Securing Medicine Supply Chains Through Blockchain Based Trustworthy Certification

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Abstract. The need to protect the integrity and authenticity of medicines is essential in this sector, namely for public health. There are many challenges in the traditional supply chains with counterfeit drugs, data manipulation and lack of transparency being a few. We propose a solution to achieve secure medicine supply chains through Trustworthy Certification using blockchain in this paper. This is done with the help of a permissioned blockchain network, where smart contracts are used to store product registration data, quality checks and results ensured at nodes, ownership transfer information as well as granting viewing permissions only for concrete groups. According to performance data on an eight-core CPU, work is distributed in a uniform manner and can be pushed onto the higher performing cores. High-memory commodity requirement in memory usage graphs, but blockchain manages it well. In addition to this, the system allows for extensive analysis and optimization given detailed supply chain datasets from product specifics, shipping detail down including supplier data. Initial results showed enhanced traceability, security and efficiency of the system opening a door for pharmaceutical supply chains to change from counterfeit-laced phony drug markets into systems that are capable of delivering genuine medication safely up to end consumers. The work that my supervisor and the future will be to integrate IoT devices for real-time monitoring and machine learning applications which can provide the same predictive analytics as in conventional methods.

Keywords: Pharmaceutical Industry , Blockchain, Trustworthy Certification, Medicine Supply Chains.

1 Introduction

The integrity and authenticity of medicines are critical to assuring quality for human health in the ever more complex world that is faced by latter day pharma. Medication supply chains are intricate webs of multiple parties such as manufacturers, distributors, pharmacies and regulators. There are multiple stages in this process that can be exploited by bad actors - from counterfeit drugs and data tampering, to inefficiencies which may compromise the quality and safety of pharmaceutical products. They are also centralized and depend on manual processes, which can lead to tampering, fraudulence via double counting or inflating bills of lading inclusive of many other types of problems. These gaps underscore the current demand for novel solutions that can deliver stronger security, visibility and accountability within supply chain operations.

Blockchain is a saga for solving these problems making it the transformational solution in each case. Through the use of blockchain, by using their core features decentralisation and immutability allows a trustless setup which enables end to end

management across pharmaceutical supply chains where all stakeholders can track exactly what is going on. All transactions and the movement of medicines can be recorded on a blockchain, meaning that once something is updated or submitted it cannot be changed giving us an immutable ledger. Where the source and quality of drugs play a direct role in patient wellness, this degree of security is even more vital - your patients may well have allergies or other contraindications against alternative sources!

Smart contracts add one more to the list of how blockchain technology can be leveraged in supply chain management. Instead they are self-executing contracts where the terms of the contract between buyer and seller are directly written into lines of code allowing for execution based on predefined conditions reducing reliance on intermediaries therefore cutting out risk from human error. Smart contracts can be used for a number of purposes within pharmaceutical supply chains including product registration, quality assurance checks through quality control and testing procedures to ensure the integrity of drug potency before it reaches patients; ownership transfers between manufacturers abroad and their home base companies domestically or directly with hospitals needing specific medications without third-party brokerage services managing logistics from foreign countries at more cost effective rates as well all while enabling real-time verification that only authorized customers will have access too. Not only do these automated processes increase efficiency, but they also mean that everyone from the leader of procurement to a young salesperson knows what can be interpreted as unambiguously true facts.

This paper proposes a complete system for trusted certification based on block chain to ensure the safety of medicine supply chains. The concept is to create a permissioned blockchain network on platforms like Hyperledger Fabric, which facilitates utilizing smart contracts and delivers high-level security. Each step in the supply chain is then tracked and verified, from manufacturing to quality checks and distribution until it finally reaches pharmacies before being dispensed.for the consumers The blockchain keeps an unalterable record of the transactions so that any fraud or forgery is made evident and nullified.

The initial testing made on the proposed system is very promising in terms of performance. For us, we see thatCPU usage graphs show CPU resource allocation - performance cores handling the heaviest tasks- while memory usage shows how well your system can cope with high demands. Furthermore, the data is very rich - including specific product types and prices, stock levels as well shipping times among others which might provide a lot of details on how to effectively optimize supply chain operations. These outcomes illustrate substantial gains in traceability, security and operational effectiveness that blockchain technology has the power to bring about for pharmaceutical supply chains.

2 Literature Review

Musamih et al.healthcare is a complex supply chain enterprise with numerous touch points across multiple organizations and regions, essential to keep the daily services running. This complexity causes problems with the veracity in data transmission, transparency lack of and reduced traceability creating a propitious environment for issues like counterfeit drugs compromising health and triggering economic losses.

Research suggests that an end-to-end track and trace system for pharmaceutical supply chains is key to preventing product tampering, reducing counterfeiting of drugs. Current systems are inherently centralized which brings in data privacy issues and lack of transparency This paper presents a traceability facilitated framework for the security over healthcare supply chains using smart contracts and decentralized off chain storage with ethereum blockchain. Smart contract will see to data provenance,   less intermediaries and immutable transaction history By presenting the architecture of such a system along with details on algorithms, testing and cost / security analyses are provided to demonstrate its potential in enhancing traceability [1].

Jadhav et al. **,**the pandemic introduced supply chain, patient data management and claims processing use-cases in healthcare to a different level of technology.Deployment & Scalability This is essential because elements of a supply chain are woven into healthcare, and any disruption may bring long-term harm if relevant data contains errors. Cryptocurrencies on the blockchain are secure, but that means nobody can "take them back," either - and there is anywhere from traceability to full transparency if you use certain privacy-focused cryptocurrencies built into healthcare systems. With Coin-Jump's blockchain solutions, you can trust that your data is safe at all times and allows only for secure retrieval of this information without having to store it in any way, which greatly helps with keeping the product creation or tracking process boosted. This study is a literature review regarding Blockchain's influence on healthcare supply chains by analyzing 61 papers written between the years of 2019 and 2021. It also acknowledges the common supply chain problems plus, its scope in leveraging Blockchain solutions [2].

Panda et al**.** it is hard to coordinate stakeholders, manage inventory in all places and it also brings various discomfort of registration over different nodes leading problems related drug status. Additionally, centralized medical supply chains are expensive and inefficient with little market analysis functionality. All transfers of batches must be stored on a blockchain platforms thereby solving that issue. Medicines are registered by the pharmaceutical companies and their batch details can be uploaded on network git. For a trade to happen, approval is needed from the sender and receiver at their respective exchanges (which keeps records of every single transaction that ever happens on it-fraud-proof). A unique DApp for tracking, immutability, transparency   and audit automation and trust. Abstract: The paper gives the general observations about Blockchain technology, platforms and its dependencies and how we can implement using smart contracts/javascript. Potential advancements may include installation of IoT chips in order to provide real-time updates on batch conditions [3].

Omar et al**.** the COVID-19 pandemic has laid bare weaknesses in healthcare, especially when it comes to emergency preparedness and risk mitigation as well as supply chain management. The COVID-19 pandemic put a strain on the availability of PPE due to insufficiently transparent, visible, and traceable supply chains - demonstrating that robust solution for transparency is needed. By using it, the
management and tracking of PPE are inherently more transparent because blockchain provides decentralised control that is associated with security features such as traceability and fully auditable transactions. This research describes a blockchain solution, backed by Ethereum smart contracts in order to automate PPE supply chain management, the related framework and algorithms according to it as well costing and security consideration [4].

Ahmad et al. ,the rush on COVID-19 medical equipment and supplies in 2020 laid bare global supply chain flaws, as well as a lack of capacity for managing hazardous waste. Lack of traceability & insecure: They are highly centralized, which means they have serious risks like being prone to single point of failure due non-traceable activity. In this paper, we propose a decentralized blockchain mesh-work solution that is applied to automate the chain process of COVID-19 health care devices by engaging both solid data management solutions using Ethereum Blockchain and IPFS. This paper discusses waste handling rules, algorithms to handle those and system level design principles along with detailed implementation guides as well as a cost & security analysis report demonstrating how affordable this solution can be Threshold [5].

Azzi et al. , in a supply chain, organizations are connected through people and activities that organize resources to move products from suppliers to customers while assuring quality at the same time. Centralized systems are prone to fraud and corruption. The Blockchain has given us a much better view and more possibilities on how we can handle the supply chain of our goods. In, the paper studies advantages and challenges of interconnecting blockchain into supply chains by a combination of both theoretical and practical principles to identify prerequisites towards establishing an operational Blockchain-based Supply Chain Management system [6].

Alkhader et al. (2021),the COVID-19 pandemic exposed weaknesses in medical device and supply production systems that should be globally dispersed for digital decentralized manufacturing. This paper provides a framework for enabling decentralized manufacturing and supply of medical devices by proposing the use of blockchain technology with Ethereum smart contracts to offer secure and transparent transactions. It utilizes highlight IPFS to store IOT-based gadget records and fabricating subtleties. The paper describes system architecture, algorithms, implementation particulars and testing details including cost/security analysis to show that the solution is economical in expense and robust against security threats [7].

Nanda et al. ,this is true for providing secure platforms in a variety of sharing services like medical data, anti-money laundering or supply chain management. Healthcare supply chain security, transparency, fake medicines and high costs are all current challenges. This paper proposes a new technique Novel Approach for Integrated IoT With Blockchain in Health Supply Chain (NAIBHSC) The blockchain and the IOT are used together to increase both privacy functionalityDictate through secure, and also modify all other effective amalgamation of cost-effective efficiency. Experiments demonstrate that NAIBHSC clearly improves response time and decrease latency, with respect to the original one [8].

Alsadi et al. the latter ones are all part of complex supply chains, which make transparency and traceability comparatively difficult - especially in relation to autonomous vehicle manufacturing. In this paper, we introduce TruCert: an blockchain solution that secures the way of product credential by providing irrefutable certification for automotive supply chain. The Ethereum blockchain and smart contracts are utilized by TruCert for improved quality assurance and resilience. This work presents details on the system design, data model and implementation along with cost and security analysis to validate its efficacy as described in our previous paper [9].

Kamath et al. ,one possible application for blockchain tech in health care is that it allows to store and manage securely information about one's medical history. While blockchain was introduced for digital transactions, it has since been integrated into tourism, real

estate and voting among others. It answers issues related to the pharmaceutical industry, data management as well in healthcare it helps with drug traceability. On this subject, a study examining the effects of blockchain on one sector (i.e., healthcare) and one problem in current approaches is presented [10].

Liu et al.,the increased drug safety awareness requires improved traceability and transparency up the supply chain. It helps enterprises that have long-deployed tradition database-based systems managing data, which are rigid and leads to headache of manipulation due having too many stakeholders. In this paper, the authors present BIoT3 a five-layer blockchain and IoT-based platform of drug traceability. It leverages IoT using Hyperledger Fabric to track drug identity, on chain/off-chain processes and smart contracts. Case studies present evidence of its efficacy, as well as the potential for large scale implementation outside highly academic settings [11].

El Azzaoui et al. ,the core issue of concern in the medical vertical is security, now becomes more significant due to COVID-19. Why Cyber-attack on weak security: Need Advanced Security for Protection In this paper, an Integrative approach of Blockchain and Information Hiding Techniques (IHT) is proposed to improve the security in healthcare supply chain networks. The framework has shown feasibility and enhanced security by using Hyperledger smart contracts [12].

Jamil et al. ,fake drugs comprise 10-30% of medicines in developing countries. The side effects of these drugs are different and they avoid regulatory authorities. In this work, a blockchain Hyperledger Fabric based approach is being proposed to store drug supply chain records for secure transactions. Drug and patient records are stored in smart contracts that grant time-limited access. We validate this claim through experiments comparing our system with others using the Hyperledger Caliper toolkit for performance benchmarking [13].

Abdallah et al. ,pharma supply chains are very different today than they were 30 years ago, much more complex and involving global manufacturers (+ CMOs), suppliers (API to packaging material) & finally consumers. It then becomes a question of trust and transparency - online pharmaceutical sales raise serious concerns in these areas. This paper presents a decentralized blockchain framework built on Ethereum smart contracts to regulate inuk sales without a middleman. To make sure that the medicine is delivered safely, smart contracts keep a record of actions as well provide secure payment dispersal and supervision IoT container status all while providing consumer refunds due to breaches in terms on contract. [14]

Omar et al.,the COVID-19 pandemic shone a blinding light on weaknesses in the healthcare supply chain, specifically around widespread shortages of PPE. Due to the visibility and tracking lost within supply chains, chainchains needs quintessential robust solutions. In this paper a blockchain-approach has been described and implemented with the help of Ethereum smart contracts for PPE supply chains to provide transparency, security and traceability. This framework will automatically performs task and data exchange, ensuring the economic feasibility and effectiveness with cost analysis as well as security analyses [15].

Ouf, Shimaa et al. ,this paper is an approach provide a design to enhance the security of pharmaceutical supply chain based on IoT, semantic web, and blockchain technologies. This architecture enhances the transparency of drug material flow and

data representation in real-time over every phase of the lifecycle, starting from raw materials to patient usage. The system would help to create a more efficient, transparent and secure supply chain by integrating these technologies besides   protecting the consumers from fake drugs hence ensuring patient trust and satisfaction [16].

Agarwal et al. ,in practice, managing the supply and production of goods through several stakeholders is known as Supply Chain Management (SCM), which usually involves a layer that sits in the center coordinating where things needs to be done. Security, transparency, traceability and fraud are key concerns in traditional SCM systems. However, blockchain fabrics offer a decentralized environment ensure safe data management and validation of transactions. This paper provides a survey of blockchain adoption in SCM and analyzes 97 relevant articles to expose the benefits as well as challenges from viewpoint. This study highlights the contribution of blockchain in a SCM and its services like transparency, trust-breaking and anti counterfeiting while placing open research issues to bridge gaps [17].

Sreenu et al.,during pandemics, immunization is essential; however complex global supply chains are the reason for problems such as those seen with falsified, substandard and expired vaccines. I first investigated the development of a granular, all-three-peaks track and trace system. To the best of our knowledge, none has proposed a blockchain and IoT deployed system for vaccine supply chain to this level using Hyperledger Fabric transaction model based on data ownership or stakeholder interaction. That system improves resilience and traceability, with performance evaluations that demonstrate either are outperforming other schemes on throughput and latency [18].

Sunny et al.,when transparency meets trackability and traceability, it increases visibility into supply chains. Centralized solutions still struggle with data manipulation and single points of failure. Decentralized ledger technology aka blockchain addresses these issues. Through this paper, blockchain-based traceability solutions are being reviewed with a focus on supply chain visibility enhancements. It
has shown a Proof of Concept for cold chain scenario on Microsoft Azure Blockchain Workbench which has following advantages [19].

Akhtar et al.,recent developments in ICT have increased the interest on where products come from. Historical data is immutable due to making consensus over the network by blockchain. Pharmaceutical Supply Chain - It is important to prevent counterfeiting drugs so those medicines must be traceable. Chapter 5: A comprehensive comparison of Ethereum (as a permissionless blockchain platform) and Hyperledger fabric in terms of supply chain traceability with pseudo codes, challenges faced by developers and future research directions [20].

Ahmadi et al.,pharmaceutical supply chain fraud and abuse have become major problems. In this paper we are going to describe how the supply chain change can be achieved, using IoT and blockchain technologies by keeping records that cannot be tampered with as well updating drug governance. A blockchain system deployed on Io T can increase efficiency and credibility in the healthcare sector by enabling traceability from ingredient source to consumer as shown at [21].

Selvaprabhu ,efficient SCM: In times of emergency, like a pandemic or natural calamity efficient Supply Chain Management (SCM) essential. Lack of coordination   and structured approach cause counterfeits, cost increases lead to traffic jams. The data integrity and transparency are guaranteed by blockchain technology as a result of its

distributed,decentralized nature. One investigation scrutinizes the capacity of blockchain in SCM and current work along with future developments are backtracked on agriculture, health facilities sector and e-voting cases [22].

Dwivedi et al., Supply Chain Management (SCM): The practice of safely transport a specific product from an entity to the next is central for any SC2 participants. Traditional SCM systems can fall victim to manipulation, downtime or even fraud if proper authentication and data integrity are not implemented. Decentralization, transparency and immutability - as features of blockchain technology could resolve all these issues. In another work improving the resilient and privacy-preserving sharing of information against any attack on smart contracts, authors adopted a blockchain based solution to share data securely among actors in pharmaceutical supply chains by using both secure distribution channel via smart contract with consensus mechanism as it can be deployed at reasonable costs [23].

Fiore et al. ,supply chain (SC) is a network of entities, information and products that creates value for customers. In this review, the literature discussing how blockchain can solve supply chain challenges in healthcare is outlined, mainly drugs and medical devices supply chains along with blood/ organs / tissues. A total of 28 studies were included following a systematic review, which the majority aimed to be implemented as smart contracts. While significant interest can be inferred from these results, the paucity of real-life applications may indicate that those who are interested in this work either cannot find or engage with it [24].

Al-Rakhami et al.,as you can see, appropriate data and strategic processes are critical elements of any supply chain - however friction due to lack of mutual trust may prevent their successful implementation. Connects four: blockchain technology, free of illicit real currency betting Aggregator Nov 9 Fast and safe data sharing based on trust is possible. Yet as seen with non-IoT-optimized blockchains, they tend to be slow and consume large amounts of computing power. A trust model for IoT-based supply chain to reduce the computational, storage, and latency overhead while improving security in terms of simulation proof [25].

Mezquita et al.,while the goal of blockchain protocols is provide traceability of tracked assets in a supply chain system, maintaining an immutable audit trail across systems-of-systems prove to be more challenging. This proposal introduces a model for tracing the location of assets on multiple blockchain supply chains with cryptographic verification and asset standard definitions across all of them. Its application in the pharmaceutical sector shows its operational benefits [26].

Cui et al., the electronics supply chain has increased in complexity with globalization, and it is a difficult task to ensure the security and integrity of electronic parts. This paper describes a blockchain-enabled, non-destructive traceability framework for electronic parts using permissioned Hyperledger. Every chip in the supply chain is closely tracked and traced by this framework which has detailed feasibility analysis supporting it [27].

Xie et al. ,due to the special nature of bio-drugs, personalized medicine urgently needs it as a weapon, and its supply chain faces a series challenges. It presents a new blockchain based interoperability framework running on QuarkChain with smart contracts developed in Proof-of-Authority,i.e., PAQS. Live tracking ensures transparency and control during transportation, keeping the medicines secure from theft, spoilage by deviation in temperature or counterfeiting. This is where the design

of a blockchain that relies on stochastic simulation comes in, which can ensure supply chain reliability and efficiency. Initial studies indicate good performance [28].

Mani et al. (2022),the medicine supply chain is a complex, multi-stakeholder space resulting in convoluted processes and little traceability. This comes about to show the consequences we face due to counterfeit drugs and disparities in operations etc. A Cloud based Blockchain-powered architecture which solves these as it guarantees traceability, data storage and privacy plus quality assurance. It provides large scale encourage since it is a built in the IPFS for off-chain storage with Hyperledger Blockchain on chain management system that makes possible higher efficiency and usability [29].

Munasinghe et al. (2023),one of them is Vacledger, a blockchain-assisted system designed to follow rip-off COVID-19 vaccines. It incorporates four smart contracts with the use of a private-permissioned blockchain in facilitating regulatory abidance, vaccine registration, inventory accumulation and geo-location tracking. It records activities, and trades made in an immutable way without any difference of algorithmic complexity from the current one. It indicates secure and efficient supply chain management which may also work for other industries [30].

Sharma et al. (2024),new Blockchain application for increased security and authentication in the medicine supply chain It allows for a higher level of transparency, traceability and integrity of data about the products with QR code watermarking techniques tofaclitste product verification such as Hyperledger Fabric.
Built-in buyer validation and high performance, scalability, resource efficiency by dissecting simulations with demonstrated functionality [31].

Li et al.the rise in sales of medical devices has meant that incidents than require more comprehensive supply chain management have also increased. The proposed article suggests the integration of RBAC and ABAC models to manage access control at a dynamic granular level in medical device supply chains using blockchain for genuine, security-enhanced traceability. The deployment of the system on Hyperledger Fabric allowed us to achieve high transaction rates, reliable stability and security [32].

Alsadi et al. ,the quality assurance of production must be improved which directly leads to an even better transparency and traceability within supply chain networks, especially for autonomous vehicles. TruCert (Blockchain Use Case 2) - TruCert is a blockchain-based product certification solution that powers resilience in supply chains. This is thanks to its smart contracts and oracles for both interoperability with other systems, as well as the capability of certified parts from more than just tier 1 suppliers. Its design, performance and security assessments have shown its efficiency and possible use for future work [33].

3 Proposed Methodology

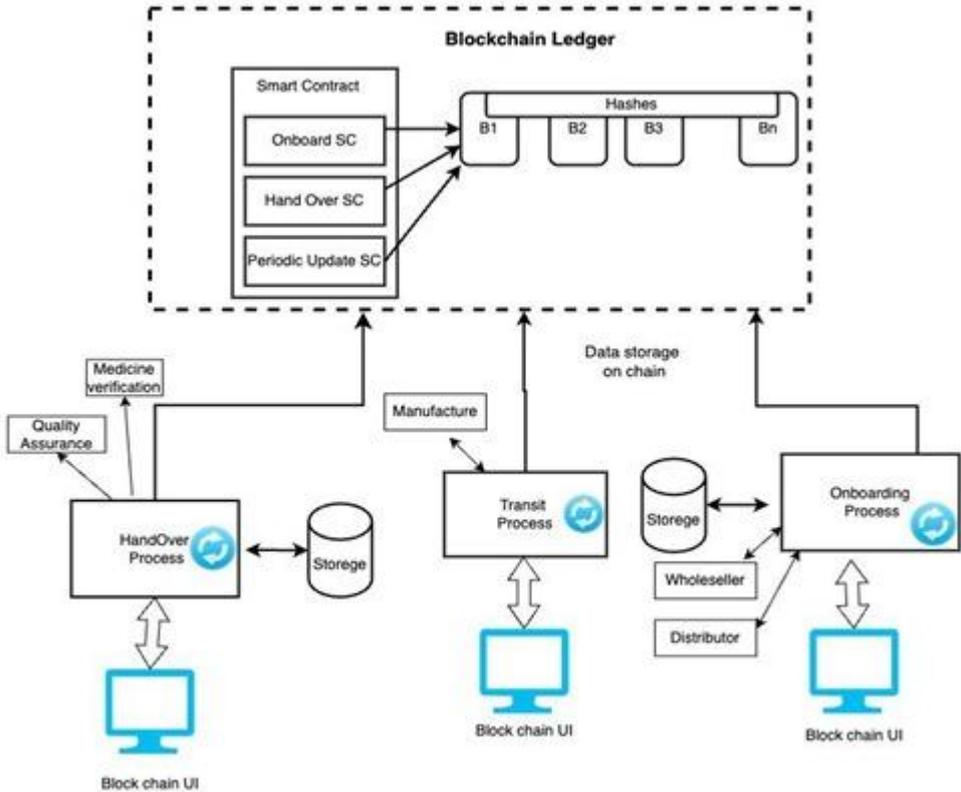**Proposed Architecture -** given in Fig.1

Fig. 1. Proposed working architecture

3.1.1 Blockchain Ledger

1. Smart Contract: Contains three types of smart contracts (SC):

Onboard SC: Manages the initial registration of pharmaceutical products onto the blockchain.
Hand Over SC: Oversees the transfer of ownership or custody of products as they move through the supply chain.
Periodic Update SC: Ensures regular updates of product status and other relevant data.

2. Hashes (B1, B2, B3, ..., Bn): Represent the cryptographic hashes of transaction blocks, ensuring data integrity and immutability within the blockchain ledger.

3.1.2 Processes
1. **Onboarding Process:**
   o Involves the initial registration of products onto the blockchain.

- o Includes data such as product details and manufacturer information.
- o Uses blockchain UI for interaction.
- o Data is stored on-chain.

2. **Transit Process:**
   - o Manages the transportation of pharmaceutical products from the manufacturer to the wholesaler or distributor.
   - o Ensures data related to transit conditions and status is updated and stored on the blockchain.
   - o Involves interaction with blockchain UI for monitoring and verification.

3. **HandOver Process:**
   - o Deals with the handover of products at various checkpoints. o Ensures verification of medicine and quality assurance at each handover point.
   - o Uses blockchain UI for verification.
   - o Data from the handover process is stored on-chain.

3.1.3 Data Storage and Interaction

1. **Data Storage on Chain:** Centralized blockchain ledger where all data related to the supply chain processes are securely stored.
2. **Storage:** Represents physical storage locations at different stages (e.g., manufacturer, wholesaler, distributor) with data interactions logged on the blockchain.
3. **Blockchain UI:** User interfaces at different stages for interaction with the blockchain ledger to verify and update information.

3.1.4 Data Flow and Verification

1. **Medicine Verification:** Performed during the handover process to ensure authenticity and quality of pharmaceutical products.
2. **Manufacture to Storage:** Products are manufactured and stored, with all relevant data being updated on the blockchain ledger.
3. **Transit and Quality Assurance:** Products are transported to the next stage, with ongoing updates and verifications logged on the blockchain to ensure transparency and traceability.

3.1.5 Stakeholders

1. **Manufacturer:** Produces pharmaceutical products and initiates the onboarding process.
2. **Wholesaler/Distributor:** Intermediate entities that handle storage and distribution, ensuring continuous updates to the blockchain ledger. 3. **Quality Assurance:** Ensures the quality and integrity of products at each stage, verified through blockchain interactions.

This blockchain-based system aims to enhance the traceability, security, and efficiency of the pharmaceutical supply chain by leveraging decentralized technology and smart contracts to manage and verify transactions.

Proposed TruCert Model for Pharmaceutical Supply Chain

3.2.1 Initialization

1. **Setup Blockchain Network:**
   1. Deploy a permissioned blockchain network using Hyperledger Fabric.
   2. Define and deploy smart contracts for tracking and verifying pharmaceutical products.

3.2.2 Entities

1. **Participants:**
   1. Manufacturers
   2. Wholesalers
   3. Distributors
   4. Pharmacies
   5. Regulatory Bodies
   6. Consumers

2. **Data Structures:**
   1. ProductBatch: Contains details about the batch of pharmaceutical products.
   2. TransactionRecord: Contains transaction details for each transfer of product batch.
   3. SmartContract: Handles product registration, transfer, verification, and validation.

3.2.3 Steps

1. **Product Registration:**
   1. Manufacturer creates a ProductBatch with details like batch ID, production date, expiry date, and composition.
   2. Manufacturer invokes the RegisterProduct smart contract function to register the batch on the blockchain.
   3. Blockchain generates a unique hash for the ProductBatch and records it in a new block.

2. **Quality Assurance:**
   1. Quality assurance team verifies the product quality and updates the status in the blockchain using QualityCheck smart contract function.
   2. The quality status and verification date are recorded in the blockchain.

3. **Transfer of Ownership:**
   1. When the product batch is ready to be transferred to a wholesaler, the manufacturer invokes the TransferOwnership smart contract function.
   2. The transaction details including sender, receiver, and timestamp are recorded in the blockchain.
   3. Wholesaler verifies the batch upon receipt by invoking the ReceiveProduct smart contract function, confirming the transfer.

4. **Distribution:**
   1. Wholesaler transfers the product batch to distributors or pharmacies using the same TransferOwnership and ReceiveProduct functions. 2. Each transfer is recorded as a TransactionRecord in the blockchain. 5. **Product Verification:**
   1. Pharmacies and consumers can verify the authenticity of the product by invoking the VerifyProduct smart contract function.

2. The function retrieves the product batch details and transaction history from the blockchain, ensuring the product is genuine.

6. **Regulatory Compliance:**

1. Regulatory bodies can access the blockchain to audit the entire supply chain.
2. They can invoke AuditSupplyChain smart contract function to ensure compliance with regulations and trace any issues back to their source.

7. **Counterfeit Detection:**

1. Any discrepancies in the transaction records or product details trigger the AlertCounterfeit smart contract function.
2. The function flags the suspicious batch and notifies all participants in the supply chain.

Algorithm Flow

Initialize :Blockchain Network
Define Smart Contracts: RegisterProduct, QualityCheck, TransferOwnership, ReceiveProduct, VerifyProduct, AuditSupplyChain, AlertCounterfeit FOR each Manufacturer
Create ProductBatch
CALL RegisterProduct(ProductBatch)
CALL QualityCheck(ProductBatch)
WHILE ProductBatch not expired
CALL TransferOwnership(ProductBatch, Wholesaler)
CALL ReceiveProduct(ProductBatch, Wholesaler)
FOR each Distributor
CALL TransferOwnership(ProductBatch, Distributor)
CALL ReceiveProduct(ProductBatch, Distributor)
FOR each Pharmacy
CALL TransferOwnership(ProductBatch, Pharmacy)
CALL ReceiveProduct(ProductBatch, Pharmacy)
FOR each Consumer
CALL VerifyProduct(ProductBatch)
END FOR
END FOR
END FOR
END WHILE
FOR each RegulatoryBody
CALL AuditSupplyChain()
FOR each ProductBatch
IF discrepancies detected
CALL AlertCounterfeit(ProductBatch)
END IF

The pharmaceutical supply chain protocol initializes a blockchain network and defines smart contracts for product registration, quality checks, ownership transfer,... First manufacturers would create and record product batches, confirm its quality and transfer

ownership to wholesalers. Wholesalers then take the product, and they move it throughout their parts of the network (distributors or pharmacies), first with each node calling out to relevant smart contract functions that are called with all details needed for this kind of transaction. The VerifyProduct function allows consumers to validate the authenticity of a product. The supply chain is audited regularly by the Regulatory bodies. When such differences are found in any product series, the Alert Counterfeit function is invoked to warn. This assures a safe, transparent and traceable pharma supply chain.

Algorithm : On-board Process for Pharmaceutical Supply
Chain Requirements:

● **Inputs:**

1. partNo: Part number
2. manufacturer: Manufacturer of the part
3. manufacturingDate: Manufacturing date of the part
4. supplierID: Supplier ID
5. isCertified: Certification status
6. VIN: Vehicle Identification Number
7. IPFSFiles: Files stored on the InterPlanetary File System
8. truckID: Truck identification number
9. pkitMAC: MAC address of the pkit
10. location: Location data
11. regDate: Registration date

Require: partNo, manufacturer, manufacturingDate
Require: supplierID, isCertified, VIN, IPFSFiles
Require: truckID, pkitMAC, location, regDate
if partNo $\notin$ RegisteredParts[] then
 onboardRecord ← partInputs
 ID ← 1
 Type ← onboard
 Data ← location
 event ← ID + Type + Data
 ID ← ID + 1
 ▷ Store part record
 ▷ Store part Event
else
 error ← Part already exists. Can't be added.
end if

Description:
1. **Input Validation:**
   1. Check if partNo (Part number) is not already in the
      RegisteredParts[] array.
   2. If the part number is not registered, proceed with the onboarding
      process.
2. **Onboarding Record:**

      1. Store all part inputs (partNo, manufacturer, manufacturingDate, supplierID, isCertified, VIN, IPFSFiles, truckID, pkitMAC, location, regDate) into onboardRecord.

3. **ID and Event Creation:**
    1. Initialize ID to 1.
    2. Set Type to onboard.
    3. Assign location data to Data.
    4. Create an event string by concatenating ID, Type, and Data.
    5. Increment ID by 1.

4. **Store Records and Events:**
    1. Store the onboard record and the event into the blockchain or the relevant storage system.

5. **Error Handling:**
    1. If partNo is already in RegisteredParts[], return an error message indicating that the part already exists and cannot be added again.

Algorithm : HandOver Process for Pharmaceutical Supply Chain Requirements:

- **Inputs:**
    1. partNo: Part number
    2. deliveryDate: Delivery date
    3. deliveryLocation: Delivery location
    4. inspectionReport: Inspection report
    5. QADocs: Quality assurance documents

Require: partNo, deliveryDate, deliveryLocation
Require: inspectionReport
Require: QADocs

if partNo ∈ RegisteredParts[] then
 handoverRecord ← partInputs
 ID ← getNextID()
 Type ← handover
 Data ← deliveryLocation
 event ← ID + Type + Data
 ▷ Update Part info
 ▷ Store part Event
 else
 error ← Part is not registered. Can't complete process.
end if

Description:
1. **Input Validation:**
    1. Check if partNo (Part number) is already in the RegisteredParts[] array.
    2. If the part number is registered, proceed with the handover process.

2. **Handover Record:**
   1. Store all part inputs (partNo, deliveryDate, deliveryLocation, inspectionReport, QADocs) into handoverRecord.
3. **ID and Event Creation:**
   1. Retrieve the next available ID using getNextID().
   2. Set Type to handover.
   3. Assign deliveryLocation data to Data.
   4. Create an event string by concatenating ID, Type, and Data.
4. **Update and Store Records:**
   1. Update the part information in the relevant storage system.
   2. Store the handover event into the blockchain or the relevant storage system.
5. **Error Handling:**
   1. If partNo is not in RegisteredParts[], return an error message indicating that the part is not registered and the process cannot be completed.

Algorithm : Blockchain Oracle Sample Pseudo Code for Pharmaceutical Supply Chain

Requirements:
● **Inputs:**
   1. partNo: Part number
   2. deliveryDate: Delivery date
   3. deliveryLocation: Delivery location
   4. inspectionReport: Inspection report
   5. QADocs: Quality assurance documents
   6. BlockchainNetworkID: Identifier for the blockchain network

Require: partNo, deliveryDate, deliveryLocation
Require: inspectionReport
Require: QADocs
Require: BlockchainNetworkID

gas ← estimateGas(BlockchainNetworkID)
tx ← buildTransaction(input, gas)
signedTx ← buildTransaction(tx, privateKey)
txHash ← sendRawTransaction(signedTx)

if txHash ≠ null then
 result ← transaction successfully committed
else
 error ← transaction isn't successful.
end if

Description:
1. **Estimate Gas:**
   1. Calculate the required gas for the transaction using the blockchain network ID: gas ← estimateGas(BlockchainNetworkID).

2. **Build Transaction:**
    1. Create the transaction object with the necessary inputs and estimated gas: tx ← buildTransaction(input, gas).
3. **Sign Transaction:**
    1. Sign the transaction using a private key to ensure authenticity and security: signedTx ← buildTransaction(tx, privateKey).
4. **Send Transaction:**
    1. Send the signed transaction to the blockchain network: txHash ← sendRawTransaction(signedTx).
5. **Transaction Verification:**
    1. Check if the transaction hash (txHash) is not null to confirm that the transaction was successfully committed.
        ▪ If true, set the result to "transaction successfully committed".
        ▪ If false, set the error to "transaction isn't successful".

4 Implementation and Results

Hardware requirement

Some hardware requirements for securing medicine supply chains using blockchain based credibilitycertification system are powerful servers with multiple processors and large memory size to support high intensity computation ofblockchain operations including calling smart contract functions. It is recommended to have these servers with multiple CPU preferably multi-core and at least a minimum of 32GB RAM to handle bulk transaction processing, data crunching. Also, significant storage needed to store blockchain data and transaction logs so have SSDs with min 1 TB of capacity. To enable seamless communication amongst the blockchain network it should have high-speed internet connections with low latency. Hardware security modules (HST) can be used to secure the cryptographic keys and sign transactions in a manner that is ensurely trusted. Not only must the server be equipped with backup power supplies and cooling for high availability, but also firewalls or layer of protection to prevent unauthorized access if nothing else.

Dataset

This study collected the dataset used with regards to supply chain analytics from a Fashion and Beauty startup who had been observing his/her client makeup product supply chain. It provides us with many features essential for data-driven decision making. Some of these features are product type, SKU, price availability etc along with sold products count and the generated revenue. If you are wondering, it also allows you to take customers demography along with stock levels as well as lead time and order quantities. Information around shipping (shipping times, carriers and costs) is added along with supplier details such as name, location, lead time & production volumes. Manufacturing aspects are represented through features such as manufacturing lead time, costs and inspection results or defect rates. It also contains transportation modes, routes and the costs associated with these to give a complete picture of all nodes in the end-to-end supply chain from suppliers through your manufacturer operations to customers. The Thingstream plugin captures a treasure trove of data, allowing for rich

analysis and interpretation to help optimize everything around the supply chain and the movement of products/ services.

Blockchain network creation

Creating a blockchain network for securing medicine supply chains through blockchain-based trustworthy certification involves several key steps: **Step 1: Define Objectives and Requirements**

1. **Objectives**: Secure the supply chain, ensure product authenticity, improve traceability, and prevent counterfeit medicines.
2. **Requirements**: Identify hardware and software needs, establish network participants (manufacturers, distributors, pharmacies, regulatory bodies), and define data and transaction types.

Step 2: Choose a Blockchain Platform

1. **Platform Selection**: Choose a suitable blockchain platform such as Hyperledger Fabric, Ethereum, based on requirements for permissioned or permissionless networks, scalability, and security features.

Step 3: Configure Network Nodes

1. **Nodes Setup**: Set up nodes (peers, orderers, and clients) on the blockchain network. Each node represents a participant in the supply chain.
2. **Hardware**: Ensure each node has sufficient computational power, memory, and storage as per the hardware requirements.

Step 4: Establish Smart Contracts

1. **Smart Contracts**: Develop and deploy smart contracts to handle product registration, quality checks, ownership transfers, receipt confirmations, product verification, supply chain audits, and counterfeit alerts.

Step 5: Implement Security Measures

1. **Encryption**: Use robust encryption techniques to secure data and transactions.
2. **Access Control**: Implement role-based access control (RBAC) or attribute based access control (ABAC) to restrict access to authorized participants. 3. **HSMs**: Integrate hardware security modules (HSMs) for secure key management and transaction signing.

Step 6: Network Deployment

1. **Deployment**: Deploy the blockchain network nodes on cloud infrastructure or on-premises servers.
2. **Connectivity**: Ensure high-speed and reliable network connections between nodes.

Step 7: Testing and Validation

1. **Simulation**: Conduct simulation tests to validate network performance, transaction throughput, and security protocols.
2. **Validation**: Test smart contracts to ensure they function as intended and handle all defined processes accurately.
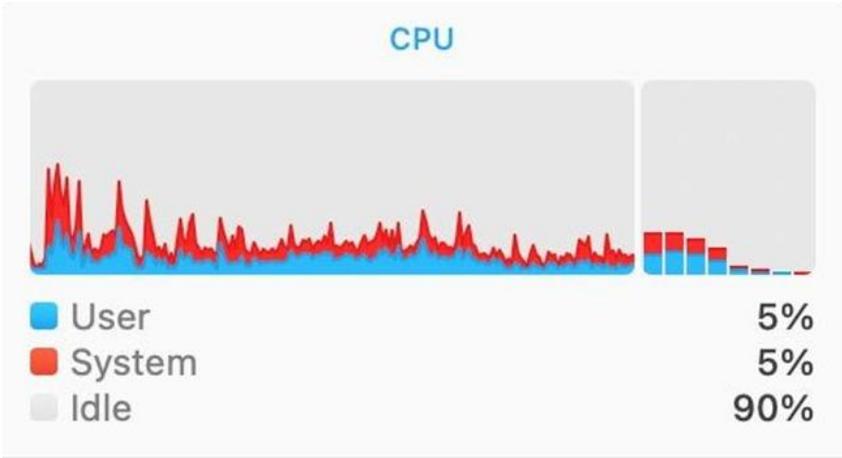
Illustrative example

Fig. 2. The CPU usage statistics for a system.

The figure 2 shows the CPU usage statistics for a system. It indicates that 5% of the CPU is utilized by user processes, another 5% is used by system processes, and the remaining 90% of the CPU is idle. The graph visualizes the CPU activity over time, with the red area representing system process usage and the blue area representing user process usage. The significant idle percentage suggests that the system is largely underutilized during the recorded period.
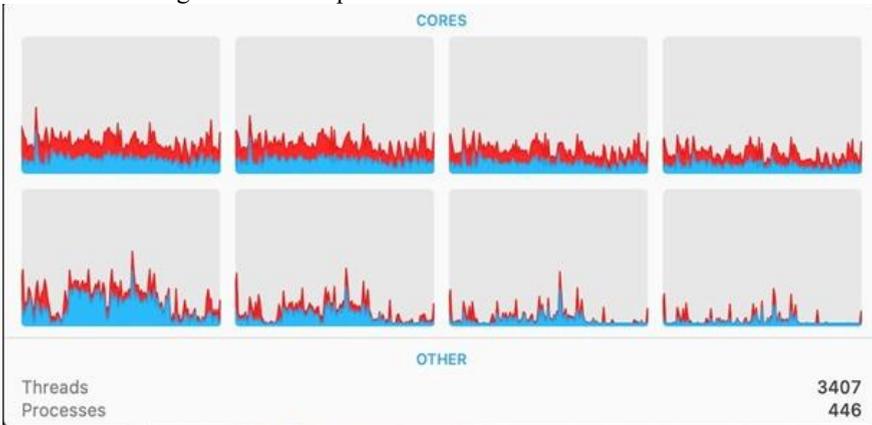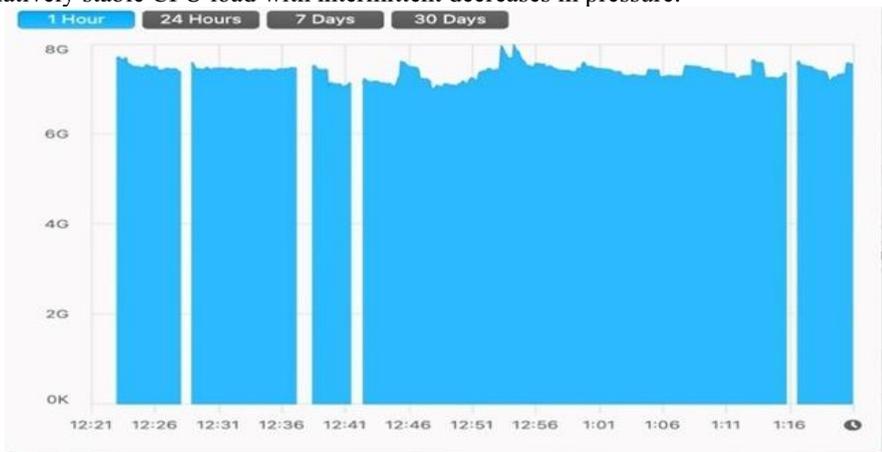

Fig. 3. The CPU usage across eight cores.

The figure 3 displays the CPU usage across eight cores, with each core's activity represented in separate graphs. The red areas indicate system process usage, while the blue areas show user process usage. Across all cores, the CPU activity shows moderate and relatively consistent usage patterns, with notable spikes in some cores. Despite these spikes, a significant portion of CPU capacity remains idle. The system is running 3407 threads and 446 processes, indicating a moderate workload spread across multiple cores without overloading any single core.

Fig. 4. One-hour graph of CPU pressure.

The figure 4 shows a one-hour graph of CPU pressure, indicating the percentage of CPU utilization over time. The blue areas represent the pressure on the CPU, which mostly hovers around 50-75%, with occasional drops to 0% at regular intervals. The data points reflect a consistent usage pattern with periodic dips, suggesting brief moments of inactivity or lower demand on the CPU. At the highlighted time, 11:13:18 AM on July 20, 2024, the CPU pressure was at 59%. Overall, the graph illustrates a relatively stable CPU load with intermittent decreases in pressure.

Fig 5. one-hour graph of memory usage, measured in gigabytes (GB).

The figure 5 shows a one-hour graph of memory usage, measured in gigabytes (GB). The blue area represents the memory usage, which remains consistently high, near the 8GB mark, with periodic drops to 0GB at regular intervals. These drops likely indicate moments of significant reduction or release of memory usage. Despite these occasional dips, the overall memory usage stays close to the maximum capacity, reflecting sustained high demand on the system's memory resources over the observed period.
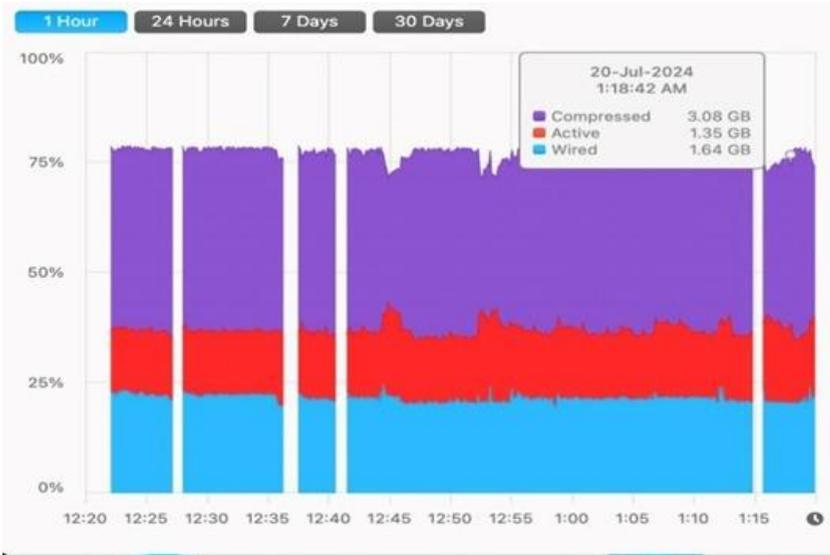
Fig 6 One-hour graph of memory usage categorized into compressed, active, and wired memory.

The figure 6 displays a one-hour graph of memory usage categorized into compressed, active, and wired memory. The blue area represents wired memory, the red area indicates active memory, and the purple area shows compressed memory. Throughout the hour, memory usage remains high, with significant portions allocated to compressed memory (peaking at 3.08 GB), active memory (1.35 GB), and wired memory (1.64 GB). The graph shows periodic drops to 0%, suggesting moments when memory usage significantly decreases or resets. Overall, the system maintains a substantial memory load, primarily dominated by compressed memory, indicating efficient use of available resources to manage high memory demand.

Fig. 7 One-hour graph of CPU usage, divided into system (red) and user (blue) processes.
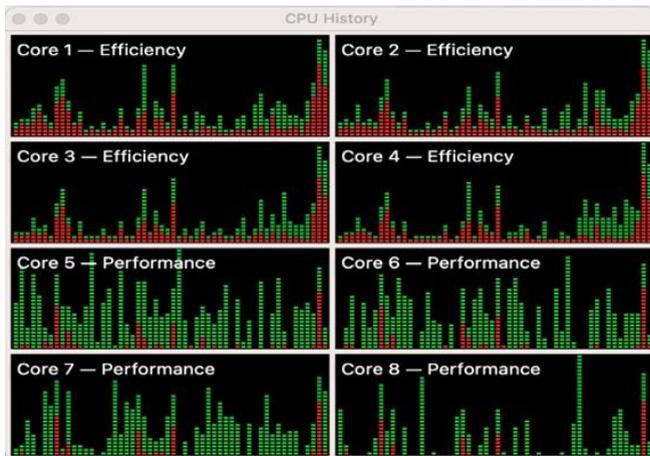
The figure 7 presents a one-hour graph of CPU usage, divided into system (red) and user (blue) processes. Throughout the period, CPU usage fluctuates with multiple peaks, particularly around 12:25, 12:45, and 12:55, where the system usage shows significant spikes. The graph indicates that system processes consistently dominate over user processes, with system usage reaching up to 8.6% and user usage up to 7.0% at 1:15:36 AM on July 20, 2024. Despite these fluctuations, overall CPU usage remains relatively low, suggesting that the system is not heavily taxed during this time frame.

Fig. 8. One-hour graph of CPU load averages.

The figure 8 shows a one-hour graph of CPU load averages, with data points representing 1-minute, 5-minute, and 15-minute intervals. The blue area indicates the 1-minute load average, while the red and black lines represent the 5-minute and 15-minute load averages, respectively. Throughout the hour, the CPU load fluctuates, with noticeable spikes around 12:34 and 12:59, where the 1-minute load average peaks significantly. At 1:15:18 AM on July 20, 2024, the load averages are 1.7 for 1 minute, 1.8 for 5 minutes, and 2.1 for 15 minutes. The overall trend shows periodic increases in CPU load with subsequent decreases, reflecting varying demands on the system over time.

Result

Fig. 9 The CPU history for eight cores, categorized into efficiency cores (Cores 1 to 4) and performance cores (Cores 5 to 8).

The figure 9 displays the CPU history for eight cores, categorized into efficiency cores (Cores 1 to 4) and performance cores (Cores 5 to 8). Each graph shows the CPU activity over time, with green bars indicating user process usage and red bars indicating system process usage. The efficiency cores (Cores 1 to 4) generally show lower and more consistent usage, while the performance cores (Cores 5 to 8) exhibit higher and more variable usage patterns, reflecting their role in handling more demanding tasks. The activity spikes in the performance cores indicate periods of intensive processing. Overall, the figure illustrates the distribution of workload between efficiency and performance cores, optimizing resource usage based on task requirements.

5 Conclusion And Future Work

This research shows that securing medicine supply chains through blockchain-based trustworthy certification can have a significantly positive impact on the transparency, traceability, and security of pharmaceutical products. The approach provides the necessary tools to address the growing concerns regarding counterfeit drugs, the validity of data, and the efficiency of existing supply chains in a globalized world. The use of smart contracts for product registration processes, quality checks, ownership transfers, receipt confirmations, product verification by end-users, supply chain audits, and alerting the authorities about counterfeit products ensures a secure and immutable record of all transactions. In addition to reducing the overhead caused by information sharing, the method also establishes the trust necessary for all players in the supply chain to verify and authenticate the origin of all pharmaceutical products. The trustworthy system for securing medicine supply chains may be improved in a number of ways. One possibility is to integrate Internet of Things devices to allow for real-time monitoring and updates on pharmaceutical product status at any point in time. This development would require more complex smart contracts that can accept changing data from multiple sources; any alterations to the product status need to be documented as transactions.

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