table 10 provides the major operations in the platform, and their amount of gas consumption. Eight main operations consider in this step which is follows the vaccine operation through the network.

Table 10. Gas consumption of operations in smart contract.

Operation	Gas	Description
insert_new_vac	166,010	Upload the vaccine certificate information to the contract
draw_vac	31,104	Take the certain quantity of vaccine from the stock and modify the batch information
create_order	260,252	Create a new vaccine shipment order and upload it to the contract
create_transfer_order	184,081	Create a new capacity order and upload it to the contract
check_avaliable_transfer_order	68,441	According to the information of the vaccine to be shipped order and the transportation capacity order, the transportation capacity order that meets the requirements is selected
match_orders	102,271	Add the vaccine to be shipped order to the shipment capacity order, which means that the shipment order is carried by the enterprise that issues the shipment capacity order
set_order_status	42,799	After the medical institution's warehousing inspection, change the order status to indicate that it has passed the inspection
evaluate	110,853	Medical institutions evaluate the logistics companies according to the four indicators proposed, and upload the scores to the contract for storage

We compared the gas consumption of proposed platform with Cryptokitties [50] and LucidSight-MLB-NFT [50], so our proposed platform has the same level of gas consumption. This indicates that the complexity of the proposed platform is almost same as the existing one.

We built two network environments for the evaluation of time consumption. A single LAN, and two separate LANs. In order to compare the results with each other, a consortium chain with two nodes for each network is developed, by considering that one of the nodes is used for mining process in the network. We applied ten transactions with an immovable amount of gas consumption for both networks. To achieve this, we used *estimatedGas* method, which is provided in the Web3 toolkit, and we measured the execution time of the smart contract by *sendTransaction* method. It is clear that two separate LAN networks have better performance compared to a single LAN network. Therefore, the execution time of the transaction is significantly affected by the network environment. In this respect, the execution time within the single node can almost be neglected. The high-level initialization configuration for this setup is detailed in Figure 6. For our experimental environment, we configured two mining threads, initialized the test chain, and executed the mining operations. By analyzing the block timestamps, we accurately measured the time differentials. The results demonstrate that, assuming constant computational power, time consumption scales linearly with an increase in the difficulty parameter, whereas the

nonce value exhibits an exponential decrease. Figure 7 illustrates the relationship between mining difficulty and execution time within the proposed framework. As previously noted, the platform operates on the Go Ethereum client, utilizing a dedicated network node to handle the mining process.

```
{
  "config": {
        "chainId": 10,
        "homesteadBlock": 0,
        "eip155Block": 0,
        "eip158Block": 0
    },
  "alloc"      : {},
  "coinbase"   : "0x0000000000000000000000000000000000000000",
  "difficulty" : "0x02000000",
  "extraData"  : "",
  "gasLimit"   : "0x2fefd8",
  "nonce"      : "0x0000000000000042",
  "mixhash"    : "0x0000000000000000000000000000000000000000000000000000000000000000",
  "parentHash" : "0x0000000000000000000000000000000000000000000000000000000000000000",
  "timestamp"  : "0x00"
}
```

Figure 6. Initialization configuration of test chain.

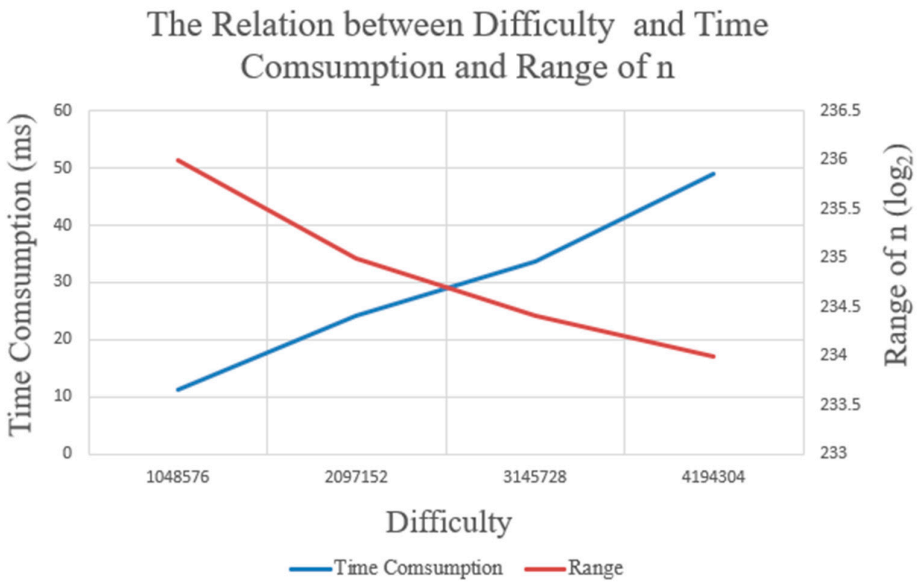


Figure 7. Relation between difficulty and time consumption and range of n.

7. Discussion

The integration of the Fuzzy Analytic Hierarchy Process (FAHP) into a consortium blockchain architecture provides a more robust decision-making framework than traditional centralized logistics management systems. Centralized tracking platforms often suffer from limited transparency, fragmented data ownership, and manual intervention, which can undermine trust and consistency in logistics provider evaluation. In contrast, the proposed platform demonstrated an overall selection accuracy of 93.21%, precision of 90.23%, and an F1-score of 92.32% over a one-year evaluation period, indicating that the system consistently identifies high-performing 3PL providers while minimizing the risk of selecting mismatched logistics partners. Unlike the two-stage model [48], which primarily focuses on horizontal logistics coordination outcomes such as increased delivery

frequency and network coverage, the proposed methodology emphasizes vertical integration across the vaccine supply chain. In particular, regulatory oversight by the FDA is embedded directly into the blockchain network, enabling real-time supervision of vaccine transportation through IoT-enabled temperature and location data. This vertical coordination enhances robustness by ensuring that logistics decisions are continuously aligned with safety, compliance, and regulatory requirements a critical consideration in cold vaccine distribution.

Classical AHP [47–49] has been widely applied in logistics provider selection due to its intuitive hierarchical structure and computational simplicity. However, AHP assumes that decision-makers can provide precise numerical judgments, an assumption that is often unrealistic in vaccine logistics environments. Key evaluation criteria such as service attitude, packaging integrity, and delivery reliability are inherently subjective and affected by uncertainty. These limitations reduce the robustness of classical AHP when applied to complex, real-world cold chain operations. The FAHP method adopted in this study addresses these limitations by incorporating fuzzy logic into pairwise comparisons, allowing decision-makers to express preferences using linguistic variables rather than fixed crisp values. This capability is particularly important in cold vaccine logistics, where performance indicators are influenced by stochastic factors such as traffic variability, temperature fluctuations, and human operational behavior. By explicitly modeling uncertainty, FAHP reduces sensitivity to subjective bias and improves the stability and consistency of decision outcomes under changing operational conditions. Overall, the proposed FAHP–blockchain framework achieves enhanced robustness by combining uncertainty-aware multi-criteria evaluation with immutable data recording, automated execution via smart contracts, and regulator-visible decision processes.

8. Managerial Implications and Practical Insights

The proposed blockchain-enabled FAHP platform provides several actionable managerial implications for key stakeholders in cold vaccine supply chains, including pharmaceutical manufacturers, third-party logistics providers (3PL), medical institutions, and regulatory authorities. For pharmaceutical enterprises, particularly SMEs, logistics outsourcing is often a necessity rather than a choice. However, selecting reliable 3PL providers under regulatory pressure and cold chain constraints remains complex and resource intensive. The proposed platform offers the following managerial benefits:

- Structured and objective 3PL selection: The FAHP-based evaluation framework transforms subjective logistics assessments into a quantifiable and transparent decision process.
- Reduced selection risk: Historical performance scores recorded on-chain minimize the likelihood of choosing underperforming logistics providers.
- Cost optimization: Preliminary smart contract screening eliminates infeasible providers before detailed evaluation, reducing negotiation and evaluation overhead.
- Performance-based contracting: Immutable on-chain performance records enable long-term performance benchmarking and incentive-based contracts.

By integrating uncertainty-aware multi-criteria decision-making with blockchain traceability, pharmaceutical companies can transition from experience-based provider selection to data-driven strategic logistics management.

9. Conclusions and Future Work

This paper presents a blockchain-enabled platform for the evaluation and selection of third-party logistics (3PL) providers in cold vaccine supply chains. By integrating blockchain technology with the Fuzzy Analytic Hierarchy Process (FAHP), the platform

enables transparent, secure, and data-driven decision-making, ensuring the integrity and efficiency of vaccine logistics operations. Smart contracts automate core processes such as 3PL evaluation, vaccine order execution, and real-time monitoring, while IoT integration facilitates continuous tracking of temperature and transport conditions.

The developed platform was validated through a one-year simulation using real-world data provided by collaborators, validating high operational accuracy (93.21%), precision (90.23%), recall (94.50%), and an F1-score of 92.32%. These results confirm the platform's robustness in consistently selecting top-performing 3PL and minimizing errors in provider assessment. Furthermore, performance metrics of smart contract gas consumption and execution time were within acceptable industry standards for case study, supporting the system's feasibility for deployment in practical settings.

Beyond technical performance, the proposed platform addresses pressing challenges in the vaccine supply chain, such as traceability gaps, regulatory compliance, and decision bottlenecks in logistics provider selection. By positioning regulatory bodies like the FDA as supervisory nodes within a consortium blockchain, the system promotes decentralized governance and enforces compliance without compromising data integrity or privacy.

To further advance this research, future work will focus on the following areas: Machine learning integration, in this respect we will explore the integration of machine learning algorithms to enhance the predictive capabilities of the FAHP engine. This will allow for adaptive weight adjustments based on seasonal shifts or changing logistics priorities. Multi objective decision-making, we will consider additional factors, such as carbon emissions, sustainability metrics, and broader cost optimization, will be incorporated into the selection criteria. Finally, through interoperability and scaling, we aim to expand the platform's interoperability with national immunization systems and extend its application to other pharmaceutical logistics domains to facilitate broader global impact.

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Appendix A. Vaccine Order Management Smart Contract

```
pragma Solidity >= 0.5.12 < 0.6.0;
contract enterprise_inventory {
struct vaccine {
string _name;
string _inspection_num;
string _lot_num;
string _type;
string _size;
uint _Expiration_ts;
uint _batch;
}
address _owner;
string _enterprise_name;
mapping(string => vaccine) _vaccine_info;
event Insert_new_vaccine(address sender, string enterprise_name, string name, uint batch);
event Draw_vaccine(string name, uint draw_num, uint rest_num);
constructor(string memory enterprise_name, address owner) public {
_enterprise_name = enterprise_name;
_owner = owner;
}
modifier check_sender() {
require(msg.sender == _owner, “Only the enterprise can modify the info”);
}
function insert_new_vaccine(
string memory name,
string memory inspection_num,
string memory lot_num,
string memory Type,
string memory size,
uint Expiration_ts,
uint batch
) public check_sender {
_vaccine_info [name] = vaccine(name, inspection_num, lot_num, Type, size, Expiration_ts, batch);
emit Insert_new_vaccine(msg.sender, _enterprise_name, name, batch);
}
function get_vaccine_info(string memory name)
public view
returns (string memory lot_num, string memory Type, string memory size, uint Expiration_ts)
{
lot_num = _vaccine_info [name]._lot_num;
Type = _vaccine_info [name]._type;
size = _vaccine_info [name]._size;
Expiration_ts = _vaccine_info [name]._Expiration_ts;
}
function get_rest_batch(string memory name) public view returns (uint batch) {
batch = _vaccine_info [name]._batch;
}
function draw_vaccine(string memory name, uint draw_num) public check_sender returns (uint
rest_num) {
require(draw_num <= _vaccine_info [name]._batch, “There is not enough vaccine for drawing”);
rest_num = _vaccine_info [name]._batch-draw_num;
_vaccine_info [name]._batch = rest_num;
emit Draw_vaccine(name, draw_num, rest_num);
}
}
```

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