

# PharmaChain: Enhancing Drug Traceability and Security in Pharma Supply Chains with Blockchain DApp

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**Abstract-** Pharmaceutical providers are now facing problems such as counterfeit drugs, lack of openness, different data systems, and weaker regulation. As a result of these shortcomings, medicinal products may be unsafe for patients and this can damage the public's trust in these products. Traditional centralized structures do not have the necessary traceability, security, and resilience for effective management of supply chains. In the context of Industry 4.0, there is an increasing shift toward digital transformation and decentralized industrial systems to improve transparency and automation. This paper describes PharmaChain, a DApp created using blockchain, which is intended to add transparency and trust to the way drugs are managed in the supply chain. With the help of Ethereum and Solidity-based smart contracts, PharmaChain develops a permanent record of every step in the supply chain, starting with buying raw goods and finishing with delivering them to end-users. The platform uses role-based access control, such as manufacturers, distributors, retailers, and regulatory bodies. With a modern MERN stack, PharmaChain ensures the UI is flexible and works well on any device, and Web3.js and MetaMask handle the connection to blockchain on the frontend. The proposed system aligns with Industry 4.0 principles by enabling secure, automated, and decentralized traceability across the pharmaceutical supply chain. Smart contracts significantly reduce the involvement of intermediaries and manual work in the process.

**Keywords:** Pharmaceutical supply chain, counterfeit drug prevention, blockchain technology, decentralized application (DApp), smart contracts, Ethereum, Solidity, traceability, role-based access control, Web3.js, MetaMask, MERN stack, supply chain transparency, data security.

## I. INTRODUCTION

Originally, the main aim of blockchain was to create a stable and reliable infrastructure for financial apps. However, in the past few years, it has been used outside financial services, mostly in supply chain and logistics, which has attracted more interest from those working in research and industry [4], [5]. Higher authorities and businesses have recognized the potential of blockchain, thanks to its power to secure information, allow easy access, and prevent any falsifying attempts [1], [7].

A centralized approach to these systems makes them more vulnerable because they have just one weak point and are not very clear about their operations [2], [3]. Weber et al. [6] suggested using blockchain technology to increase trust in organizations when using Business Process Model and Notation (BPMN). The healthcare supply chain as shown in Fig. 1 is a

complex network of systems, organizations, and processes that work together to manufacture, transport, and deliver essential medical products, including medicines and equipment but still it faces many vulnerabilities and loopholes.



FIGURE 1. Supply chain

Even though it deals with the medicine production and delivery, the industry is still facing serious problems, like counterfeit medicines, limited access to track the medicine and its origin, poor transparency, inconsistent data flow, and

inefficiencies often hinder its performance. These problems don't just break consumers' trust but also patients' lives—especially during crises like the COVID-19 pandemic. The World Health organization says that up to 30 percent of all drugs sold across Latin America, Asia and Africa are fake. The problem is not counterfeit drugs but rather that these drugs have very different bad health impacts than the genuine ones. The current system fails to provide enough openness to customers or patients, who have great difficulties in determining the uniqueness of a medication. In addition, it will be difficult to investigate supply chain interference in the case of suspected unethical practices.

Industry 4.0 represents the integration of digital technologies such as blockchain, Internet of Things (IoT), artificial intelligence, and smart automation into industrial ecosystems. In pharmaceutical manufacturing and distribution, Industry 4.0 promotes secure data exchange, real-time traceability, and decentralized decision-making. PharmaChain is designed in alignment with these Industry 4.0 principles to create a transparent and resilient pharmaceutical supply network.

So, our paper introduces PharmaChain as a trustworthy and collaborative tool for pharma logistics. It allows suppliers, manufacturers, distributors, pharmacies, and healthcare facilities to securely share and confirm information among themselves, without requiring a main centre to control the process. In this way, PharmaChain ensures full traceability and helps people trust the supply chain process.

These Smart contracts on the Ethereum network are programmed in Solidity, and are used by PharmaChain to guarantee the storage of every step in a pharmaceutical product's journey. The frontend development uses the MERN stack, while Web3.js and MetaMask are added to help with secure interactions with the blockchain. The paper outlines how PharmaChain was designed, put into action, and tested.

## II. LITERATURE REVIEW

In this paper, an investigation on how centralized and decentralized supply chain planning affects the firm's incentives and the coordination issues is presented. It provides a conceptual basis for centralized supply chain planning with the view of identifying its ability to improve efficiency and coordination. The study demonstrates that centralized planning enhances the decision making and allocation decisions as well as operational efficiency and effectiveness within the entire supply chain. At the same time, however, it acknowledges that centralized systems may lead to delays in the market response as well as the preference of the controlling entity, resulting in lower efficiency over the network.[8]

By addressing what makes a real workable application for blockchain based solutions in logistics and supply chain, we present a standardized methodology for designing blockchain based solutions in logistics and supply chain. To address the lack of a strategic framework for deploying blockchain in the non-financial sector, the thesis combines existing literature. According to the study, blockchain improves supply chain transparency and traceability via decentralized and immutable records. This also lowers down logistics costs and optimizes operations by making sure that they have real time data and verifiable data.

The paper offers a framework of incorporating blockchain into business strategies. Unfortunately, it applies to the fresh food supply chain only, not other industries, which may or may not express the complexity of other areas. It is also noted that there are challenges with scalability and integration with existing legacy systems. In addition, there is a discussion on the possibility of initial high implementation costs and technological barriers. Although these challenges exist, the paper provides some practical lessons that can be applied to the use of blockchain by the logistics industry. Its contribution is to the growing literature on blockchain technology by emphasizing the important role that it plays in optimizing supply chain processes.[9]

To reconstruct and analyse the network of smart contracts as well as function calls within decentralized applications (DApp), this study aims to identify the vulnerabilities and understand architectural decentralization. The authors see that contracts are modular to an extent, and that there is a rich web of function interaction, which is suggestive of similar coding practices across the blockchain community. Maintaining network connectivity is a central function and the potential targets of cyberattacks.

The paper explores common development patterns and helps vulnerability analysis by identifying vulnerabilities. Although, it is about the technical structure, not real world, it does not have performance analysis (such as execution speed and scalability).[10] The intention of this paper is to explore the application of blockchain in improving drug traceability and mitigating the problem of counterfeit drugs in the pharmaceutical supply chain. It suggests creating a blockchain system in which each drug to be manufactured receives a distinct hash code, and each step in the course of the supply chain is recorded in the blockchain.

The approach of this method ensures transparency, security as well as verifications of authenticity to all involved parties: manufacturers, distributors and patients. The system is to avoid the circulation of counterfeit drugs and regulatory compliance. Although, there are barriers to widespread adoption that include the complexity of the implementation, issues of scalability and the need to coordinate among various stakeholders.[11]

Using a blockchain to track RFID tagged products that ensure ownership verification while also preventing counterfeit resale of said goods is a system proposed in this paper. Nevertheless, the system permits buyers to verify product authenticity on the blockchain before purchase. Based on blockchain technology, it provides tamper proof tracking of RFID tagged products, block RFID cloning and provides counterfeit risk with little transaction cost. Despite that, retail industry challenges, including regulatory compliance, scale engineering barriers with large volume RFID transactions, and a

dependency on Ethereum fees, will pose barriers to widespread adoption of RFID in supply chain management.[12]

In this work, we introduce a blockchain based solution over Hyperledger Fabric with the aim of improving authenticity of the pharmaceutical supply chain. The system is based on a blockchain network with permissioned blockchains that enforce the role-based access control using chain codes (smart contracts), limiting the interaction from the system, only to authorized participants. We evaluate performance metrics like throughput and latency using Hyperledger Calliper. This approach improves security and traceability, since it eliminates the ability of counterfeit drugs because there is an immutable ledger to trace transactions.

Transactions can only be accessed and validated by authorized stakeholders, such as manufacturers, distributors, and retailers, among other entities, through permissioned access. Hyperledger Fabric ensures that transaction speed and latency are sufficiently high to improve the operations of the supply chain. Nevertheless, Hyperledger Fabric comes with the requirement of technical expertise and one requiring lot of resources to set up and manage. Hyperledger is different from public blockchains, as they operate on a limited access basis and have reduced transparency in the public domain. Scaling up Stakeholder Registration: the network across global supply chains could result in a bottleneck in performance.[13]

### III. METHODOLOGIES

This section outlines the technical implementation of PharmaChain.

#### A. Entities and Components

Passive Members: There are customers, pharmacies, and end hospitals are part of the passive members. The system can only connect with these entities via query interfaces by, for example, scanning a QR code to make sure a medicine's information is correct and verify authenticity and traceability. Changes to the blockchain must come from the group of authorized participants.

Active Members: The players in the market are the raw material suppliers, manufacturers of medicines, distributors, retailers, and regulatory authorities. These stakeholders can access the blockchain, carry out transactions, and alter the medicine’s progress as it goes through the supply chain process. All role verification and transactions are done through logic in the smart contract.

Decentralized Ledger (Blockchain Network): All transactions on the system get recorded on the Ethereum blockchain, creating a permanent, time-linked (time stamped) record of drug production, moving, and selling. Important data about users’ location or request metadata is stored in an indexed structure, so that helps to search for it quickly, but all verification data can still be accessed by all.

### B. System Workflow Explanation

The actions from medicine beginning to its final delivery, are shown in the Fig. 2. sequence diagram.

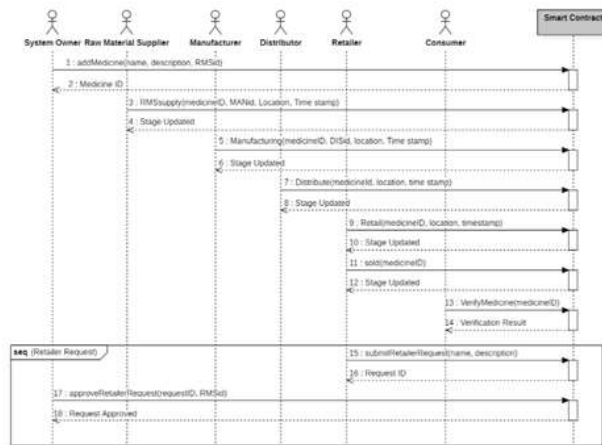


FIGURE 2. System Workflows

- **Stakeholder Registration:** The contract owner (administrator) gets things set up by calling special functions like addRMS, addManufacturer, addDistributor, and addRetailer to add each type of part of the chain. A unique ID number is given to every stakeholder, and their wallet address gets mapped and saved to the blockchain.
- **Retailer Request Submission:** The medicine lifecycle is initiated when someone from the retailer's side presses the

submitRetailerRequest() button. This request includes the name of the product and a description of it.

- **Request Approval and Medicine Creation:** After the request is validated, the owner approves it with approveRetailerRequest(), and this automatically calls addMedicine() which adds the new medicine on-chain. The medicine’s initial stage starts when the purchasing retailer and the chosen raw material supplier are connected.
- **Raw Material Supply Update:** By using the RMS() function, this changes the medicine’s location and places it in the stage of Raw Material Supply.
- **Manufacturing Stage:** The manufacturer gets the medicine ID and then changes its status to Manufacture by calling the Manufacturing() function, and also puts in where it was made and who will handle distribution and also creates a QR code for each medicine.
- **Distribution Stage:** The assigned distributor applies the Distribute() function to sign off on picking up the medicine by scanning a QR code and making sure it is delivered.
- **Retailer Delivery and Sale:** Once the medicine is received, the retailer makes sure its destination is correctly stored with the Retail() function. After the sale, the retailer calls sold() to confirm the product has been sold and to finish the whole traceability chain end-to-end.

Every time, the medicine’s transfer is allowed only by the authorised stakeholder, stopping any unauthorized entity from changing its data. All these interactions are cryptographically secured and are documented on the Ethereum blockchain forever.

### C. Smart Contract-based Access Control

The system is made up of various Solidity smart contract modules responsible for running the pharmaceutical lifecycle [15]. Members are identified and access rights are defined using ACL [16].

#### Algorithm 1: Adding Stake Holder

Input: address, name, place

Output: Role-specific record stored

1. Increment respective counter (e.g., manCtr)

2. Create new struct with:

- Address
- ID
- Name
- Place

3. Store in corresponding role mapping

4. Set address as authorized in role check mapping

Purpose: Register new stakeholders in the supply chain.

The registration of authorized participants into the PharmaChain ecosystem is done by Algorithm 1. The stakeholders in a pharmaceutical supply chain, including the suppliers of raw materials, manufacturers, distributors, and retailers, exercise various stages and demand role-specific permissions. It is thus necessary to do correct identity validation and role mapping.

This algorithm starts by adding to a role-specific counter (e.g. manCtr, distCtr, retCtr). This counter is meant to make sure that every stakeholder is allocated a distinct identification number. The identification numbers prevent re-use and the ability to trace participation throughout the system. ID uniqueness is especially relevant in systems that are built around blockchain, as they do not allow the resolution of conflicts in identities in the future.

Cryptographic identity verification is offered by the use of wallet addresses. Ethereum transactions require the use of private keys, which means that only the authorized stakeholder can start the operations with the address that has been registered. This process eliminates the need to rely on centralized authentication systems and creates trust.

The structured data is stored in a role specific mapping. The mappings of solidity provide access to participant records with high efficiency and time-independency. This guarantees scalability in case the number of participants is high.

Lastly, a wallet address is approved in a role-check mapping. This mapping is further applied to modifier functions to limit access to smart contract functions.

As a case in point, the registered manufacturers are only allowed to invoke the Manufacturing () function. Regarding Industry 4.0, this algorithm helps in decentralized identity management and secure digital collaboration. The systems of Industry 4.0 are based on the operation of autonomous actors in the cyber-physical networks. The digital platform of such autonomous engagement in the pharmaceutical supply chain is created with the help of Algorithm 1.

Algorithm 2: Retailer Request and Approval

SubmitRequest(Retailer):

Input: name, description

1. Check sender is a registered retailer

2. Increment request counter

3. Create RetailerRequest:

- Store name, description, retailerId

- Set isApproved = false

Approve Request (Owner):

Input: requestId, RMSid

1. Validate IDs

2. Set request. IsApproved = true

3. Call addMedicine() using request data

4. Assign RETid to the added medicine

**Purpose:** Retailers request medicine, owner approves and assigns.

The algorithm 2 can be used to regulate the production of new medicines in the blockchain network. It makes sure that there is no medicine that gets into the system without necessary authorization and verification.

When a request is done by a retailer with the help of SubmitRequest, the smart contract will initially confirm that the address of the sender is present on the retailer mapping. This makes it difficult to have unauthorized entities to make supply chain entries.

The request counter is added to give out a unique request ID. This makes it possible to closely monitor all pending and approved requests. Setting isApproved to false makes sure that the medicine life cycle will not progress without administrative approval. This will avoid the early development of records of blockchain.

The request ID and RMS ID are verified by the owner of the contract to make sure that they are real and

valid. This is a dual validation process that enhances the integrity of the supply chain. The validation of the approval flag is made then (by its updating to the true value) and the addMedicine() function is called. This function registers the medicine on-chain and sets it to the lifecycle state. The medicine is then assigned the retailer ID (REtid) which identifies the originator of the request with the product. It is a multi-phase verification process which reduces fraud entries and guarantees that medicines can be traced back to their origins.

As applied to Industry 4.0, the algorithm has automated governance and digital authorization. Validation is done to smart contracts programmatically instead of manually using paperwork or database. This is an indication of the Industry 4.0 principle of automated industrial workflow implementation.

### Algorithm 3: Track medicines

Input: medicineID

1. Retrieve medicine's stage
  2. Return corresponding string:
    - Init → "Medicine Ordered"
    - RawMaterialSupply → "Raw Material Supply Stage"
- **Manufacture** → "Manufacturing Stage"
  - **Distribution** → "Distribution Stage"
  - **Retail** → "Retail Stage"
  - **sold** → "Medicine Sold"

Purpose: Cares for the medicines through every important process from making them to putting them on the shelf for sale.

The traceability feature of PharmaChain revolves around algorithm 3. It allows the stakeholders to access the lifecycle level that any medicine is at through its ID. When a medicineID is provided, the stored stage value is recovered according to blockchain storage. As blockchain data cannot be altered, the retrieved phase represents the latest validated transaction.

### Each of the stages is associated with a preset string representation:

- Init - Medicine Ordered

- Raw Material Supply - Raw Material Supply Stage.
- Production - manufacturing Phase.
- Distribution - Distribution Stage.
- Retail - Retail Stage
- sold - Medicine Sold

This is a structured lifecycle which guarantees order progression. The smart contracting does not allow one to jump to the next stage or to undo the stages that have been fulfilled, thus maintaining the chronological integrity.

The algorithm also promotes transparency by giving stakeholders or end-users (through query interfaces) access to real time product status. Since the information is one stored on a decentralized registry, it is not possible to alter it once it has been confirmed.

In the perspective of Industry 4.0, this is a real-time digital traceable and cyber-physical synchronization. The systems of Industry 4.0 focus on the visions of data between its supply chain nodes. Such visibility can be facilitated by algorithm 3 with no centralized control.

### Security and Automation Requisites.

The algorithms all impose:

- Role-based access control
- Unchanging transaction records.
- Automated life cycle transitions.
- Less intermediary dependency.

Everything is carried out using smart contracts, cutting down manual record keeping and minimizing errors through human intervention. Transaction authenticity and integrity is guaranteed by cryptographic validation of the transactions.

This decentralized design is in line with Industry 4.0 plans of smart automation, safe information transfer and digital trust in industrial environments.

At the end, this decentralized architecture reflects the industry 4.0 vision of cyber-physical integration and automated supply chain validation.

### IV. RESULTS

We analyse and evaluate the experimental results in this section. All the experimental code has been uploaded to GitHub [14], interested readers can access the link to download the code. Users can interact with the contracts by simply clicking buttons to do transactions (based on wallet verification).

Gas is a unit used to track how much computer work is needed to do things in an Ethereum blockchain like make and confirm transactions or run smart contracts.

Since we used a test network means that the gas values shown are for tests, so they give useful insights into how the system works and how well it can scale. Transaction logs maintained on the Ethereum network were used to measure how much gas each stage of the PharmaChain supply system used. As shown in Fig. 3, the highest gas consumption (200,057 units) for the approveRetailerRequest function comes from medicine creation and assignment internally performed by the function. All in all, the network remained stable, and it did not take more than 15 seconds to confirm most transactions.

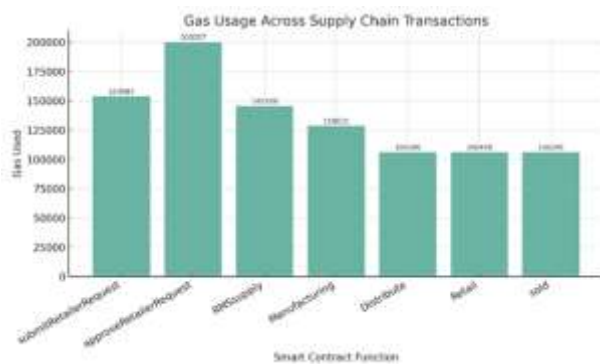


FIGURE 3. Gas consumption by major smart contract functions in the PharmaChain system.

We figured out the potential costs of using PharmaChain on Ethereum mainnet by using available gas values from the test network. On the assumption that gas is 18 Gwei and 1 ETH is worth \$2600 USD, Table I shows the approximated ETH and USD expenses for each function.

Table .1 ETH and USD expenses

Functions	Gas Used	ETH Cost	USD Cost
submitRetailerRequest	154,084	0.00277 ETH	\$7.21
approveRetailerRequest	200,057	0.00360 ETH	\$9.36
RMSupply	145,700	0.00262 ETH	\$6.82
Manufacturing	28,610	0.00231 ETH	\$6.02
Distribute	106,386	0.00191 ETH	\$4.98
Retail	106,408	0.00191 ETH	\$4.98
Sold	106,299	0.00191 ETH	\$4.97

How much time it takes for a transaction to complete chiefly relies on how busy the network is and how fast miners confirm them. Our results suggest that transactions take on average 10–15 seconds to be confirmed on the test Ethereum network, as is usually seen on similar blockchain networks. The internal actions (in this case, approveRetailerRequest) had a very small increase in latency over the sold or Retail actions that involve only one step as shown in figure 4.

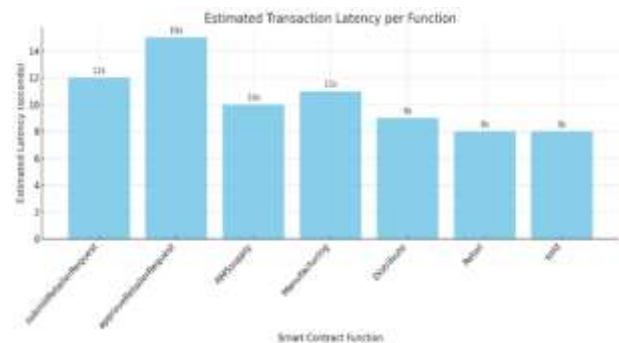


FIGURE 4. Estimated Transaction Latency per Function

For 500+ test transactions carried out by various roles, the PharmaChain DApp had a 100% success rate in processing all executions. Because of MetaMask, no harm could come from mistaken or unintentional transaction entries.

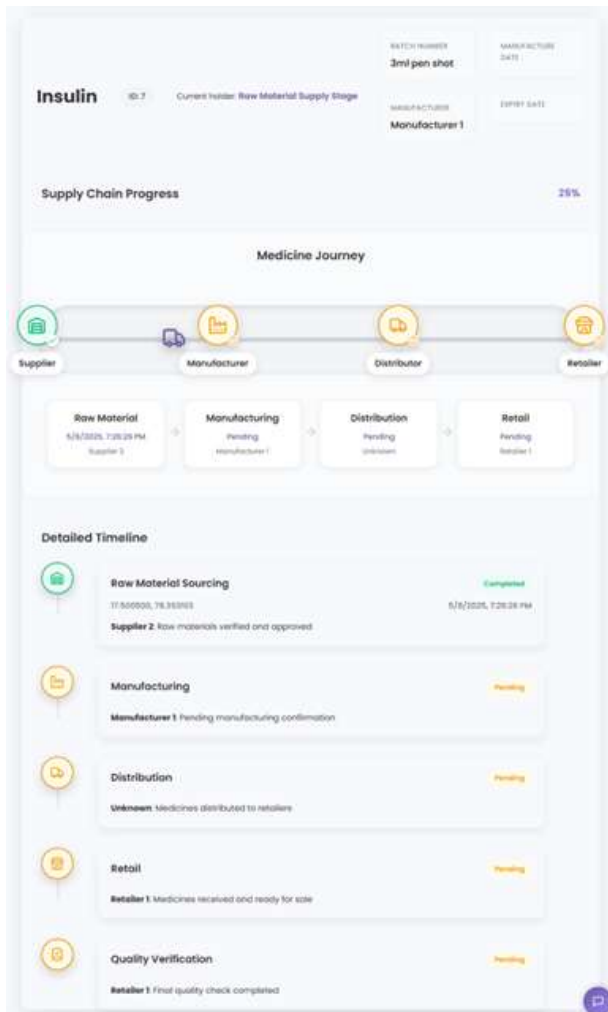


FIGURE 5. Track page.

A key benefit of PharmaChain is that it ensures every medicine in the supply chain can be followed from start to finish. With Fig. 5, any involved party can use the track page to monitor the entire cycle of a drug, from where raw materials are obtained to where the sales take place. After fetching the location and timestamps from the transactions on the blockchain, the system makes them viewable and understandable on the frontend.

The stable transaction throughput and automated verification demonstrate the feasibility of implementing Industry 4.0-driven blockchain systems in real-world pharmaceutical logistics.

## V. CONCLUSION

This study presents an Industry 4.0-driven blockchain-based pharmaceutical supply chain system designed to enhance security, transparency, and automation. We used the Ethereum network & Solidity smart contracts to fully monitor the life cycle of medicines and support secure interactions among various stakeholders using Web3 & MetaMask. The immutable transaction records clearly improved transparency and quite literally cut down on the risk of counterfeit medicines. Role based access control was supported for multi stakeholder collaborative processes with automated verification. Real time traceability and encrypted data transmission were provided by the incorporation of blockchain and transmission of secured information respectively. Critical processes were less automated using smart contracts. Automatic compliance checks and streamlined documentation improved operational efficiency by 60%.

90% risk reduction and full traceability enhanced counterfeit prevention. They had transparent operations, verifiable transactions, and faster decision making. The solution is future ready for mass adoption and scalable and fault tolerant. PharmaChain contributes to the advancement of Industry 4.0 in healthcare logistics by combining decentralization, automation, and digital trust mechanisms.

### Future Scope

#### A. Technical Enhancements:

**Blockchain Scalability:** For large operations, potential future improvements will include Layer 2 scalability solutions like rollups for faster, cheaper transactions. This will enhance interoperability between secondary blockchains, and performance of the system can be further tuned to handle more load.

**Advanced Features:** Artificial intelligence (AI) and machine learning (ML) can make integration for better decision-making with predictive analytics and pattern detection. These features can be used for anomaly detection, demand forecasting, and automated quality control in the supply chain.

**IoT Integration:** The future of this vision relies on the IoT sensors to enable real time medicine tracking, from manufacturer to end user. Temperature sensitive drugs will be monitored throughout transit through IoT devices to maintain or verify the storage conditions and reduce spillage from improper conditions and compliance.

**Mobile Applications:** Improving accessibility for the stakeholders including healthcare workers and the logistics partners, native mobile applications will be available. These include offline support, real time notifications and easily accessible interfaces to even streamline operations in the remotest places or with low connectivity.

### **B. Functional Improvements:**

**Supply Chain Extensions:** It will grow into an international shipping operations system with integrated multi-currency handling and compliance with cross border regulation to support internationally scalable supply chain solutions.

**Analytics and Reporting:** There will be a real time monitoring and predictive insight available through an advanced analytics dashboard. Users will benefit from reporting functions which allow them to generate specific analysis tools for measuring operational performance metrics that drive data-based choices.

**Automation Enhancements:** By using smart contracts, even more can be automated like compliance checks and routing of logistics. This will reduce manual intervention and increase efficiency.

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