RESEARCH PAPER

Blockchain-Based Secure and Transparent Vaccine Delivery using Smart Contract Framework

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ABSTRACT

In conventional vaccine delivery systems, information related to vaccine production, storage, transportation, and distribution is often fragmented and inaccessible to all stakeholders, making the system vulnerable to data manipulation, lack of transparency, and inefficiencies. During biological disasters or pandemic outbreaks, the rapid development and equitable distribution of vaccines are critical to controlling the spread of disease. The success of such large-scale vaccination programs depends on the availability of a secure, transparent, and interoperable distribution network that can be monitored and verified by all authorized stakeholders, including manufacturers, distributors, healthcare providers, and regulatory authorities. This work proposes a blockchain-based framework that leverages smart contracts to provide secure and transparent management of the vaccine supply chain. The proposed prototype facilitates transparent vaccine registration, storage monitoring, distribution tracking, and vaccination record management while enabling beneficiaries to self-report post-vaccination adverse effects. By ensuring data integrity, traceability, and decentralized access control, the proposed framework enhances stakeholder trust, minimizes the risk of data tampering, and improves the overall efficiency and reliability of vaccine delivery.

Keywords**:** Blockchain, Smart Contract, Biological Disaster, Pandemic Outbreak, Vaccine Delivery
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INTRODUCTION

The biological disasters or pandemic outbreaks are incredibly simple to transmit and puts a lot of strain on the society and healthcare system at large[1]. Fighting the pandemic has necessitated tremendous efforts. In this situation, the rapid deployment of a vaccine is vital for pandemic control [2]. To manage the supply chain for biological disaster vaccines, various problems must be overcome in terms of data transparency, trackability and traceability, immutability, audit, and trust[3, 4]. The use of technology has become important in helping to meet human needs [6, 7, 8]. The blockchain plays an important role in the healthcare sector by effective data sharing between healthcare providers. Here, the records are updated as the vaccines are transferred from one entity to another in the supply chain, thus providing transparency throughout the delivery [9].

A blockchain-based framework is implemented in the proposed work to facilitate and ensure vaccination delivery that is completely trackable and traceable, transparent, auditable, dependable, trustworthy, and secure[10]. A security and cost analysis is carried out to determine the affordability and resilience of the proposed blockchain-based solution in the face of potential security threats and flaws [11, 12].

The vaccine specifics will be kept in the blockchain using smart contracts written in the Solidity programming language. These smart contracts are tested using Remix- Ethereum IDE before being deployed using True framework on the Ethereum blockchain (Ganache) network. We use metamask via the injected web3 to publish the smart contract to the ethereum blockchain [13].

The significant contributions of the proposed system are as follows:

- To manage quality in the distribution of vaccines and reduce the fraud of counterfeit medicines.
- Increase efficiency and simplify the whole delivery process by automating the purchase, accurate cost, and preventing data tampering using hashing.
- Records are updated as the vaccines are transferred from one entity to another in the supply chain, thus provides transparency throughout the delivery process.

LITERATURE SURVEY

Antal et al. presented a blockchain technology-based system for ensuring data reliability and immutability in the case of vaccination beneficiary registration, preventing identity theft and impersonation[14]. Smart contracts are created to manage and monitor correct vaccine supply conditions against vaccine producers' safe handling requirements, making all network peers aware. With the COVID-19 vaccine distribution tracking needs in accordance, a prototype was built utilising the Ethereum test network, Ropsten. The Etherscan is used to check and confirm the results of each on-chain action, exhibiting various features of the proposed system such as registration of vaccination actors and safety rules, vaccine tracking, and delivery.

The use of various cutting-edge developments to build the delivery systems, such as RFID tags, sensors, and smart contracts to maintain vaccine quality requirements. Sunny et al. designed a framework for improving visibility and providing a transparent supply chain, and tracking the temperature and humidity of the vaccines throughout the supply chain using smart contracts[15]. The Ethereum ecosystem's Contract Application Binary Interface (ABI) is used to communicate with contracts from both inside and outside the blockchain and allow contract-to-contract interaction.

Blockchain technology and smart contracts can prevent counterfeit drugs since the vaccine's journey can be tracked from manufacturer to pharmacy. Transparency is the extent to which all entities have shared access and understanding of product-related info. IoT based container captures information like temperature, pressure, location, humidity, as proposed by Azzi et al.[16]. As a future viewpoint to ensure transparency, two smart contracts can be deployed. One for keeping track of expiration date of the Vaccines and the other for storing the Vaccine related data. If the agreed clause is violated, corresponding info will be broadcasted to the entire blockchain network. The expiration date of each brand and batch of medicine can be noticed to supply chain members.

In the health and medical industry, information management is still a challenge. As a result, a unique intelligent system for vaccination supply chain supervision is required. Radio-frequency identification (RFID) is a safe and well-established technology that is commonly utilised in public transportation and membership cards. As proposed by Yong et al., this technology can replace the number system used in traditional vaccine systems, which can be easily counterfeited and cause the hidden danger of forged records[17]. To improve the vaccine accountability and track vaccine expiry, smart contracts can be used. By using smart contracts, vaccine expiration can be easily determined by comparing the initial vaccine details entered during the time of dispatch with that of the details entered in each phase of the supply chain, thereby helps in maintaining the quality of vaccine products.

In terms of product visibility, tracking, and process automation, blockchain technology in supply chain and logistics provides a lot of advantages. As proposed by Hasan et al., smart containers can be employed with a blockchain-based technology for shipment supply chain management[18]. The approach uses the Ethereum blockchain's smart contract characteristics to regulate and control the relationship between the shipment's transmitter and recipient, as well as offer details on system interaction between members of the supply chain. Using web3 API, the client can interact with the blockchain and access and retrieve the functions

stored in the smart contract, ensuring that the details provided in each phase are accurate and matches that of the initial product details, failing which the package gets aborted.

A use case for blockchain technology in healthcare was presented by Clauson et al.[19]. These use cases can be applied to use smart contracts to enhance trust and transparency. Sharma et al. employed smart contracts to determine the expiration of vaccines, which helps to preserve product quality [20].

Abbas et al. developed a blockchain system combining machine learning and smart contracts [21]. The recommended blockchain approach can improve vaccine tracing while also preventing fraud.

Haq and Esuka presented a system for the pharmaceutical industry to track drugs from production to delivery to patients [22]. A medicine's effect on a patient will be noted for future use. Only authorized parties will be allowed to enter the network and submit information to the blockchain that will be maintained on a permissioned blockchain.

MATERIALS AND METHOD

As shown in Figure 1, initially, all the entities in the supply chain network agree to a contract that contains vaccine-related information and the price. After the contract is signed and initiated by all entities, the manufacturer creates a new batch of medicines and updates the batch details in the blockchain. Transporter receives details after each entities updates the vaccine details and is ready to be shipped to the next entity. It is then shipped to the distributor through Transporter, and the quality check is done.

The distributor updates the vaccine delivery status and then ships it to the next entity in the supply chain through the transporter. This process is continued until the vaccine reaches pharma and a particular batch of medicine is successfully delivered. If any of the details entered in each phase is incorrect, then all the entities get notified, leading to the smart contract violation. Upon successful vaccine delivery completion, the amount wallet address) and the vaccine batch id will be emitted and recorded in the transaction logs. specified in the contract gets credited automatically to each participating entity.

Registration of the Entities:

The objective of the Entity registration, which the admin does, is to provide the Authenticity to the proposed system through which only an authentic person can add data to the Blockchain network, which will then be recorded in the transaction logs. Once the admin registers the user as an entity, the admin will assign roles to each of the added entities such as supplier, manufacturer, wholesaler, distributer, and pharmacy. Once the role is assigned to each of the entity, then the entities are allowed to add vaccine-related data into the network. Once the user is added and the role is assigned to each of the entities, event userUpdate, userRoleUpdate will be triggered, which updates the smart contract status on the transaction logs visible to all entities on the supply chain.

The entity-related records are stored in the reference variables defined in the Storage smart contract shown in Pseudo code 1. The records are stored in structures, which contain the pointers for accessing each entity-related record shown in Pseudo code 2.

Creating Vaccine Batches:

In the proposed system, Admin will create the vaccine batches that will then be transferred to the intended pharmacy shown in Pseudo code 3. Each of these created batches has its own batch Id that uniquely identifies them and is computed using keccak256 hashing function based on the current timestamp, which is then converted to address type value. This batch details contain information related to the quantity of the vaccine that has to be transferred and the wallet address of all the involved entities in the supply chain.

Once the details are filled, and the admin creates the batch, nextAction value, which holds the next entity details, will be set to the primary entity i.e., the raw material Supplier. This nextAction value is updated each time the entities update the vaccine delivery details onto the network. Event CreateVaccineBatch with the user address (admin

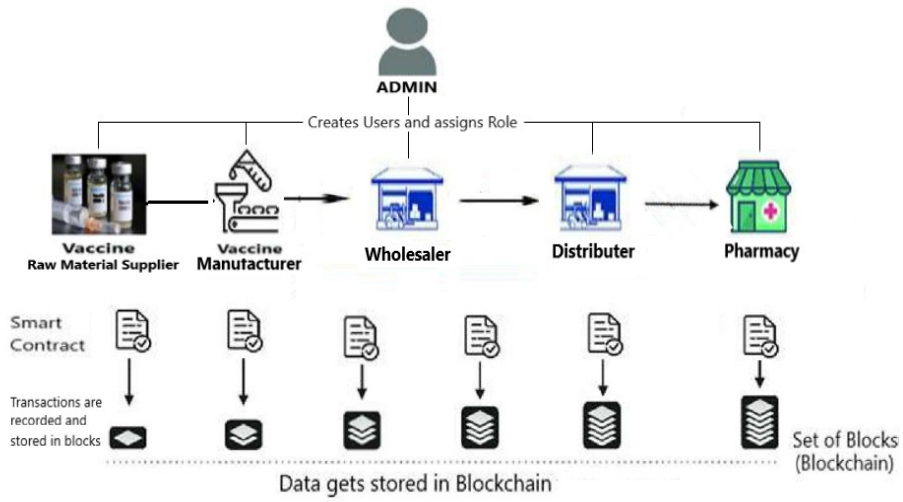

Figure 1. Architecture Diagram of Vaccine Delivery System

Pseudo Code 1: Storage Smart Contract

1. # Declaring the variables to hold entity related records
   user // reference variable to hold user related records in a structure
   basic_Details // reference variable to hold Batch related records in a structure
   supplier // reference variable to hold supplier records in a structure
   manufacturer // reference variable to hold manufacturer related records in a structure
   wholesaler // reference variable to hold wholesaler related records in a structure
   distributer // reference variable to hold distributer related records in a structure
   pharma // reference variable to hold pharmacy related records in a structure
2. Initializing the struct pointers
3. #Defining the getter and setter function for each of the entity
   Function getUserRole(user_address)
   return user_Role
   End function

   Function getNextAction(batch_no)
   return next_Action
   End function

   Function setUser(user_details)
   user = user_details
   return true
   End function

   Function getUser(user_address)
   return user
   End function

Pseudo Code 2: SupplyChain User Smart Contract

1. Define the Events
   event UserUpdate(user,name, contact,role)
   event UserRoleUpdate(user,role)

2. Define SupplychainStorage reference variable
3. Call the getter setter functions defined in Storage contract and emit the Events

```
Function updateUser(user_details)
   status= Call SupplychainStorage.setUser with user_details
   emit UserUpdate Event
   emit UserRoleUpdate Event
   return status
End function

Function getUser(user_address)
   status= Call SupplychainStorage.getUser with user_address
   return status
End function
```

Pseudocode 3: Vaccine SupplyChain Smart Contract

1. Define the Events

```
event CreateVaccineBatch(user,batch_no)
event DoneSupplying(user,batch_no)
event DoneManufacturing(user,batch_no)
event DoneWholesaling(user,batch_no)
event DoneDistribution(user,batch_no)
event DonePharmaDelivery(user,batch_no)
```

2. Define the modifier
3. Define SupplychainStorage reference variable
4. Call the getter setter functions defined in Storage contract and emit the Events

```
Function getNextAction(batch_no)
   action= Call SupplychainStorage.getNextAction with batch_no
   return action
End function

Function getBatchDetails(batch_no)
   action= Call SupplychainStorage.getBasicDetails with batch_no
   return action
End function

Function addBatchDetails(batch_Data)
   batch_no=Call SupplychainStorage.setBatchDetails with batch_Data
   emit CreateVaccineBatch((user,batch_no)
   return batch_no
End function
```

Adding Vaccine Related Data by the Entities:

The goal, in this case, is to allow the entities to add vaccine related data into the blockchain network, which will be visible to all the peers on that network, thereby provide transparency throughout the delivery process. Figure 2 shows the sequence of activities that takes in the proposed vaccine delivery system using smart contracts.

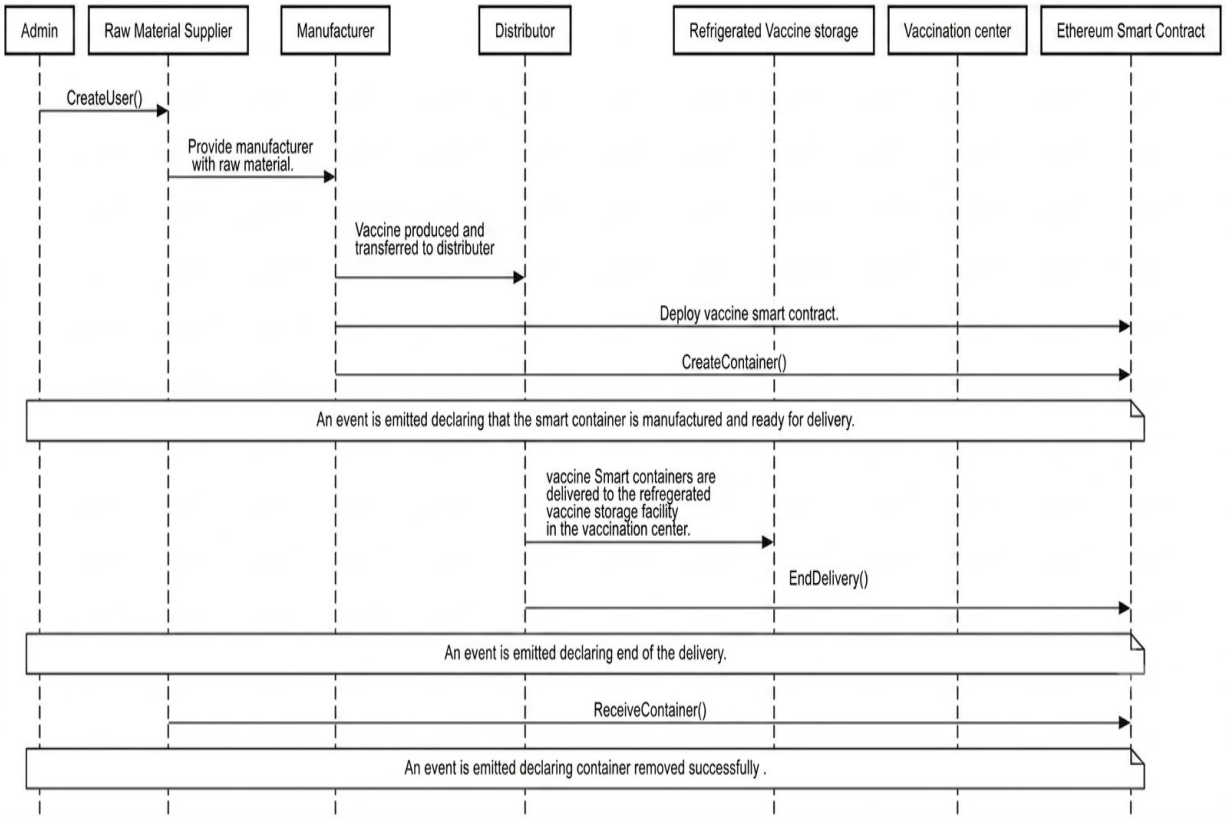

Figure 2. Interactions among Different Entities of Proposed System

For each entity trying to add the vaccine data, we define a modifier named isValidPerformer which uses the keccak256 hashing function to check whether the user is valid to perform the transaction. The hash value is computed for the user's role, which is then compared with the hash value of nextAction value. In this way, vaccine data updation happens in sequential order, one entity after the other. It also prevents tampering with the data by any of the entities. In addition to that status of the data addition (true or false) will be returned at the end of each transactions.

To update the transaction logs on the blockchain network, events such as DoneSupplying, DoneManufacturing, DoneWholesaling, DoneDistribution, DonePharmaDelivery will be emitted with the user wallet address who have performed a transaction and the batch number for which the changes were made. Thus, all the entities nextAction value will be set to the next entity when the previous entity adds the vaccine details into the network.

will be aware of whatever changes the peers make in the blockchain network. For each transaction, a timestamp will be recorded along with the shipper and receiver wallet address, cost of the vaccine package, shipper and receiver name, description of the package. When the transaction is initiated, getter and setter functions defined in the smart contracts for each of the entities will be called and executed automatically, thus provides accuracy in the data updation process shown in Pseudo code 4. Once the vaccine package is successfully delivered to the pharmacy, upon acknowledgment by the pharmacy, the nextAction will be set to Done, which indicates the completion for that particular batch id.

Pseudo code 4: Smart Contract for Adding Vaccine Data

```
Function updateManufacturerData(batch_Data)
   status=Call SupplychainStorage.setManufacturerData with batch_Data
   emit DoneManufacturing event
```

```
    return status
End function

Function getWholesalerData(batch_no)
    action=Call SupplychainStorage.getWholesalerData with batch_no
    return action
End function

Function updateWholesalerData(batch_Data)
    status=Call SupplychainStorage.setWholesalerData with batch_Data
    emit DoneWholesaling event
    return status
End function

Function getDistributerData(batch_no)
    action=Call SupplychainStorage.getDistributerData with batch_no
    return action
End function

Function updateDistributerData(batch_Data)
    status=Call SupplychainStorage.setDistributerData with batch_Data
    emit DoneDistribution event
    return status
End function

Function getPharmaData(batch_no)
    action=Call SupplychainStorage.getPharmaData with batch_no
    return action
End function

Function updatePharmaData(batch_Data)
    status=Call SupplychainStorage.setPharmaData with batch_Data
    emit DonePharmaDelivery event
    return status
End function
```

RESULTS AND DISCUSSION

The smart contracts tested on Remix IDE individually and later deployed them on Ganache (Blockchain visualization Framework) to evaluate our blockchain-based system. We have used the default accounts which are provided by default in Ganache, by considering them as individual entities on the supply chain. We have hosted the GUI of this proposed system locally using XAMPP. We have used the truffle framework for the deployment of smart contracts on the Blockchain network.

Smart Contract Deployment:

We start by deploying the smart contracts on the Blockchain network using the truffle framework shown in Figure 3.

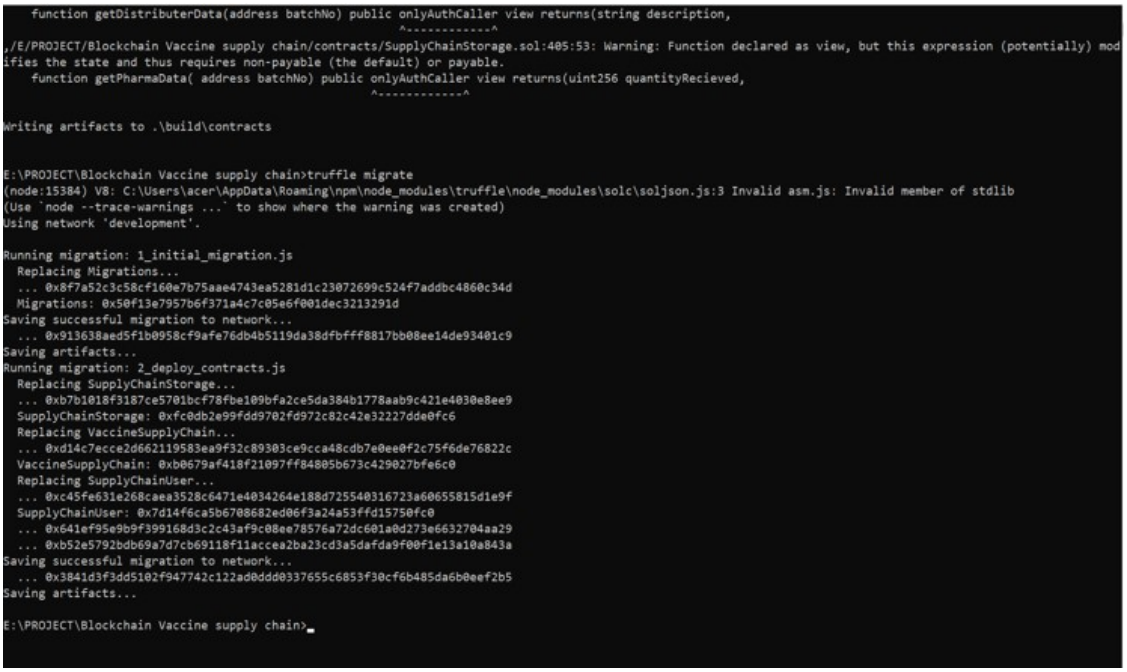

Figure 3. Smart Contracts Deployment

Registering User and Assigning Role:

Smart contract will be called when the user is created, and the admin assigns a role which is shown in Figure 4. Admin must use his own Ethereum address to sign the transaction that triggers the smart contract deployment, registering the users and assigning them a particular role.

Figure 4. Blockchain Transactions for User Creation and Assigning Roles by Admin.

When the users are created, and the admin assigns roles, events are emitted and recorded in the transaction logs shown in Figure 5.

Figure 5. userUpdate and userRoleUpdate Events Emitted and Recorded in Transaction Logs.

Vaccine Batch Creation:

Next, when the admin creates the vaccine batch, smart contracts will be triggered which is shown in Figure 6. Admin should sign the transaction for creating the batch, after which the batch id will be generated, and entities can add vaccine data when it is transferred.

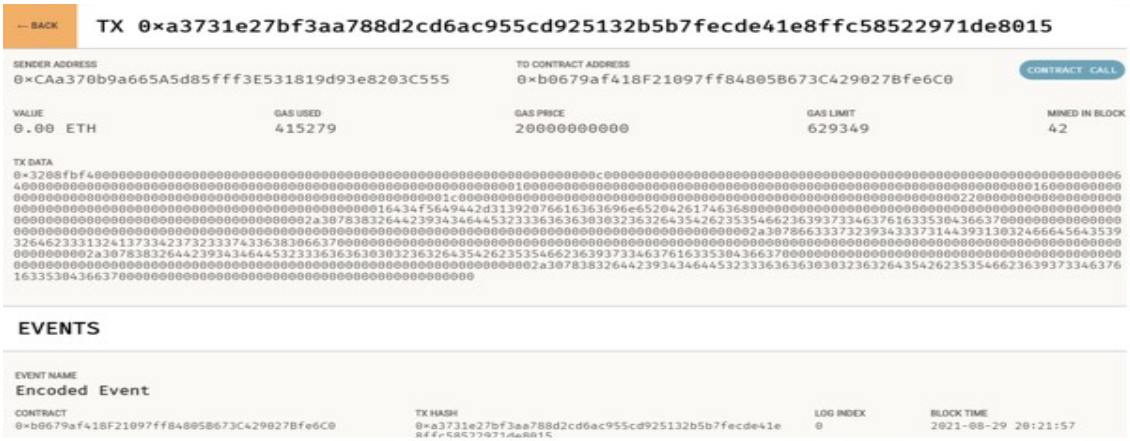

Figure 6. Blockchain Transactions for Vaccine Batch Creation.

Once the creation of the batch is complete, entities can login and update the vaccine data as and when they receive it in a sequential manner (order of updation happens from Supplier to Pharmacy) according to how the entities receive the vaccine package. Here we use metamask for signing and initiating the transactions and connecting with the blockchain environment. For testing, we use the default wallets that are already available on Ganache for different entity logins. Once the vaccine batch is created, the first entity in the supply chain i.e., Raw material supplier will be notified, and once he ship's the raw material to the manufacturer, he will add details of it onto the blockchain network, which will be recorded as a transaction and stored in the blocks which are visible to all the entities.

Figure 7. Transaction Signed by the Supplier which is Stored in Blocks in Blockchain Network.

In Figure 7, the supplier had initiated a transaction signed by him and has added the vaccine raw material data into the blockchain network, which will help us be visible to all the entities. Once the manufacturer receives the raw material, he will update the data by signing a transaction, and this process continues for all the entities. At last, when the pharmacy receives the vaccine, they will update the received package data, and the nextAction value will be set to 'Done', which indicates the batch is completed. This way, the transactions are stored whenever any entity adds data to the blockchain network, as shown in Figure 8.

Figure 8. Transaction Signed by Entities

Once the vaccine data is recorded as a transaction, it will be available to all the network entities, thus providing transparency throughout the supply chain. Figure 9 shows the Batch overview where each entity can view the status of all the vaccine batches.

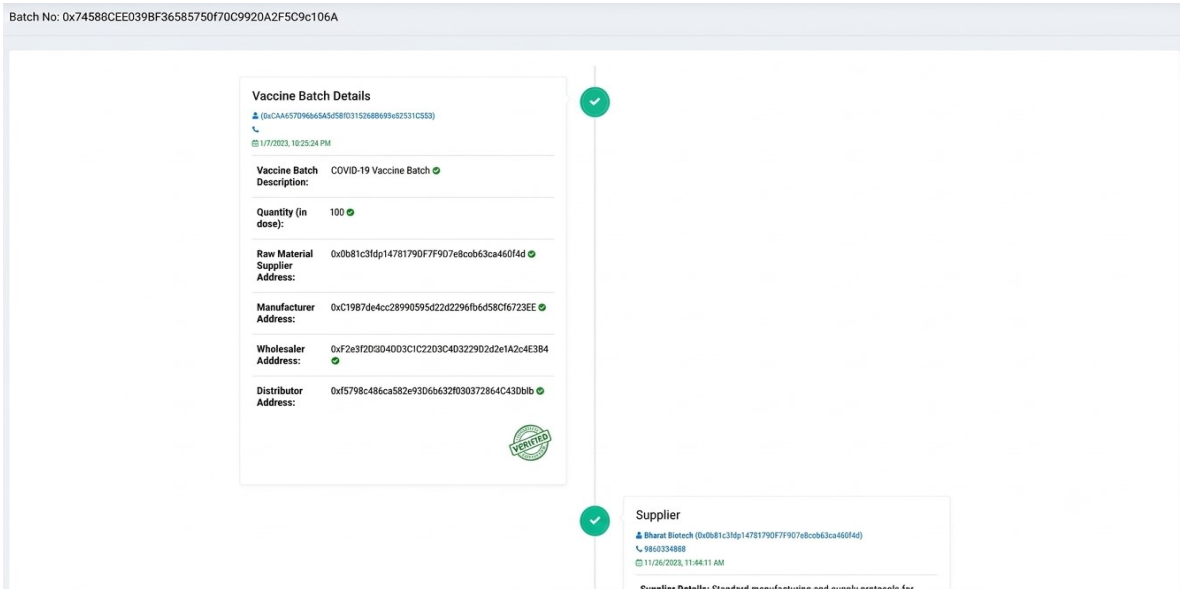

Figure 9. Vaccine Batch Overview

Throughput

Here we have measured the throughput in terms of smart contract deployment time in seconds on the blockchain network. Figure 10 shows the time in which each of the smart contracts got deployed. As

a result, the ownable smart contract was deployed in 0.5secs followed by storage smart contract, which got deployed after 2.5 secs, VaccineSupplyChain and SupplyChainUser contracts in 3.5 and 4.5 seconds, respectively.

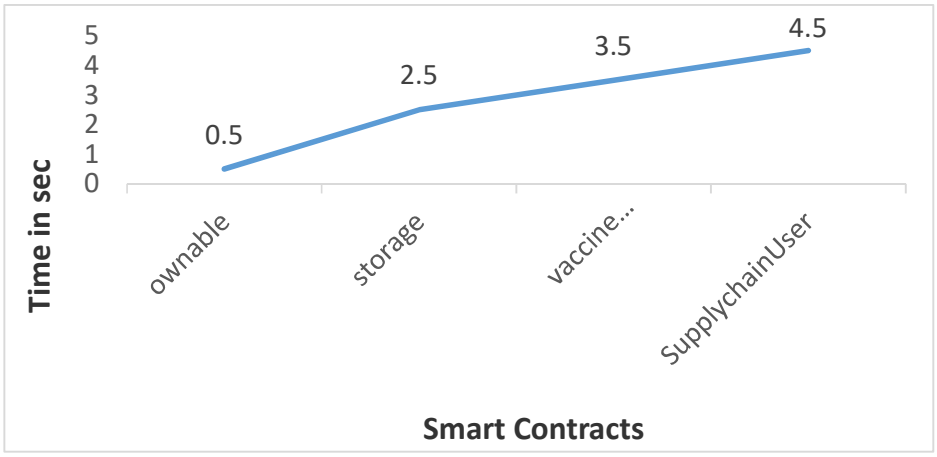

Figure 10. Smart contracts deployment time in seconds.

For each recorded transaction, there will be a certain amount of gas price that has to be paid. These gas limits will vary from one transaction to another. Each block contains a certain number of transactions in it. These blocks are then interlinked to form a Blockchain network. Figure 11 shows the gas usage for different transactions.

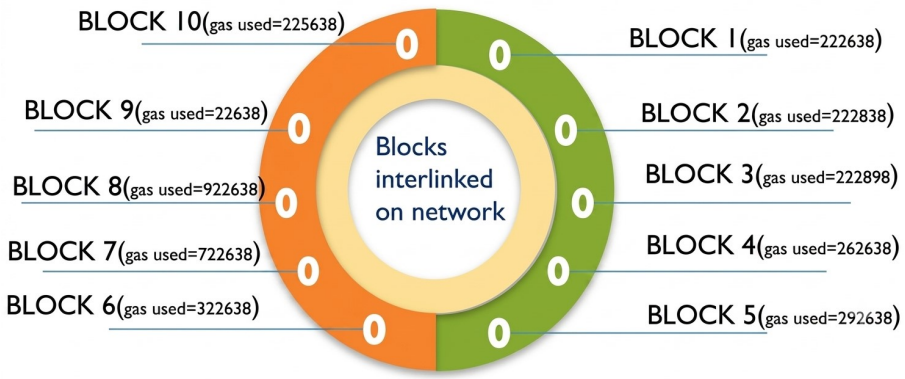

Figure 11. Gas Usage for Each of the Transactions

CONCLUSION

In the proposed work, we designed the blockchain enabled model for the traceability of vaccine registration, vaccine stock details and organisation, and self-reporting of adverse effects of the vaccine. Blockchain ensures the preservation, visibility, and accuracy of vaccination beneficiary registration, eliminating identity theft and impersonation. Decentralized smart contracts are used to track and monitor vaccine delivery against the producer's agreed rules for safe operation. In the present work, we deployed Smart Contracts on Ganache (a Blockchain Visualization Framework) for simulating Blockchain Network and for testing the Smart contract. As future work, it will be deployed on the public Ethereum network, which will be helpful in the healthcare sector by effective data sharing between healthcare providers.

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