Blockchain Enabled Healthcare Supply Chain: Review, Case Study and Future Opportunities

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***Abstract*—Blockchain is a major component of future smart healthcare that can improve the security, reliability, trust and automation of healthcare supply chain processes. Blockchain has several applications in areas such as medicine procurement, supply chain tracking, and drug traceability. In this study, we present a review of recent works in the area of Blockchain-enabled healthcare supply chains with a particular focus on pharmaceutical supply chains. We categorize the literature into three major areas namely, procurement, asset management, and system efficiency improvement. We also present a case study of efficient smart contracts for the pharmaceutical supply chain in which we identify different stakeholders of the pharmaceutical supply chain and develop different functions and tasks to be performed by each stakeholder and their interactions with each other. We implement the proposed smart contract in Remix Integrated Development Environment (IDE) using solidity language and evaluate the transaction cost of each function used in the smart contract. Lastly, we also present future opportunities on using Blockchain-enabled healthcare supply chain.**

***Keywords*—Blockchain; smart contracts; healthcare; supply chain**

I. Introduction

Blockchain is an upcoming technology that has applications in many domains. Many application areas such as transportation, health care, banking, etc. can benefit from Blockchain technology [1], [2], [3], [4], [5], [6], [7]. The essence of Blockchain is to secure the data in a distributed manner without the need of a central node for authentication purposes. Thus, Blockchain is a concept that can revolutionize the way the data is secured and managed [8], [9], [10], [11], [12].

The key concept of Blockchain is to store data in the form of blocks that are connected such that the current block contains a hash function of the previous block. This connectivity property as well as the acceptability of only a pre-defined hash function makes Blockchain super secure. To change data in one block, it is needed to tamper data in other blocks too [13], [14], [15], [16]. Moreover, generation of the pre-defined hash function is a computationally heavy task that requires nodes with large processing capacity known as mining nodes [17], [18], [19], [20], [21]. Similarly, a block is only accepted in a Blockchain if more than half of the nodes give consensus to the data. This property also provides additional security to the Blockchain. Blockchain is thus an intelligent way of securing data in a distributed manner [22], [23], [24], [25], [26], [27].

Smart contracts are programs that implement certain conditions as per a particular contract. Contrary to traditional contracts, smart contracts can automate the way contracts are managed and smartly use the technology to check application-specific conditions. Smart contracts provide a reliable solution that does not require a trustable central authority. Smart contracts have many applications in scenarios, where application reliability depends on fulfilling certain conditions [28], [29], [30], [31], [32], [33]. As an example, in a medical supply chain, the temperature of the medicines needs to be maintained. Hence, a smart contract can be developed to monitor the temperature of medical supplies. It is important to note that smart contracts require inputs from the Internet of Things (IoT) sensors and the transmission of data to a server. Based on these inputs, smart contracts can check the permissible conditions issue directions, and make appropriate decisions. Smart contracts are managed using Blockchain technology. Thus, Blockchain-enabled smart contracts are a secure way of implementing and automating checks [34], [35], [36], [37], [38].

The focus of this study is to provide a survey of recent work related to Blockchain and smart contracts in the area of healthcare supply chain. The particular focus of this study will be on the pharmaceutical supply chain. A traditional healthcare supply chain requires manual negotiations and interactions between manufacturers and pharmacies. The goal of the smart contracts-based supply chain is to automate the process of medicine procurement. Another challenge that is part of the healthcare supply chain is the manual checking of different medicine-related parameters such as acceptable temperature while transporting, expiry date of medicines, etc. The smart contracts can include different checks to verify these conditions before purchasing of medicines.

The main contribution of our work is summarized as follows:

- We present a review of recent work related to using Blockchain in healthcare environment. We categorize the related works into three major groups. The first is related to procurement, the second is based on asset management, and the third one is related to system efficiency improvement.
- We present a case study in which we propose a framework of a smart contracts-based pharmaceutical supply chain and identify various stakeholders in the process including the Healthcare Management System (HMS), manufacturers, distributors, pharmacies, and hospitals. We develop different functions for each stakeholder that can be embedded in the smart contracts along with various associated conditions. We

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also develop a sequence of events to highlight the interactions between different stakeholders in the smart contracts-based pharmaceutical supply chain. We implement the proposed smart contract in Remix IDE using solidity language and investigate the transaction gas cost of various functions and methods.

- We present several future opportunities related to the utilization and implementation of Blockchain for the healthcare supply chain.

The rest of the study is organized as follows: Section II presents an overview of the healthcare supply chain, related works regarding the use of Blockchain and smart contracts in different systems, and an overview of different survey papers related to Blockchain-enabled healthcare. Section III presents the classification of work in the area of Blockchain-enabled healthcare supply chain. Section IV, Section V and Section VI present a review of recent works related to procurement, asset management, and improving system efficiency in the Blockchain-enabled healthcare supply chain, respectively. Section VII presents a case study in which we present a proposed smart contract along with its various functions and methods, and highlight the sequence diagram of the smart contract. Furthermore, Section VII also describes smart contract implementation on Remix IDE and presents smart contract cost-related results. Section VIII presents different open challenges and future opportunities. Finally, Section IX present the conclusions.

II. Related Work

A. Overview of Healthcare Supply Chain

The healthcare supply chain refers to the interconnection of different procedures, processes, and networks that enable the distribution of medicines and other healthcare items from manufacturers to patients. Our particular focus in this study is on the pharmaceutical supply chain which starts with the research and development of a drug. Different trials and tests are conducted to verify the effectiveness of the drug. After the verification phase, the drug is manufactured on a large scale by different manufacturers that ensure quality assurance by following different quality control procedures [39], [40], [41]. The drugs are purchased by different distributors and further sold to different pharmacies and hospitals. A drug regulation authority controls the safety and quality of the product and ensures that different regulations are met. Finally, the drug is purchased by the end customer [42], [43].

During the supply chain, different processes are involved and interaction between different stakeholders takes place. Monitoring and tracking of these processes are needed to efficiently control them [44], [45], [46]. The related data needs to be efficiently and securely stored. Moreover, the privacy of communication between stakeholders needs to be maintained. All of these issues can be handled by Blockchain and smart contracts, thus improving the efficiency of the supply chain [47], [48].

B. Use of Blockchain for Different Applications

Several works have investigated the use of IoT, Blockchain, and smart contract technology for different applications. In [3], the authors presented a smart contract validation mechanism for supply chain applications. A smart contract was created for better use of data structures in the mining process at the miner nodes.

In [5], a Secure Electronic, Health Medical Record (EHR/EMR) solution was proposed using Blockchain technology. In the proposed solution, data or medical records are shared in a secure manner utilizing various techniques such as multiple authentication schemes for improved security and access control of Medical Reports (MR), data management, and other safety requirements. The proposed technique consists of three phases, first is the authentication by using a Quantum Cryptography Algorithm (QCA), the second one is the encryption by using Advanced Encryption Standard (AES) and the last is the data retrieval by using a Secure Hash Algorithm (SHA).

In [6], the authors investigated the use of the Ethereum Blockchain platform for educational systems. A smart contract for online examination system was created using the Ethereum Blockchain. The system allows to use of the NodeJS server runtime environment and the MongoDB database system. The system utilized several examination related data to develop the smart contract.

In [7], the authors proposed a Mobile-Healthcare algorithm using the Blockchain network. The proposed algorithm develops smart contracts between doctors and patients by using Blockchain. The patients send different sensor data to the nodes participating in the Blockchain. The work minimizes the delay between the patient and the doctor in case of emergency. In a short time, the doctor can send the medical report to the patient in a secure manner. The work also discussed about the 51% attack on the system in which majority mining is done by a particular group and has control over it.

In [8], the authors proposed a relationship between big data analytics, Blockchain, and the Internet of Things (IoT). Blockchain is a secured database technology for real-time data transition and IoT is used to connect different devices, sensors, and databases over the Internet. Blockchain resolves two major problems in IoT applications, one is to develop trust between nodes, the second is to ensure the data privacy.

In [10], the authors proposed the use of Blockchain technology to create an upgraded diabetes Electronic Medical Record (EMR). The medical information was separated into two sections. The data of the medical institution was in one category, and the data of the patient was in another category. The patient's medical records were stored with authentication, privacy, and security such that no physical medical documents were required.

In [11], the authors proposed a solution for secure patient data sharing using the hyperledger fabric framework-based permissioned Blockchain network. Hyperledger fabric was used as a private Blockchain which can be programmed as required. A new member of the Hyperledger fabric must be enrolled through the Membership Service Provider (MSP). A smart contract was written in the hyperledger of fabric with the help of Chaincode.

In [12], the authors proposed the safe and reliable sharing of data between different nodes by using the Blockchain. With the help of the decentralized database, the work proposed a secure financial data sharing. In [49], the authors discussed different challenges in the supply chain and presented the solution to these problems with Blockchain technology. It was shown that the Blockchain improves the efficiency of supply chain.

In [22], the authors discussed use of Blockchain to conserve perishable food products in the supply chain. Everyone from the farm to the customer can see the temperature of the product with the use of a distributed ledger. The data in the Blockchain can not be changed. As a result, the proposed technology can reduce different types of food losses.

In [23], the authors discussed the agri-food supply chain system with different problems related to trust, lack of transparency, economic losses, and enterprise brand value. It was shown that the food industry supply chain can be improved by using Blockchain.

In [24], the challenges related to the medical supply chain were discussed. The current supply chain processes fail to provide security, transparency, and trust-like features. Also, the system is centralized and cause failure in case of any fault in the central server. By using Blockchain technology, the authors provided secure information exchange between different stakeholders. The InterPlanetary File System (IPFS) storage system was used to store, fetch, and share data in the Blockchain.

The utilization of Blockchain in vehicular networks was discussed in [25]. Data management for applications such as traffic control, route scheduling, and information exchange was enabled using Blockchain. In [26], a review of different works related to security and privacy of Blockchain was presented.

A Blockchain-based smart contract development environment was proposed in [27]. The work consists of two parts, the first part was a novel transaction framework using smart contract and second part was comparison with the current available smart contracts.

In [28], authors proposed a Blockchain based healthcare system. Every hospital uploads the patient's record on the Blockchain and with the help of a mobile application, patients or authorized users can retrieve records on the mobile. The Blockchain in the application ensures data security and data authenticity.

In [29], authors proposed the use of Blockchain's decentralized nature to handle challenges such as frequent network disconnectivity. Integrating IoT with Blockchain was proposed in [30] for reducing the appointment time of doctors. Blockchain technology provides an active feedback loop to improve the tracking of patient health related data.

In [31], authors presented Blockchain-based smart grid cybersecurity techniques. The data was protected by storing it in a Blockchain network and having it validated by peers in the same network. Advanced smart grid activities like load forecasting, local redistribution, and disaster recovery could all benefit from the validated data.

C. Comparison with Other Related Survey Papers

We present a comparison of other survey papers related to Blockchain-enabled pharmaceutical supply chains and health care in Table I. While there are many survey papers available on the utilization of Blockchain in health care, there are a limited number of reviews or survey papers on the topic of pharmaceutical supply chain. The work in [50] is focused on the advantages of Blockchain for pharmaceutical cold chain. The review in the paper is mostly related to asset management for improving the pharmaceutical cold chain.

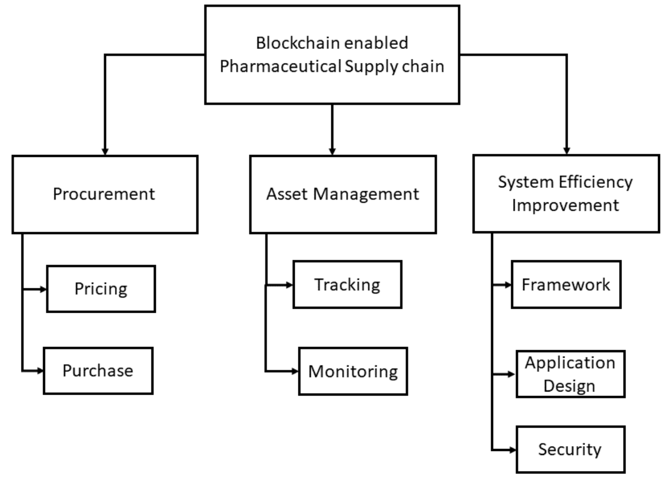

Fig. 1. Classification of work related to Blockchain-enabled pharmaceutical supply chain.

In [51], the review paper is related to handling counterfeit drugs and patient privacy using Blockchain. Similarly, the paper [52] is focused on areas of preventing counterfeit drugs, and tracking and tracing of drugs during their production and distribution life cycle.

The paper in [53] is focused on healthcare applications and presents a survey of work on topics such as data management, healthcare insurance, and supply chain. The survey paper in [54] is focused on the security and interoperability of healthcare applications using Blockchain.

Most of the current survey papers are focused on asset management of pharmaceutical supply chains or other healthcare applications. In addition, most of the review papers are from 2020 to 2022. Most of the recent survey papers are focused on other healthcare applications. Thus, the distinguishing feature of our survey paper is that it reviews three major aspects of the pharmaceutical supply chain and presents recent related works. Moreover, our study also presents a smart contract-based case study to highlight how Blockchain can be utilized for managing the pharmaceutical supply chain.

III. Classification of Work in Blockchain-enabled Pharmaceutical Supply Chain

The work related to the use of Blockchain in the Pharmaceutical supply chain can be classified into three major categories, as shown in Fig. 1. These categories include procurement, asset management, and system efficiency improvement. Further to these categories, the work within these categories can be divided into several subcategories, as discussed below.

TABLE I. Comparison of Our Survey Paper with Other Related Papers

Year	Focus	Procurement	Asset management	Efficiency improvement
2021 [50]	Pharmaceutical cold chain	✗	✓	✗
2022 [51]	Counterfeit drugs Patient privacy	✗	✓	✗
2022 [52]	Counterfeit drugs Tracking Tracing	✗	✓	✗
2020 [53]	Healthcare applications Data management Health insurance Supply chain	✗	✗	✓
2023 [54]	Security Interoperability	✗	✓	✗
Our paper	Pharmaceutical supply chain Smart contract based case study	✓	✓	✓

A. Procurement

Procurement in the supply chain refers to the purchasing of pharmaceutical items and goods. Procurement has a vital role in ensuring that high-quality medicines, vaccines, and raw materials are purchased from the correct sources at a good price.

1) Purchase: The first aspect of procurement is the purchase itself [55], [56]. This means finding the right sources to obtain raw materials. Blockchain can provide a distributed and secure database of these sources [57]. Similarly, purchasing also involves finding reliable manufacturers, distributors, and pharmacies.

2) Pricing: The second aspect of procurement is pricing in which different stakeholders in the supply chain communicate with each other to agree on the pricing of a product. Blockchain can significantly improve the pricing process as it can provide automated smart contracts to evaluate and negotiate the pricing of drugs [58], [59].

B. Asset Management

Asset management is a critical part of the supply chain as it can track and monitor the medicines and drugs during their transportation from manufacturers to distributors and then further to pharmacies. In the context of Blockchain-enabled pharmaceutical supply chain, most of the work can be categorized into tracking and monitoring of medicines [60], [61].

1) Tracking: Tracking involves the management of different medical products during the supply chain. The management includes tracking of raw materials, machinery, and equipment for manufacturing and inventory. With tracking of these products, stakeholders can find the real-time location of medical products and raw materials, and also ensure that the inventory is right quantities. Based on real-time tracking, storage requirements can also be optimized. By using different IoT sensors, Blockchain-based data management, and smart contracts, efficient and secure tracking of inventory can be managed [62], [63].

2) Monitoring: Medical products are dependent on environmental factors to maintain their quality and correct working. Factors such as temperature and humidity need to be maintained within certain thresholds so that these products work at their best. Smart contract-based solutions can regularly monitor these conditions and separate the products that do not follow the required conditions during the supply chain [64].

C. System Efficiency Improvement

Blockchain solutions can be used to improve the supply chain system efficiency such as providing secure data management and prevention against information leakages.

1) Framework: Blockchain-based supply chain framework involves designing solutions that integrate with the current pharmaceutical supply chain system. It also means designing new Blockchain-based systems and process flows to optimize the supply chain. Moreover, the development of IoT solutions, new smart contracts, and data management techniques fall under this category.

2) Application design: The application design involves Blockchain-based new or evolved versions of previous applications related to the pharmaceutical supply chain. Such applications include new payment methods, stakeholder communication, inventory management, and real-time tracking. Such applications enhance the supply chain user experience and improve the efficiency of the supply chain system.

3) Security: Data security is a key challenge for the pharmaceutical supply chain. Data related to medicines is private and sensitive, hence it is critical to find secure solutions [65], [66]. Blockchain provides an efficient data management method that can provide secure access control, immutable data record keeping, privacy of data storage, and resilience to cyber attacks [67], [68], [69].

IV. Recent Works Related to Blockchain-based Pharmaceutical Procurement

The recent work related to Blockchain-enabled pharmaceutical procurement is shown in Table II. In [1], a smart

TABLE II. RECENT WORKS RELATED TO BLOCKCHAIN-BASED PHARMACEUTICAL PROCUREMENT

Reference	Blockchain solution	Stakeholders	Procurement process	Results
[1]	Smart contract	GPO Manufacturer Distributor Healthcare provider	Stakeholder registration Admission fees Price update Price negotation Purchase order Delivery status Loyalty discount	Transaction gas cost Execution gas cost
[70]	Blockchain	Competing manufacturers Retailer	Wholesale price Purchase quanity Monetary gains	Blockchain benefit Blockchain cost
[71]	Blockchain Smart contract	Companies Wholsalers Users	Pricing Price history	Application development
[72]	Blockchain Smart contract	Vaccine manufacturer Vaccine unit	Cost sharing contract Revenue sharing contract	Increased profit Supply chain efficiency
[73]	Consortium Blockchain	Patients Manufacturers Health authorities Pharmacy	Value-based pricing	Framework development

contract is proposed that considers multiple pharmaceutical stakeholders such as Group Purchasing Organization (GPO), manufacturer, distributor, and healthcare provider. The proposed work presents detailed functions and methods that are involved in the procurement of medicines. These processes include stakeholder registration, admission fees, updating prices, negotiation of prices, purchase order development, finding the status of delivery, and getting loyalty discounts. The authors implemented the smart contracts in Solidity and evaluated their transaction gas cost and execution gas cost.

The work in [70] developed a Blockchain solution considering two stakeholders, two competing manufacturers and a retailer. For procurement, processes such as wholesale price evaluation, purchase quantity, and monetary gains are considered and related data is stored in a decentralized Blockchain. The work provides an analysis of the cost associated with Blockchain solutions along with their benefits.

In [71], a smart contract-based solution is proposed that considers companies, wholesalers, and users as stakeholders. The proposed work provides pricing methods and also stores pricing history in the Blockchain. This pricing history is stored securely and data changes are not possible. To verify the proposed idea, a mobile application is developed.

The work in [72] developed a Blockchain and smart contract-based technique for the vaccine supply chain. Vaccine manufacturers and vaccine units are the two stakeholders. Two major contracts for procurement include cost sharing and revenue sharing. The proposed technique shows increased profit and improves supply chain efficiency.

A consortium-based Blockchain is proposed in [73]. The work considers four stakeholders namely, patients, manufacturers, health authorities, and pharmacies. The pricing mechanism introduced by the work is based on the value added by each medicine. The paper presents the framework for the proposed value-based pricing mechanism.

V. RECENT WORKS RELATED TO BLOCKCHAIN-BASED PHARMACEUTICAL ASSET MANAGEMENT

The works related to pharmaceutical asset management that used Blockchain is shown in Table III. The work in [74] develops an Ethereum smart contract for asset management in which several features are available such as the quantity of boxes within a lot, pricing of the lot, and drug purchase from trusted manufacturers. A secure decentralized InterPlanetary File System (IPFS) is used as an offchain storage mechanism. Moreover, the system also uses onchain storage as well. Results show the gas cost of the developed smart contract and its security analysis.

In [75], a smart contract is developed for drugs that can be reused and resold. For the reselling application, a verification mechanism from the healthcare authority is proposed. A pricing management system including bidding for the available drugs is developed as part of the smart contract. A reputation ranking system for the resellers is also included. The advantage of this system is that buyers can view the previous selling history and reviews of the reseller. The evaluation of the proposed smart contract presents its gas cost and security analysis.

The work in [76] proposes an IoT and Blockchain integration for asset management. For cost cutting, the minimum distance of the transport route to deliver the medicines is calculated. A mathematical model for route selection from manufacturer to end user is presented. The work also considers environmental change monitoring using IoT sensors. In case any factor is beyond the allowed threshold, a notification is sent to the product owners and customers. Results show reduced latency and response time from the Blockchain network when

TABLE III. Recent Works Related to Blockchain-based Pharmaceutical Asset Management

Reference	Blockchain solution	Asset management methods	Results
[74]	Ethereum Blockchain Smart contract	Quantity of boxed within a lot Price of the lot Drugs from trusted manufacturer	Gas cost of smart contract Security analysis
[75]	Ethereum Blockchain Smart contract	Reselling of drugs Verification from healthcare authority Pricing management Bidding Reputation ranking of resellers	Gas cost of smart contract Security analysis
[76]	Blockchain	IoT integration Minimum distance of supply chain Mathematical model Environmental change monitoring Notification to owners and customers	Improve product life time Reduce response time
[77]	Blockchain	Forward and reverse supply chain Reduce transportation cost in forward chain Reduce recall time in reverse chain Faulty drugs recall	Reduced latency Improved throughput
[78]	Smart contract	IoT integration All data signed by stakeholders Stored in Blockchain Record of drug production life cycle	Security analysis Communication cost analysis

the proposed scheme is used. In addition, product lifetime is improved as well.

In [77], the concept of forward and reverse supply chains is introduced and implemented on a Blockchain. Authors develop mathematical models to optimize the supply chain. In the forward direction, the cost is reduced in terms of transportation and inventory costs to supply medicines from the manufacturer to the end user. The model considers vehicle type, reliability of the vehicle, and delivery distance to optimize the cost. In the reverse direction, travel time to recall faulty medicines is reduced. The Blockchain implementation is presented and the work shows reduced latency as compared to the other techniques.

The work in [78] presents a smart contract with IoT integration for asset management. Using IoT sensors, the data related to the drug production life cycle is shared and stored in a Blockchain. Furthermore, the data is signed by all the stakeholders so that no change in it can be made. Results show that the proposed smart contract achieves secure data storage. Results related to communication cost analysis are also presented.

VI. Recent Works Related to Blockchain-based Pharmaceutical System Efficiency

The works related to Blockchain-based pharmaceutical system efficiency improvement is shown in Table IV. In [79], a smart contract framework is developed for the vaccine supply chain and life cycle which improves the system's security and reliability. The proposed system ensures secure record keeping and also enables authentication of all stakeholders. Results show that the proposed framework achieves improved throughput and reduced lost number of data blocks.

The work in [80] proposes a hybrid Blockchain-based framework including both public as well as private Blockchains. A mobile application is developed for all stakeholders. The record-keeping of the drug life cycle is maintained and helps in the detection of counterfeit medicine. Furthermore, IoT is used for monitoring medicines and cryptocurrency is used for purchasing medicines. The work also shows an implementation of the proposed framework.

In [81], a permissioned Blockchain-based framework is developed to enhance the security of the pharmaceutical supply chain. The work proposes the use of secure identity for stakeholders. Similarly, drug information storage is also carried out using secure Blockchain. A secure method is proposed for updating and cancellation of transactions. The system is shown to improve throughput and reduce transaction latency.

The work in [82] proposes a consortium Blockchain to manage the pharmaceutical supply chain. A consensus algorithm is proposed for large-scale traceability of the supply chain. Furthermore, the system is divided into nodes and grouping is done to manage the system efficiently. A ranking system is developed to select trustable nodes to manage transactions in each group. The proposed system improves throughput and reduces transaction latency.

In [83], smart contracts are proposed for dynamic access control in the pharmaceutical supply chain. The work allows the management of permissions at the micro level. Two techniques are used in the proposed system. The first one is the Role-based Access Control (RBAC). This technique is combined with the second Attribute-based Access Control (ABAC) mechanism. The proposed access control improves system throughput in terms of transactions per second [83].

TABLE IV. RECENT WORKS RELATED TO BLOCKCHAIN-BASED PHARMACEUTICAL SYSTEM EFFICIENCY IMPROVEMENT

Reference	Blockchain solution	Framework features	Results
[79]	Public Blockchain Smart contract	Security of vaccine supply chain Smart contract for vaccine life cycle Secure vaccine record keeping Authentication of stake holders	Improved throughput Reduced lost blocks
[80]	Hybrid Blockchain	Mobile application for stake holders Counterfeit medicine detection IoT for medicine monitoring Cryptocurrency for purchase	Framework Implementation
[81]	Permissioned Blockchain	Secure identity of stake holders Secure drug information storage Secure transaction update or cancellation	Improved throughput Reduced transaction latency
[82]	Consortium Blockchain	Consensus algorithm for large scale traceability Divide nodes in to groups Ranking system to select trusted management nodes	Improved throughput Reduced transaction latency
[83]	Smart contract	Dynamic access control Manage permissions at micro level Combination of RBAC and ABAC	Improved throughput

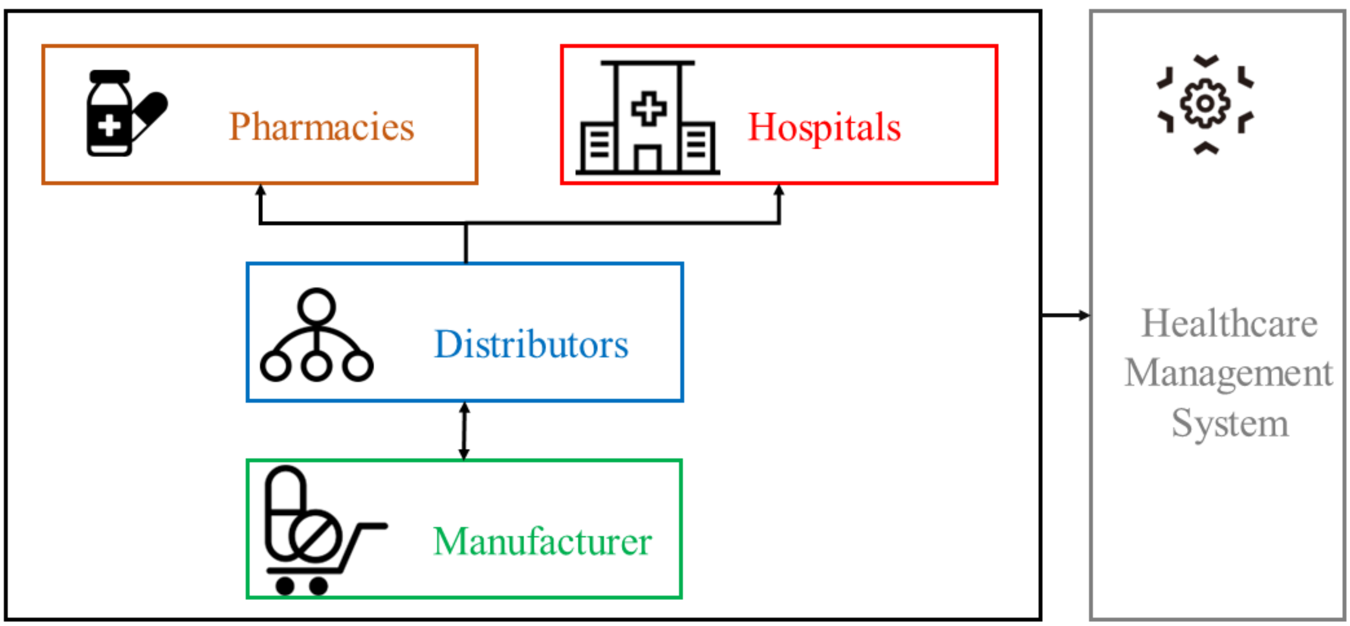

Fig. 2. Components of pharmaceutical supply chain.

VII. CASE STUDY: A PHARMACEUTICAL SMART CONTRACT FRAMEWORK

In this section, we provide a case study related to the pharmaceutical supply chain.

A. Framework

We present a framework for a pharmaceutical supply chain that uses Blockchain-based smart contracts, as shown in Fig. 2. The proposed system has five stakeholders: a Healthcare Management System (HMS), Manufacturers, Distributors, Pharmacies, and Hospitals, all of whom are part of the same decentralized Ethereum-based network. In the contracting process, we use Blockchain technology to provide transparency and data immutability.

B. Components of Smart Contract

There are five main components of the proposed smart contract, where each component is a stakeholder in the system. The role and functions of each stakeholder are described below:

1) Healthcare management system: A Healthcare Management System (HMS) is the centralized server/database that manages the healthcare records, medical processes, and pharmaceutical smart contracts. HMS interacts with different

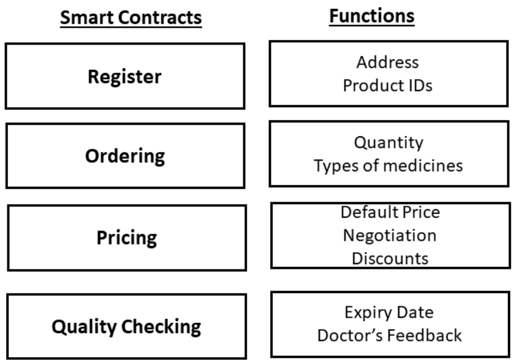

Fig. 3. Different smart contracts and functions for pharmaceutical supply chain.

stakeholders in the pharmaceutical supply chain and manages the large-scale distribution and purchase of medicines. All other stakeholders register themselves in the database of HMS to allow efficient management of the purchase process.

2) Manufacturer: A manufacturer develops and distributes medical and pharmaceutical supplies to the healthcare providers.

3) Distributor: A distributor picks the products from the manufacturing company and sends them to the service providers, i.e., pharmacies and hospitals.

4) Service provider: Pharmaceutical service providers include different pharmacies and hospitals. They purchase medicines from different distributors.

It should be noted that the distributors interact with the manufacturers whereas the service providers communicate with the distributors to enable the supply chain.

C. Description of Smart Contracts

We present the description of different smart contracts managed by the HMS in Fig. 3. There are four major categories of smart contracts, namely registration, ordering, pricing, and quality checking.

The Registration contract is used by all the stakeholders. Each stakeholder registers itself in the central HMS as a manufacturer, distributor, pharmacy, or hospital. The registration is managed using a unique address allocated to each stakeholder. Moreover, each product (i.e., medicine) is also registered and provided a unique ID. Once the registration process is finished, the central database of HMS has a city-wide record of each stakeholder in the supply chain.

The ordering contract is used by the stakeholders to place their orders. Separate ordering contracts are deployed between manufacturers and distributors and between distributors and service providers. The ordering contract has functions to enter the quantity of medicines and type of medicines. Each medicine is categorized into different types for the ease of storing in the database.

The pricing contract enables the purchase of medicines and finalizes the orders at a particular agreed price. It allows manufacturers and distributors to set a default price for medicines. Also, it manages the price negotiation between the stakeholders. Finally, the discounts can be issued on bulk purchases of medicines or any other annual sales event. As in the ordering contract, there are different pricing contracts between each stakeholder.

The last contract is the quality checking contract which is a key feature of the smart contract. This contract can offer many benefits in terms of maintaining the quality of medicines and automating them without the need for manual checking. Conditions such as medicine expiry date can be checked to throw away expired medicines. Different notifications can be issued for medicines that are near the expiry. Similarly, a doctor's feedback on a particular medicine is also incorporated to improve the quality-checking mechanism.

D. Implementation and Cost Analysis

In this section, we present the implementation of the proposed smart contract and its associated cost analysis.

1) Implementation: To implement the proposed smart contract between different stakeholders, we define the functions as discussed in the previous subsection. For this purpose, the Remix Ethereum platform is used. Remix IDE is an open-source platform to write, deploy, and test smart contracts. Remix IDE supports Solidity language, so all the smart contracts are written in the Solidity language. For the Graphic User Interface (GUI) in Remix Ethereum, a Java Virtual Machine (JVM) Environment is available. Ethereum helps in developing decentralized applications and development features such as rapid development, security, and interaction between applications.

We present the implementation of different contracts in the following subsections.

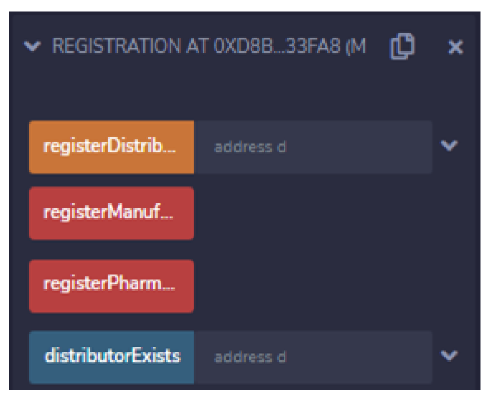

Fig. 4. Registration contract.

2) Registration contract: The Registration contract is shown in Fig. 4. The owner of this contract is HMS which will deploy this contract on its server. This contract deals with the registration process of manufacturers, distributors, pharmacies, and hospitals.

As shown in Fig. 5, this contract has different functions to check issues such as whether the addresses are already used or are available, whether the registration fee is sufficient or not, etc.

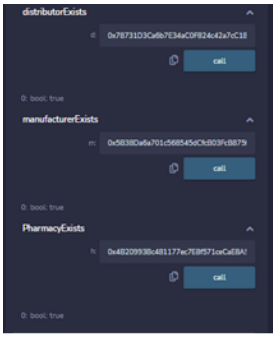

Fig. 5. Check Registered Status

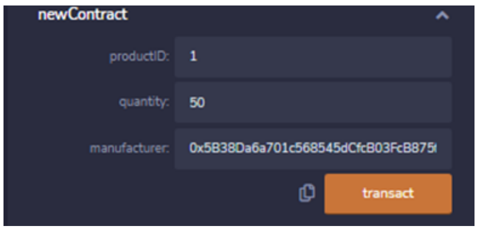

Fig. 6. New contract.

3) New contract: In this contract, the active members are the sellers and buyers, i.e., distributors can buy from sellers or service providers can buy from distributors. For example, for a new contract, options such as the product ID, quantity, and manufacturer address can be given, as shown in Fig. 6.

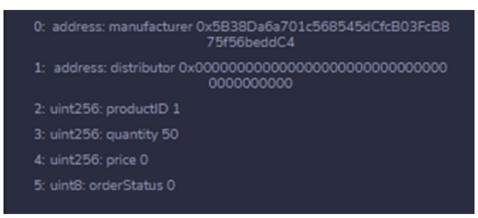

Fig. 7. Contract details.

The built-in keccak256 cryptographic function in Solidity is used for the contracts. Keccak256 converts any number of input arguments to a 32-bit hash. Three arguments (timestamp, contract deployer address, and sender address) are used in this function to generate the contract Address.

We can check the contract details by using the address of the contract, as shown in Fig. 7. The output price and order status, both are updated after the price negotiation, as shown in Fig. 8.

Based on the quantity required, the seller submits a proposed pricing. The potential buyers can show their interest in the item and a mapping with the seller is formed. As an example, the assignDistributor function is used to send orders from the distributor to the service provider, as shown in Fig. 9. This function takes two arguments, contract address and distributor address.

4) Cost analysis: The cost analysis of the smart contract can be conducted by evaluating the gas cost which measures

Fig. 8. Updated contract details.

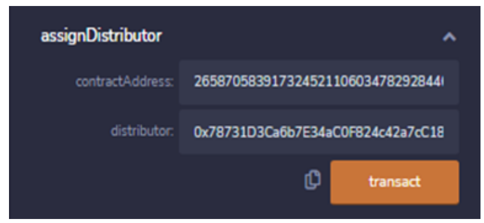

Fig. 9. Assign distributor.

the computational power required for different smart contract functions. Ehereum's native currency ether (ETH) is used for gas payments. The prices of gas are expressed in gwei, which is unit of Ether. One gwei is 10^{-9} ETH. In our case,

- GAS is the unit of computation.
- Gas price is the Ether/Gas (Amount of ether that can be paid per gas)
- Gas limit is the maximum value of gas to be used for a transaction
- Block gas limit is set by the network

The transaction fee is given by the following equation:

Transaction fee = gas used × gas price

Transactions of high gas prices will be processed faster than the low gas prices.

In the Ethereum smart contract, calling different functions require different amount of GAS. GAS is the unit of money in the Ethereum smart contract. GAS depends upon the function complexity and the time. The client can set the upper limit of gas, so for any function, the client does not spend an over amount of gas. So, if the client sets more gas limit, then the transaction will done faster. For measuring the cost, the Ethereum gas station can map the function cost in terms of gas to the corresponding currency amount (such as US dollars).

In Table V, the transaction cost of each function that is used in the registration smart contract is shown. From the above table, the highest transaction cost is for the methods used for the registration of different stakeholders with the HMS. Similarly, registering medicine products with their IDs also incurs a high transaction cost. The transaction cost is reduced for checking the existence of stakeholders in the database.

TABLE V. Cost of Registration Smart Contract Methods

Method Name	Transaction Gas Cost
registerManufacturer	49338
registerDistributor	49338
registerPharmacy	49338
registerHospital	49338
ManufacturerExist	24042
DistributorExists	24042
PharmacyExist	24042
HospitalExist	24042
RegisterProduct	39259

TABLE VI. Cost of Ordering Smart Contract Methods

Method Name	Transaction Gas Cost
InitiateOrder	58581
SetQuantity	37428
SetMedicineType	43595

In Table VI, the cost of ordering contract methods are shown. There are three methods in this smart contract. The lowest transaction cost in ordering smart contracts is for setting a single order feature. In comparison, initiating a complete order with all the input features renders a higher cost.

TABLE VII. Cost of Pricing Smart Contract Methods

Method Name	Transaction Gas Cost
SetDefaultPrice	**35621**
RequestNegotiatePrice	**76023**
RespondNegotiatePrice	**45489**
RequestDiscount	**69840**
RespondDiscount	**39284**
assignManufacturer	**58581**
assignDistributor	**58581**
contractStatus	**43595**
newContract	**113207**

In Table VII, the cost of pricing smart contract methods is shown. The first method is the setting of the default price by the entity, that is selling the medicines. The next two methods are used to negotiate prices. The buyer first requests a price that it can offer. Afterwards, the seller either agrees to the buyer's price or sends its final price threshold. Similarly, buyers can request a discount based on membership, etc. The seller responds to it either by agreeing to the discount or sending an updated price it can offer. In addition, there is a method to assign manufacturers to the distributors. Also, there is a method to assign distributors to a pharmacy or a hospital. Moreover, the highest transaction cost is for the newContract method which signs the contract between two stakeholders based on agreement on pricing and quantity. The status of the contract can also be checked using a separate method, as shown in Table VI.

In Table VIII, we show the cost of Quality Checking methods for medicine expiry checks and also for sending doctor's feedback.

TABLE VIII. Cost of Quality Checking Smart Contract Methods

Method Name	Transaction Gas Cost
CheckMedicineExpiry	40960
SendDoctorFeedback	57346

It should be noted that we show the gas cost of different methods for different smart contracts. Gas cost (Gwei) depends on the complexity of methods and time. From the results, it can be seen that the gas cost (Gwei) of the newContract method is greater than all other methods of different smart contracts.

VIII. Future Opportunities

In this section, we present future opportunities related to the Blockchain-enabled healthcare supply chain.

A. *Supply Chain Health Monitoring Metrics*

The working range of healthcare supplies in terms of temperature, humidity, and other factors varies from product to product. It is critical to design supply chain health monitoring metrics that consider all of these different parameters. Instead of using various parameters to find thresholds and conditions for smart contracts, it is more effective to use some of these health monitoring metrics. This way smart contracts will be easier to design with less number of functions and methods. This will also reduce the gas cost and transaction cost of the smart contracts.

To develop these health monitoring metrics, mathematical models may be needed that take into account thresholds of parameters with different ranges. A major challenge in this regard is that all these parameters have different operating ranges and units. Hence, it is challenging to design a single metric that gives accurate values of health monitoring. In this regard, multi-criteria decision-making algorithms such as Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) may be utilized.

B. *Gas Cost Reduction in Smart Contracts*

Smart contracts for supply chains can automate various procedures and processes. However, the major cost associated with it is the gas cost for Blockchain transactions [84], [85]. This cost may increase the overall budget of the supply chain and eventually have an impact on the prices of medicines and healthcare supplies [86], [87].

A major challenge is to reduce the gas cost of smart contracts by using efficient implementation techniques in terms of variables and data structures [88], [89]. The code of smart contracts needs to be optimized for efficient working and reduced transactions. Moreover, the number of methods can be reduced by efficient smart contract design considering the application [90].

C. Interoperability

Blockchain-enabled healthcare solutions need to be inoperable and work with different manufacturers, distributors, pharmacies, and hospitals [91], [92]. Each of the stakeholders has different priorities and preferences regarding the supply chain solutions. Factors such as cost, reliability, and efficiency are considered by each stakeholder, and decisions are made to select a particular solution based on their available budget [93], [94].

It may also happen that different stakeholders may be using different types of smart contracts and Blockchain. The developed smart contracts can be standardized and work for different types of Blockchain and associated environments [95], [96]. Moreover, algorithms and protocols are needed to communicate among Blockchains for transferring of data and tokens [97].

D. Smart Contracts for Healthcare Supplies

While the focus of the current study is on the pharmaceutical supply chain, there are many other types of items and supplies associated with healthcare. For example, procurement and distribution of health-related machine equipment such as ventilators, radiology machines, etc. Similarly, healthcare supplies also involve the distribution of surgical equipment, supplies used in laboratories, and diagnostic items [98], [99], [100].

While pharmaceutical supply chains are more focused on considering environmental factors to maintain the working condition of medicines, other healthcare supplies such as equipment may be more sensitive to road conditions and wear and tear during transportation. Thus, it is challenging to design different smart contracts for different healthcare supply chains considering individual features and characteristics [101], [102].

IX. Conclusion

This study presents a review of Blockchain-enabled healthcare and pharmaceutical supply chains. The study provides an overview of the healthcare supply chain and the uses of Blockchain in different applications. In comparison with the other survey papers on this topic, this study classifies the work done in this area into three major categories. The first is the work related to procurement, the second category is the work related to asset management and the last category is the work related to system efficiency improvement. A survey of recent work in these three areas is presented. The work also presents a case study in which we propose a smart contract involving different stakeholders for the pharmaceutical supply chain. The work describes in detail functions of the proposed smart contract framework. Also, we present details of smart contract implementation and transaction cost analysis. Lastly, we also identify major future research opportunities related to the blockchain-enabled healthcare supply chain.

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