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RESEARCH ARTICLE

A Blockchain-Based Solution for Mitigating Overproduction and Underconsumption of Medical Supplies

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ABSTRACT Billions of dollars lost has been recorded over the past decade due to the overproduction and underconsumption of medical supplies. The overproducation and underconsumption are usually due to the lack of accountability, transparency, traceability, audit, assessment, security, and trust features in the current healthcare supply chain systems. It is required to ensure that everyone is getting a fair share of medical supplies without unnecessary waste. In this paper, we propose a blockchain-based solution that ensures the commitment and accountability of all participants to prevent them from producing any unnecessary waste. We introduce five phases, such as registration, commitment, production, delivery, and consumption, to perform the waste assessment accurately and fairly. We develop four smart contracts that ensure data provenance, transparency, security, and accountability while recording all actions on an immutable ledger automatically. We utilize offchain decentralized storage to deal with the large data problem. We present five algorithms and discuss each phase of the proposed solution, along with their full implementation, testing, and validation details. We conduct the security analysis to ensure that our smart contracts are secure enough and they do not have vulnerabilities and flaws. The smart contracts code is made publicly available on GitHub.

INDEX TERMS Medical supply, medical waste, commitment, waste accountability, traceability, blockchain, Ethereum, smart contracts.

I. INTRODUCTION

In the past decade, both the amount and the toxicity of healthcare supply waste have increased significantly. Such wastes are expensive to dispose of and contribute significantly to food chain pollution through the release of persistent cumulative toxicity into the environment [1], [2]. The World Health Organization (WHO) has recommended that hospital waste be treated as special waste [3]. In recent years, healthcare supply waste has become more visible than ever during the COVID-19 pandemic, owing to the widespread use of single-use plastic and the requirement to discard personal protective equipment (PPE) after one use [4]. Despite that, hospitals dispose of many usable supplies that are in perfect condition and worth billions of dollars [5]. For example, in the United States, operating rooms produce more than 2000 tons of waste per day. Some of these wastes are unused, such as sponges, blue towels, and gloves [6]. Besides, according to a Johns Hopkins study, major hospitals in the United States waste at least $15 million in unused operating room surgical supplies that may be saved and deployed to relieve shortages, improve surgical care, and promote public health in developing nations [7]. Furthermore, the disposal of medical waste from hospitals in several countries has been regulated by codes of practice and recommendations to protect the public health and the environment [3]. On the other hand, warehouses store many medical supplies on shelves that may become old or expired and end up as waste [5]. For instance,

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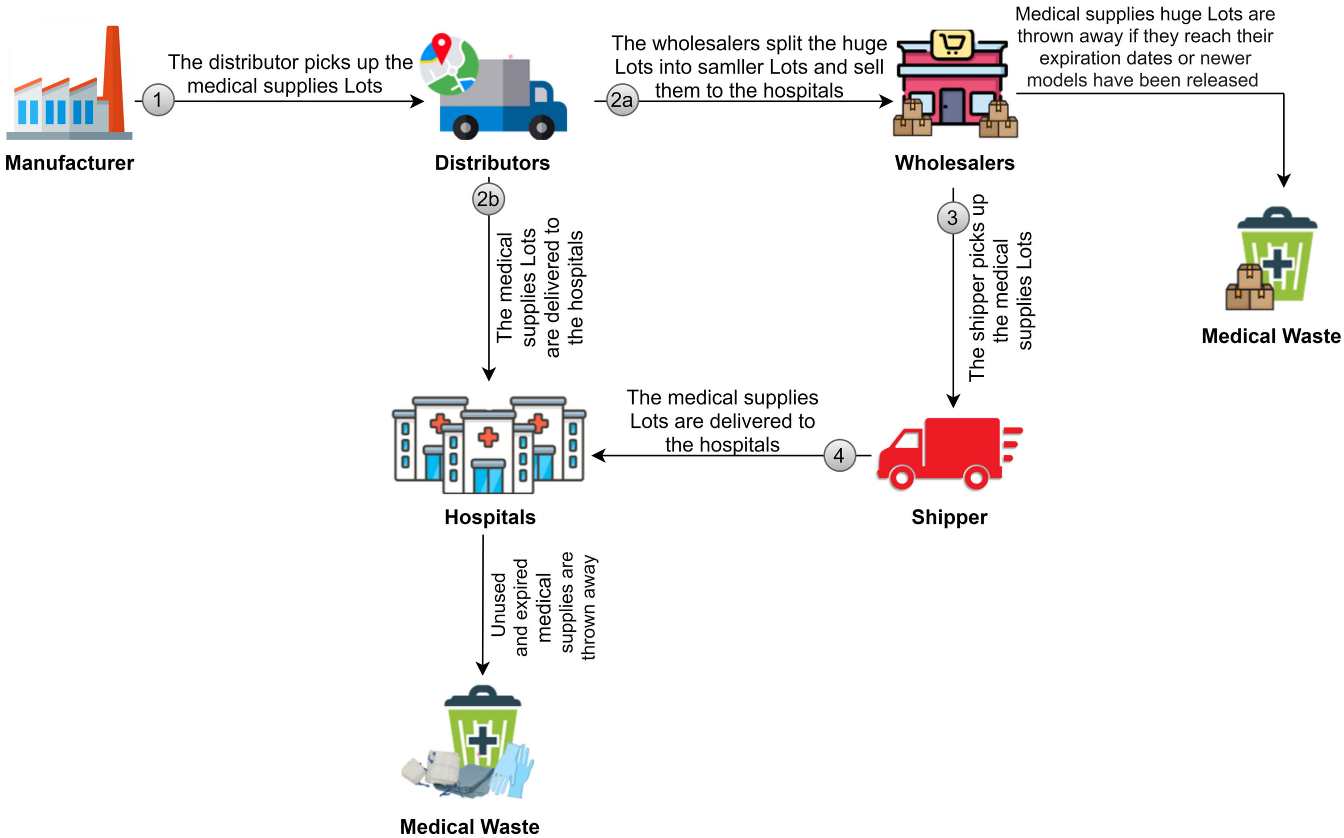

FIGURE 1. A typical flow diagram of the production, consumption, and waste generation of medical supplies.

the United States produces more than two million tons of wasted medical supplies per year, and facilities do not use many of these supplies [8].

Figure 1 illustrates a typical healthcare supply chain process. First, the manufacturer produces a certain number of lots of medical supplies. Then, the distributors pick up and deliver these lots to the wholesalers or directly to the hospitals. Next, the wholesalers split these huge lots into smaller lots and sell them to the hospitals upon their request. After that, the shipper delivers these orders to the hospitals. Finally, when the hospitals receive the supplies, some are used, while others are not, and they are thrown away as soon as they expire. Meanwhile, some huge lots are thrown away by the wholesalers if they reach their expiration dates or when newer models are released. However, under the current system, it is difficult to determine who is responsible for the massive amounts of used medical supplies that have been discarded. Are we producing more than we need or consuming less than expected?

Unfortunately, coronavirus disease 2019 (COVID-19) has already shown weaknesses in the current system, such as a lack of clear visibility into healthcare supply chains, which makes it difficult to predict when or even whether the different supplies will arrive [4]. In addition, the healthcare supply chain faces significant issues due to a lack of transparency and asymmetric information across multiple entities [9]. According to [11], the lack of an audit trail for medical supplies is one of the key hospital supply chain challenges. Besides that, from the supplier's point of view, it's hard to figure out how to match the buyer's size with the package dimensions. Today's healthcare supply chain systems have a lot of problems to solve when it comes to data transparency, accountability, immutability, traceability, audit, and trust, among other things.

In this paper, we proposed a solution for medical supplies waste reduction. Our solution helps to capture the real reason behind the large amounts of unused medical waste. Furthermore, this solution makes all actors accountable for their actions, which can be easily traced back. This is done by taking advantage of the features of blockchain technology, which stores all actions on a record that can't be changed. The main contributions of this study are as follows:

- We propose a blockchain-based solution that ensures the commitment and accountability of all the entities involved in the healthcare supply chain. It performs an assessment of medical supply waste and enables tracing for the commitment, production, delivery, and consumption phases in a secure, transparent, auditable, and trustworthy manner.

- We present the proposed system architecture, including system elements, actions, phases, and actors involved, along with their responsibilities in the healthcare supply chain and waste assessment process. We discuss the interactions among the different actors in our proposed solution as all actions are traceable, and all actors are accountable.
- We design and develop four smart contracts that register actors and ensure data provenance through producing events for all the necessary actions that occur during the different phases.
- We present five algorithms and discuss the implementation, testing, and validation details of our developed smart contracts.
- We conduct the security analysis to show that our proposed solution is secure enough against common vulnerabilities and attacks.

The rest of the paper is organized as follows. The related works are presented in Section II. The proposed blockchain-based solution is explained in Section III. In Section IV, the implementation details of the proposed blockchain-based solution are presented. Testing and validation details are provided in Section V. In Section VI, the discussion and analysis of the proposed solution are given. Section VII concludes the paper by summarizing our contributions.

II. RELATED WORKS

In this section, we present the existing blockchain and non-blockchain-based solutions related to waste management and assessment issues.

A. NON-BLOCKCHAIN-BASED SOLUTIONS

The authors in [12] proposed a web-based application called 'kabaditechno.com' that provides an online solution for collecting individual and organizational waste. This creates a unified environment for the customer, kabadi, collector, and recycler all in one location. The proposed solution is an efficient way to manage all types of waste, including the time and cost savings.

In [13], the authors examined the current state of medical waste management in Malaysia and developed some suggested strategies for managing these wastes, including material recovery and recycling, land-filling mechanisms, and economic instruments for managing these wastes. Moreover, during the COVID-19 outbreak in Bangladesh, the authors in [14] evaluated the healthcare sector's waste and offered policymakers suggestions for developing waste management strategies related to the environment and public safety.

The authors in [15] held a discussion to see if RFID tag technology could be used to track medical waste while it is delivered to a treatment plant. The RFID system would be used to determine hospital and transporter liability in order to prevent illegal medical waste disposal. As a result, they determined that combining RFID technology with big data cloud storage would prevent medical waste loss or illegal recycling by nearly 99% in medical waste management.

The aforementioned solutions are only focused on tracking the waste or improving the waste management through applications. However, the authors of [16], provided a solution that helps in monitoring and holding individuals accountable for the amounts of food wasted. As such, the waste of today will constitute a shortage of food for the generations of tomorrow. This solution depends on RFID, with the help of cloud computing and IOT sensors, where for each individual, the food waste amount that has been thrown in the trash is recorded. It shows the real-time food wastage of each individual on a website that can be used as a reference for the future. Although the solution was implemented and succeeded, the RFID technology has features that limit the success of this solution for other applications. Some tags, for example, can be turned off, and because RFID-based systems use the electromagnetic spectrum, they can be easily disrupted. In addition, this solution is fully centralized so that recorded data is only visible to admin users and controlled by them.

B. BLOCKCHAIN-BASED SOLUTIONS

In [17], the authors proposed a blockchain-based decentralized application where the collection of plastics by organizations might come from anywhere and can be tracked in a timely manner. This solution can assist in bridging the gap that exists between users and organizations, as well as in minimizing the environmental impact of plastic waste, as the reward system significantly encourages people to recycle plastic.

The authors in [18] offered a solution based on fog computing and blockchain technology. It creates a trustworthy environment in which entities involved in the waste management chain can work with one another. This method provides sufficient encouragement for residents and other waste generators to play an effective part in the separation of recyclable garbage at the point of generation. In addition, the authors in [19] created a blockchain-based solution for waste recycling data and participation. Sensors would send waste data to a blockchain smart contract. Such data includes a citizen's waste collection by category. Citizens can view blockchain data, register data, and check fee balances through a smartphone application.

In [20], the authors proposed a blockchain-based solution to deal with the e-waste generated in India. This solution can keep track of the e-waste that has been generated and encourage individuals to send their e-waste to government-regulated agencies for effective and eco-friendly disposal.

The authors in [21] proposed a decentralized Ethereum blockchain-based solution for COVID-19 medical equipment forward supply chain automation. The solution allowed data provenance for COVID-19 medical equipment and waste disposal, as well as imposed penalties on actors who violated the standard.

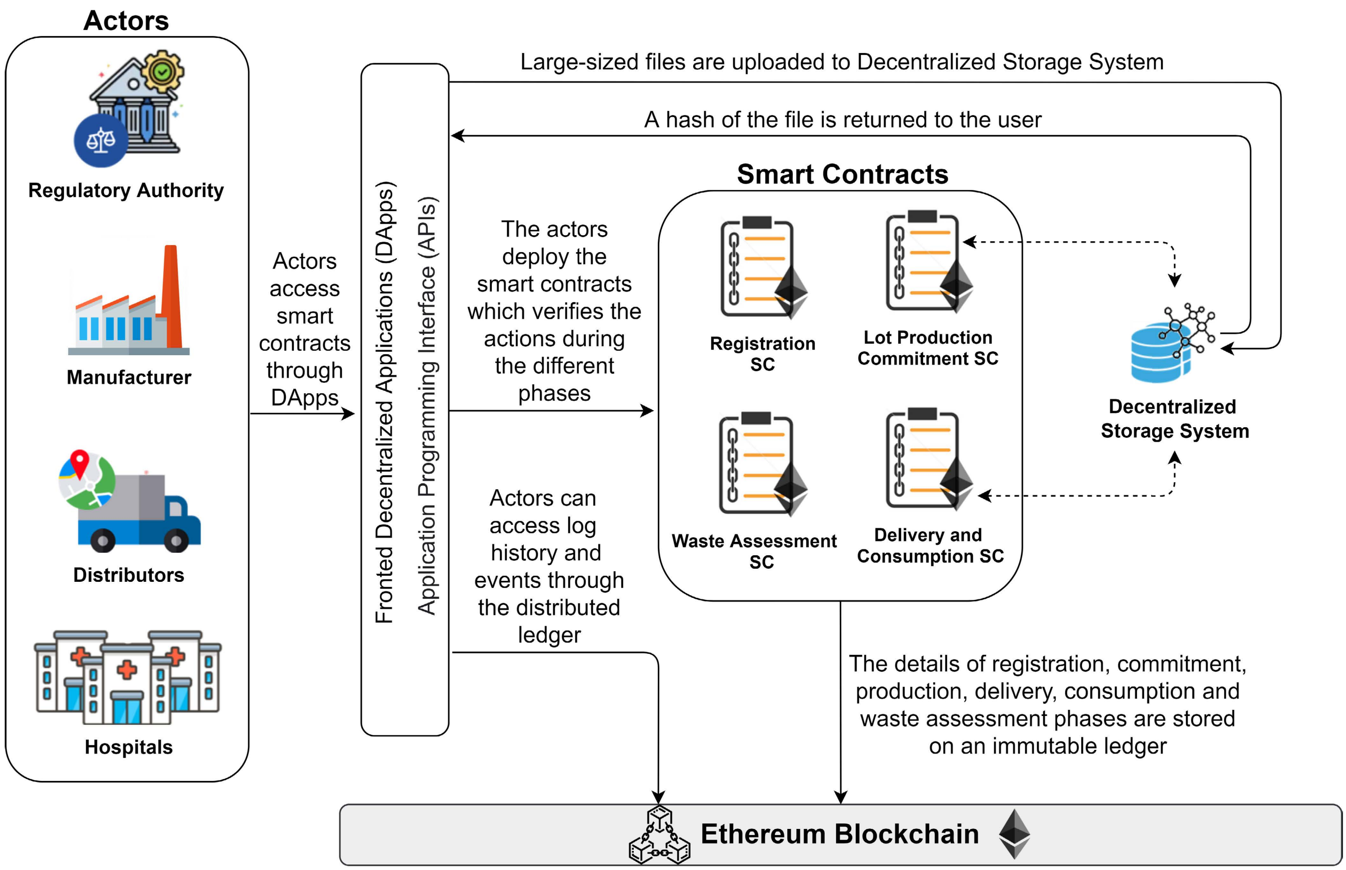

FIGURE 2. An overview of the proposed blockchain-based system architecture for medical supply waste assessment in Healthcare Supply Chain.

In [22], the authors proposed a peer-to-peer encrypted system in conjunction with a smart contract using the Ethereum Blockchain. Throughout the entire process, it increases accessibility, efficiency, and timeliness. The framework is immutable and has a high level of transaction transparency. It also permits all customers to return an item for a refund if they are unsatisfied with it.

The authors in [23] developed a decentralized supply chain model for intelligent supply chain production and distribution. This solution addresses issues in the supply chain's production and distribution system by presenting a more realistic optimization plan and advertising it to various businesses. As a result, the new reconstruction technique lowers the overall cost and reduces the total rate of delayed delivery.

The previous blockchain-based solutions have focused on using blockchain technology for management, tracking, and tracing purposes. Monitoring is enhanced by real-time tracking, while origin verification is enhanced by traceability. However, recognizing entities that do not fulfill their commitments remains challenging. For instance, a hospital cannot deny producing medical waste. Nevertheless, it can still blame the manufacturer for overproduction. So no one can make fake acquisitions, and commitment information must be on the blockchain.

III. PROPOSED BLOCKCHAIN-BASED SOLUTION

This section presents the proposed blockchain-based solution for medical supply waste assessment, along with its system architecture and smart contracts. Figure 2 shows the system elements, actions, phases, and actors involved with their responsibilities in the waste assessment and management process of the healthcare supply chain.

Our blockchain-based solution ensures the commitment and accountability of all the entities involved in the healthcare supply chain. It assesses and manages medical supply waste through the commitment, production, delivery, and consumption phases. However, with existing solutions, it is difficult to decide who is responsible for the large amounts of unused medical supplies that have been discarded. Our solution helps capture the real reason behind the large amounts of unused medical waste. Is it overproduction or underconsumption? Our developed smart contract makes all actors accountable for their actions, which can be easily traced back. This is done by taking advantage of the features of blockchain technology, which stores all actions on a record that cannot be changed. Furthermore, through these smart contracts, production approval is only given if the commitment and lot specifications are met. The transparency of the commitment details through all involved entities is one of the biggest advantages of our solution. In addition, the waste assessment phase identifies who is behind the waste, as any commitment violation will be captured and announced during this phase. The regulatory authority handles the waste assessment function while the overproduced and under-consumed amounts are automatically calculated, and the valuation case is announced.

A. ETHEREUM BLOCKCHAIN

All transaction logs and events are permanently stored on the ledger and cannot be modified or removed. Hence, the traceability, transparency, and accountability of the suggested solution are all ensured by this system element. Additionally, the distributed nature of the blockchain is what enables the Ethereum platform to be secure.

Private Permissioned Blockchains provide additional security, privacy, and confidentiality by limiting public access to transactions and data. In our proposed solution, the information related to the waste assessment phase affects the reputation of the participants in the production, delivery, and consumption phases. If the origin of the medical waste is announced every time, the reputation will be harmed, which will result in distrust and other economic losses. Overall, when the weaknesses are fixed internally, they can improve the quality of the process more than when they are publicized.

B. SMART CONTRACTS

We develop four smart contracts that are discussed below.

- ***Registration Smart Contract:*** This smart contract is responsible for registering all entities or actors involved in the healthcare supply chain. It is deployed by the Regulatory Authority, where healthcare services are administered and regulated. Furthermore, the manufacturer, distributors, and multiple hospitals are the registered actors.
- ***Lot Production Commitment Smart Contract:*** This smart contract verifies the multiple actions related to the commitment and production phases, such as the distributor's commitment, placing bids, getting approval, and starting production. It is deployed by the manufacturer, who is responsible for setting the production limitations. Moreover, distributors and bidders need to take their actions during a time window.
- ***Delivery and Consumption Smart Contract:*** This smart contract is responsible for two consecutive phases: delivery and consumption, which are done by the hospitals and their affiliated distributor. Starting delivery, reception confirmation, and delivery confirmation are the main actions during the first phase. Moreover, the calculation of the amount of medical supplies consumed is carried out during the second phase.
- ***Waste Assessment Smart Contract:*** This smart contract estimates the waste amount and who is responsible for it. It discovers the source of the violation, whether it is from the manufacturer, the committed distributor, or the hospitals.

C. DECENTRALIZED STORAGE SYSTEM

We integrate our proposed solution with offchain decentralized storage to handle large image files that are used in the production, delivery, and consumption phases. For example, the InterPlanetary File System provides low-cost off-chain storage. Data integrity is maintained by generating a unique fingerprint called a cryptographic hash, which is stored on the blockchain and accessed via the smart contract. Any modification that happens to any of the uploaded files is reflected in the associated hash.

D. SEQUENCE OF ACTIONS

Herein, we present the interactions among the different actors of our proposed solution as all actions are traceable and all actors are accountable.

Figure 3 presents the interaction of the regulatory authority, manufacturer, distributors, and hospitals with the registration and lot production commitment smart contracts. All the actors or entities are registered on the blockchain through the registration smart contract, which is deployed by the regulatory authority. Successful registration creates an Ethereum address, which is used as a reference for each actor. Once the actors are registered on the network, the manufacturer deploys the lot production commitment smart contract and specifies the minimum threshold, maximum number of packages, and commitment duration. In response, one of the distributors will call the *DistributorCommitment* function and commit to delivering the lot. Then, multiple hospitals affiliated with that distributor place bids and specify the number of needed packages. Here, the smart contract aggregates the total number of packages. However, the previous actions should be done before the manufacturer calls the *EndCommitmentTime* function. Once the time window is closed, the smart contract will emit an event announcing the production approval status, either approved or rejected. As is shown in the figure, there are three different scenarios: one for approval and two for rejection. As a response to scenario A, the manufacturer will call the *LotProduction* function to produce the lot.

Figure 4 illustrates the sequence diagram of the interaction among the manufacturer, committed distributor, hospitals, and the delivery and consumption smart contracts. This Smart Contract is deployed by the committed distributor who picks up the lot and calls the *startDelivery* function to begin the delivery process. Once the lot is received by the multiple hospitals, the *confirmationofReception* function should be called to confirm the number of packages received by each hospital. In response, the committed distributor calls the *confirmationofDelivery* function to confirm the end of the delivery process. Then, there is the consumption phase, where each hospital uses some amount and disposes of the rest as they are expired or usable but unwanted. Once the consumption phase is done, the regulatory authority will deploy the waste assessment smart contract to verify which entity is

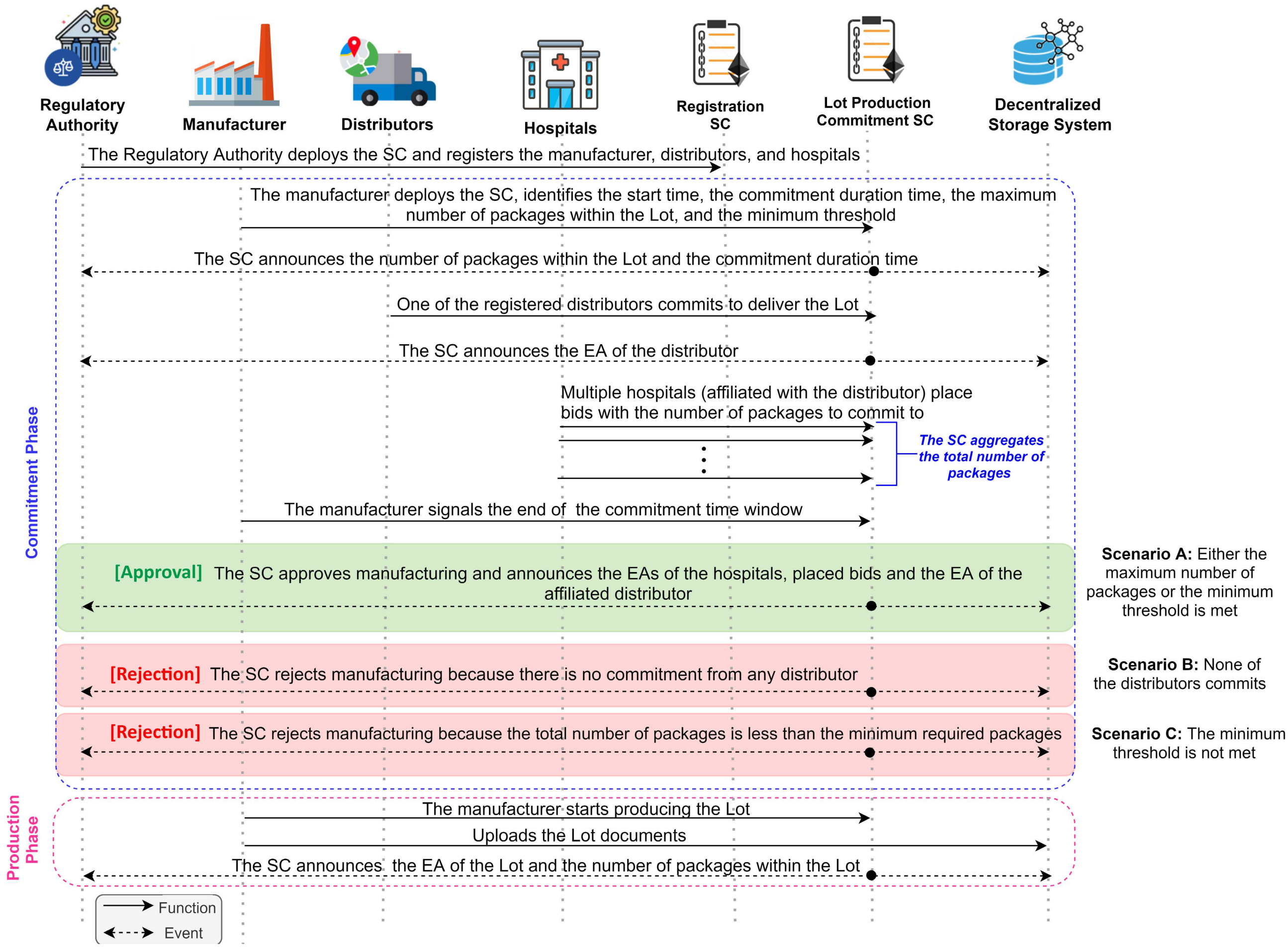

FIGURE 3. Sequence diagram showing interactions among actors and smart contracts during the production and commitment phases.

responsible for the waste amount from this lot. As shown in figure 5, there are four scenarios: one where there is no violation as the lot has been manufactured, delivered, and consumed; however, the other three scenarios are where there is a violation from the manufacturer, committed distributor, or any hospital.

IV. IMPLEMENTATION DETAILS

In this section, we present five algorithms and discuss the full implementation details of our solution. The proposed solution consists of four smart contracts that are written in the Solidity language and compiled and tested using the REMIX IDE. Solidity is a contract-oriented programming language for creating smart contracts at a high level, and REMIX IDE is an open source web application used to write, compile, and debug Solidity code. The full code has been made publicly available on GitHub.[1]

The entity relationship diagram, which represents the interactions between smart contracts and attributes, is shown in figure 6. The Registration smart contract is deployed by the regulatory authority who is responsible for registering manufacturers, distributors, and hospitals through the different functions displayed in the figure. In addition, this smart contract will have a 1 to n relationship with the production commitment smart contract, where each medical supplies lot will have a production commitment smart contract. Similarly, the relationship between smart contracts for delivery and consumption is 1 to n.

The manufacturer deployed the production commitment smart contract, which presents one lot. A distributor needs to commit to delivering the lot, and each hospital must declare its affiliated distributor. After that, each hospital can place bids before the end of the time window. Finally, the manufacturer is responsible for providing the details of the produced lot. Furthermore, the delivery and consumption smart contracts are deployed by the commitment distributor, who is responsible for confirming the delivery of the lot. Each hospital will receive a number of packages that will be consumed and disposed of with time. Despite this, these two smart contracts have a 1 to 1 relationship with each other because they represent a single lot only.

[1]https://github.com/BCManagement/Waste/blob/main/code.sol

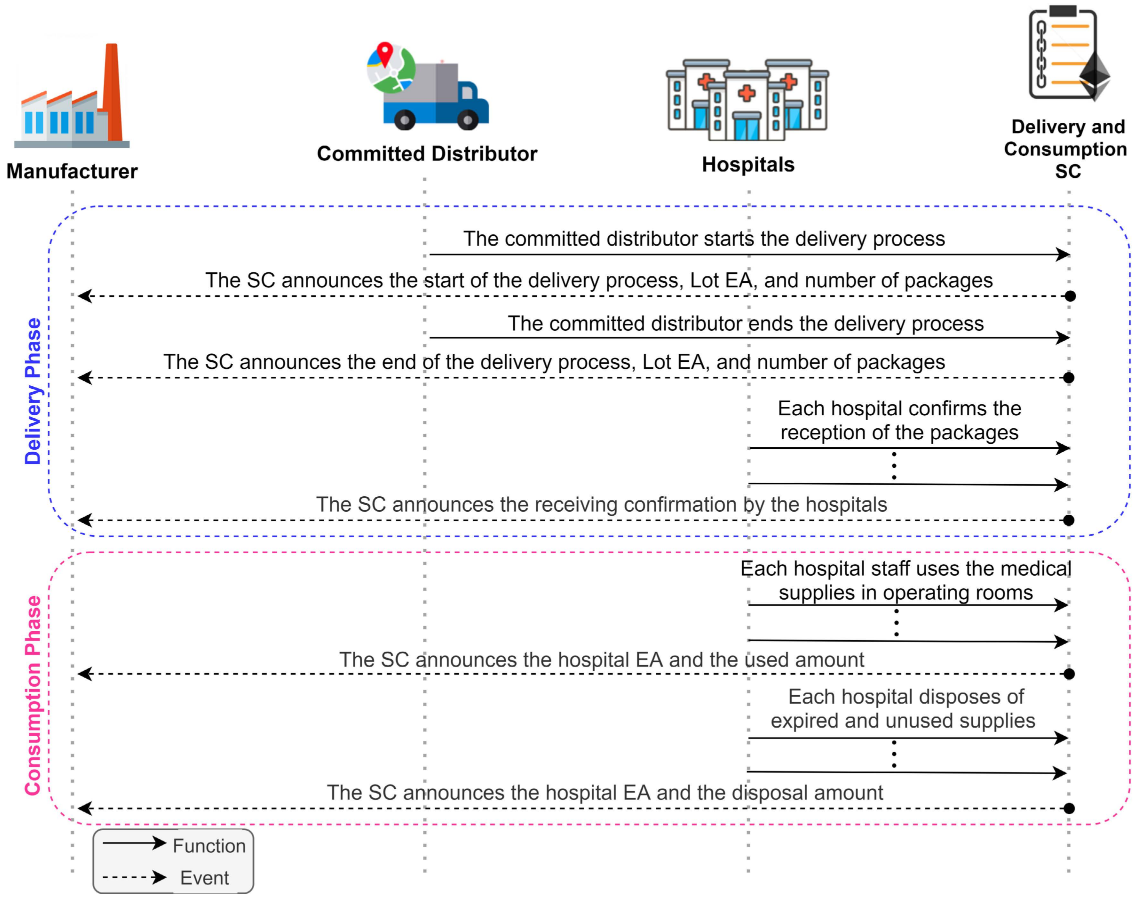

FIGURE 4. Sequence diagram showing interactions among actors and smart contract during the delivery and consumption phases.

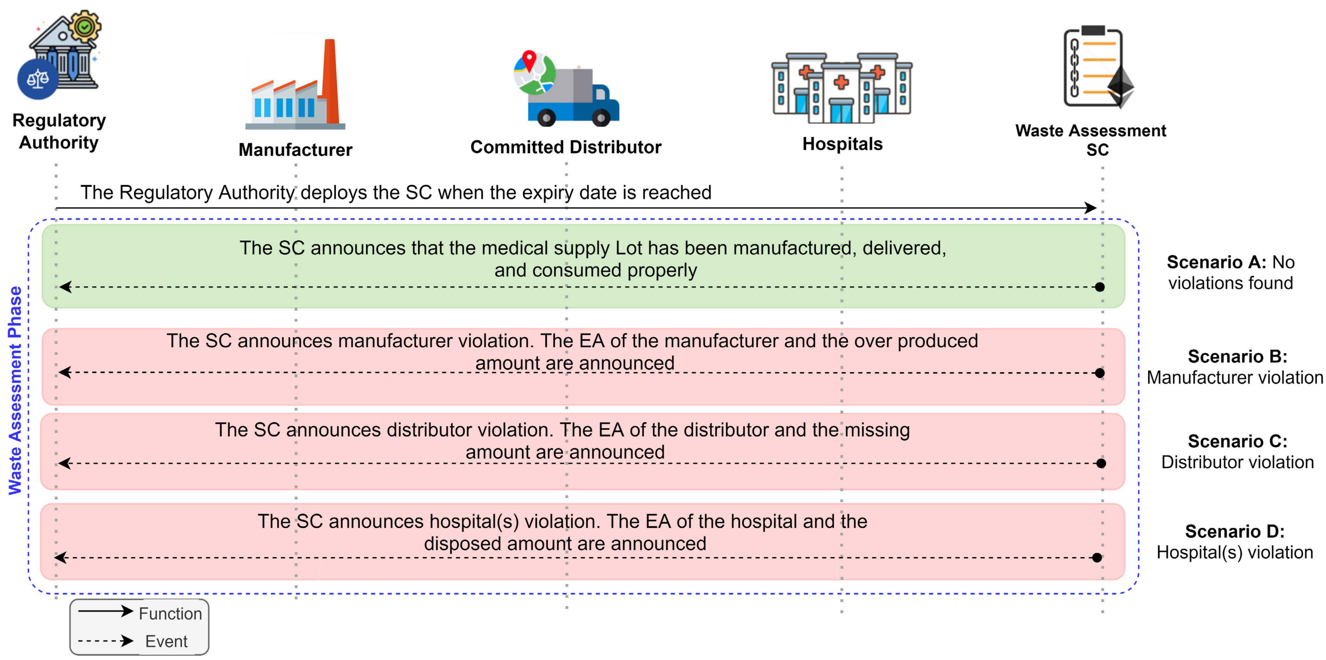

FIGURE 5. Sequence diagram showing interactions among actors and smart contract during the waste assessment phase.

The Waste Assessment smart contract is deployed by the regulatory authority when the expiration date of the lot is reached. Its goal is to document any violations that occurred during the manufacturing, delivery, and consumption phases.

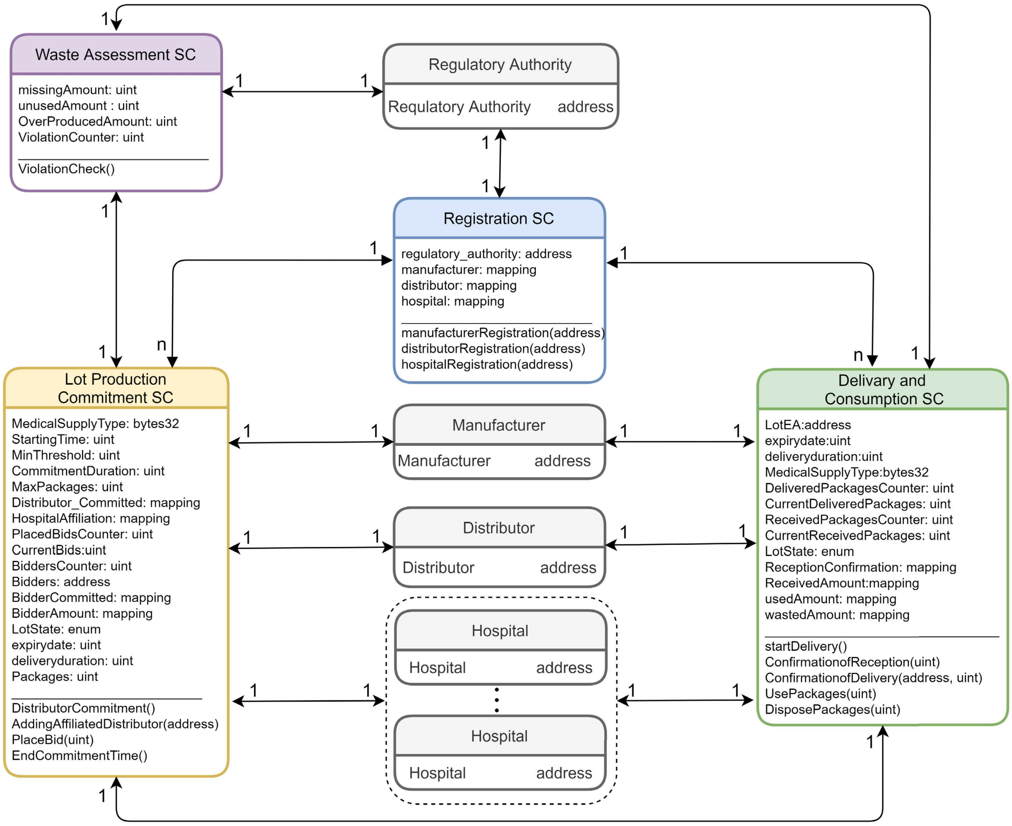

FIGURE 6. Entity-relationship diagram of smart contracts and the actors involved in each one.

The Waste Assessment smart contract can be associated with only one vaccine lot at a time; therefore, it has a 1 to 1 relationship with the production commitment and delivery and consumption smart contracts.

Detailed algorithms can help people better understand the logic behind smart contracts, so the main algorithms of the proposed solution are shown below.

Algorithm 1 represents the commitment phase, where only one distributor will commit to delivering the lot, and multiple hospitals that are affiliated with that distributor will place bids. Mainly, a successful commitment action from the distributor can occur only if some conditions are satisfied. First, the caller of the *distributorcommitemnt* function should be the distributor. Second, this action should be done before the end of the commitment duration. Third, the distributor must not have been committed to delivering this lot before. As a result, an event that shows the distributor's commitment details will be released. Furthermore, any hospital that needs to place bids must not exceed the maximum number of packages set by the manufacturer and should only call for the function once. In addition, a successful call only happens before the end of the time window. As a result, the EA of the hospital with the number of bids will be stored in an array, first In, first Out (FIFO), and the current number of bids will be updated. Despite this, the production permission will be announced only if the total current bids reaches the maximum limit. Otherwise, the manufacturer will trigger the end of the time window and give manufacturing permission depending on the commitment actions.

Algorithm 2 depicts the production phase, in which the manufacturer signals the end of the commitment time and grants permission to begin production.Lot manufacturing is rejected if the current bid is less than the minimum threshold; otherwise, it is approved, and the *LotProduction* function will be called only if the caller is the manufacturer and the lot state is not manufactured. Then an event announcing that the lot has been produced with its details, including expiry day and delivery duration, is emitted.

Algorithm 3 illustrates the delivery phase, where the commitment distributor will initiate this phase only if the lot state is manufactured within the delivery duration time. As a result, this state will be updated. After that, each hospital should confirm the reception of packages, and an event will announce the confirmation details. Lastly, the distributor must confirm the end of the process only if the number of the delivered packages equals the bidder amount of that hospital.

Algorithm 4 displays the consumption phase where hospitals can use and dispose of the delivered medical supplies packages. The details of these two actions will be announced and stored on the blockchain. This phase's data is important

Algorithm 1 Distributor and Hospitals Commitment

```
Input: PlacedBid
if (caller == Distributor) ∧ (block.timestamp <= StartingTime + CommitmentDuration) ∧ (DistributorCommitted == false) then
    Distributor_Committed[msg.sender] = true
    Emit an event shows the distributor commitment details
else
    Revert.
end
/* One of the registered distributors commits to deliver the Lot */
if (caller == hospital) ∧ (block.timestamp <= StartingTime + CommitmentDuration) ∧ (Distributor_Committed[HospitalAffiliation[msg.sender]]) ∧ (PlacedBid + PlacedBidsCounter <= MaxPackage) ∧ (BidderCommitted[msg.sender] == false) then
    PlacedBidsCounter += PlacedBid
    CurrentBids = PlacedBidsCounter
    Bidders.push(msg.sender)
    BidderCommitted[msg.sender] = true
    BidderAmount[msg.sender] = PlacedBid
    BiddersCounter += 1
    if (CurrentBids == MaxPackage) then
        Emit an event shows the hospital Commitment details
        Emit an event announcing that the time window is end
        Emit an event announcing that the production is approved
        ProductionPermission = true
    else
        Emit an event shows the hospital Commitment Details
    end
else
    Revert.
end
```

Algorithm 2 Medical Supply Lot Production

```
Input: expirydurationinmonths, deliverydurationindays, Packages
expirydurationinmonths is the expiry date of the medical supply Lot.
deliverydurationindays is the time duration allowed to deliver the Lot
Packages is the number of packages within the Lot
LotState is a customized enumerate variable that illustrates different states of manufacturing
if (caller == manufacturer) ∧ (block.timestamp == StartingTime + CommitmentDuration) then
    if CurrentBids < MinThreshold then
        Emit an event announcing that the production is rejected
        ProductionPermission = false
    end
    if CurrentBids >= MinThreshold then
        Emit the hospital Commitment Details
        Emit an event announcing that the production is approved
        ProductionPermission = true
    end
else
    Revert.
end
/* The commitment time window is closed */
if (caller == manufacturer) ∧ (ProductionPermissin == true) ∧ (Lotstate == NotManufactured) then
    Lotstate = Manufactured
    expirydate = block.timestamp + (expirydurationinmonths * 30 days)
    deliveryduration = block.timestamp + (deliverydurationindays * 1 days)
    Emit an event announcing that the Lot is produced
else
    Revert
end
```

for the waste assessment process, where hospitals can be held accountable for any waste.

Algorithm 5 represents the last phase, where the regulatory authority will perform the waste assessment when the lot reaches its expiration date. If the manufacturer overproduces, then an event is emitted announcing that the manufacturer has committed a violation. Moreover, if the distributor fails to deliver the correct number of packages, an event is emitted announcing that the distributor has committed a violation. Furthermore, if a healthcare center is performing an underconsumption action, an event is emitted announcing that the healthcare center has committed a violation. Yet, if the violation counter equals zero, then an event is emitted announcing that no violations were committed.

V. TESTING AND VALIDATION

In this section, we demonstrate the functionality and logic of the smart contracts in our proposed solution. We executed all the functions of the smart contracts in the Remix IDE. Table 1 provides a list of all participants, along with their Ethereum addresses.

The proposed solution is tested based on the following scenario: In the registration phase, one manufacturer, two distributors, and two hospitals were registered. In the commitment phase, the manufacturer is assumed to have a maximum capacity of 100 packages within the lot and a minimum threshold of 60 packages. In addition, the commitment time duration is assumed to be 30 minutes for simplicity. Moreover, *distributor A* is assumed to commit to delivering the

Algorithm 3 Delivery Process and Confirmation

```
Input: receivedpackages, deliveredPackages
receivedpackages is the number of packages that the hospital received
deliveredPackages is the number of packages that the distributor delivered
LotState is a customized enumerate variable that illustrates different states of manufacturing
if (caller == Distributor) ∧ Lotstate == Manufactured then
    Lotstate = EnRoute
    Emit an event announcing that the delivery is started
else
    Revert
end
/* The Lot delivery is started */
if (caller == hospital) ∧ (Lotstate == EnRoute) ∧ (ReceptionConfirmation== false) ∧ (receivedpackages == BidderAmount) then
    ReceptionConfirmation = true
    Emit an event announcing the confirmation of reception
else
    Revert
end
/* The Lot reception is confirmed */
if (caller == Distributor) ∧ (deliveredPackages == BidderAmount) ∧ (ReceptionConfirmation == true) then
    DeliveredPackagesCounter += deliveredPackages
    CurrentDeliveredPackages = DeliveredPackagesCounter
    if CurrentDeliveredPackages == CurrentBids then
        Lotstate = Delivered
        Emit an event announcing the confirmation of delivery
        Emit an event announcing that the delivery process is ended
    end
else
    Revert
end
```

lot; *hospital A* places 70 package bids, and *hospital B* places 30 package bids. In the production phase, it is assumed that the manufacturer produces exactly 100 packages. Next, the distributor is assumed to deliver the correct amounts to both *hospitals A and B*. In the consumption phase, it is assumed that *hospital A* uses 50 packages and disposes of 20 boxes, whereas *hospital B* uses all 30 packages that it initially committed to.

The manufacturer initiates the commitment phase by deploying the lot production commitment smart contract and announcing the conditions that must be met prior to

Algorithm 4 Consumption Process of Packages

```
Input: usedpackages, disposedPackages
usedpackages is the number of used packages
disposedPackages is the number of disposed packages
if (caller == hospital) ∧ (BidderCommitted(msg.sender)== true) then
    if (usedpackages + usedAmount + wastedAmount <= ReceivedAmount) then
        usedAmount += usedpackages
        Emit an event shows the number of used packages
    end
    if disposedPackages + usedAmount + wastedAmount <= ReceivedAmount) then
        wastedAmount += disposedPackages
        Emit an event shows the number of disposed packages
    end
else
    Revert
end
```

TABLE 1. Participant's Ethereum address.

	Ethereum Address
Regulatory Authority	0x5B38Da6a701c568545dCfcB03FcB875f56beddC4
Manufacturer	0xAb8483F64d9C6d1EcF9b849Ae677dD3315835cb2
Distributor A	0x4B20993Bc481177ec7E8f571ceCaE8A9e22C02db
Distributor B	0x03C6FcED478cBbC9a4FAB34eF9f40767739D1Ff7
Hospital A	0x78731D3Ca6b7E34aC0F824c42a7cC18A495cabaB
Hospital B	0x617F2E2fD72FD9D5503197092aC168c91465E7f2

the manufacturing process. Figure 7 summarizes this event, including the details of these conditions, such as the medical supply lot type, the maximum number of packages within the lot, the minimum threshold to start manufacturing, the commitment phase starting time, and finally, the commitment duration. Next, the commitment actions start when distributor A commits to delivering the lot, and both hospitals A and B add the affiliated distributor. After this, the second commitment is made by hospitals through placing bids. As it is shown in figure 8, hospital A placed 70 package bids, and the logs display the total number of placed bids with the Ethereum addresses of the hospital and lot. However, figure 9 shows an error as hospital A called the function for a second time, trying to place bids twice. Furthermore, hospital B placed 30 package bids, which means that the maximum number of packages within the lot has been reached. Therefore, in figure 10, an event of production approval is shown along with the total number of placed bids and other details.

The production phase is done by the manufacturer immediately after getting the production approval. After that an event is announced to give details about the manufactured lot. These

Algorithm 5 Waste Assessment

```
if caller==regulatory_authority then
    if Packages > CurrentBid then
        OverProducedAmount = Packages - CurrentBids
        ViolationCounter +=1;
        Emit an event announcing that there is a
        violation from the manufacturer
    end
    if CurrentDeliveredPackages < Packages then
        missingAmount = Packages -
        CurrentDeliveredPackages
        ViolationCounter +=1;
        Emit an event announcing that there is a
        violation from the distributor
    end
    for <i = 0; i < BiddersCounter; i++>
    do
        if usedAmount(i)< BidderAmount(i) then
            unusedAmount = BidderAmount(i) -
            usedAmount(i)
            ViolationCounter +=1;
            Emit an event announcing that the hospital
            failed to consume the whole amount
        end
        if wastedAmount(i) > 0 then
            ViolationCounter +=1;
            Emit an event announcing that the hospital
            wasted medical supplies
        end
    end
    if ViolationCounter ==0; then
        Emit an event announcing that the medical
        supply Lot has been manufactured, delivered,
        and consumed properly
    end
else
    Revert
end
```

details are the number of bids, production time, delivery duration, and expiry date. The delivery time is two days, and the expiry date is three months after the production date. After that, the delivery phase is started by the commitment distributor by deploying the delivery and consumption smart contracts. The distributor will confirm the end of the delivery after each hospital confirms its reception of packages. Then, during the consumption phase, each hospital will specify the used and disposed number of packages by calling the UsePackages and DisposePackages functions.

Finally, an event is emitted during the waste assessment phase. It is committed by Hospital A, where 20 packages were disposed of; therefore, this healthcare center is accountable for this waste. A hospital violation event is emitted with details such as the hospital Ethereum Address, the wasted

```
[
        {
                "from":
"0xa131AD247055FD2e2aA8b156A11bdEc81b9eAD95",
                "topic":
"0x44472e0be6bf8a81ef3eda56368873695146aad5b0a5
7be72cfe1e12dfcb416b",
                "event": "CommitmentDetails",
                "args": {
                        "0":
"0xAb8483F64d9C6d1EcF9b849Ae677dD3315835cb2",
                        "1":
"0xa131AD247055FD2e2aA8b156A11bdEc81b9eAD95",
                        "2":
"0x4761757a652073706f6e676500000000000000000000
0000000000000000000",
                        "3": "60",
                        "4": "100",
                        "5": "1643111577",
                        "6": "1800",
                        "_manufacturer":
"0xAb8483F64d9C6d1EcF9b849Ae677dD3315835cb2",
                        "_LotEA":
"0xa131AD247055FD2e2aA8b156A11bdEc81b9eAD95",
                        "_MedicalSupplyType":
"0x4761757a652073706f6e676500000000000000000000
0000000000000000000",
                        "_MinThreshold": "60",
                        "_MaxPackages": "100",
                        "_StartingTime":
"1643111577",
                        "_CommitmentDuration":
"1800"
                }
        }
```


FIGURE 7. Logs displaying the successful creation of the commitment requirements.

amount, and an announcement defining the violation that occurred.

VI. DISCUSSION

This section presents the cost and security analysis of the proposed solution. Also, we show a comparison between our approach and the existing solutions.

A. SECURITY ANALYSIS

This subsection presents various security metrics such as data integrity, data privacy, availability, accountability, resistance to middle man attack, and smart contracts vulnerability analysis. These metrics are examined and analyzed in our proposed solution.

For ensuring *data integrity*, three fundamental characteristics are provided by blockchain technology: data security, event traceability, and transparency in data handling. The proposed solution for medical waste assessment uses an event-based approach where each transaction is recorded and

```
[
	{
		"from":
"0xa131AD247055FD2e2aA8b156A11bdEc81b9eAD95",
		"topic":
"0x54b322c57e5fd716ea42176210ef19a7c33a794854
57d1bab230e3c503079e74",
		"event":
"hospitalCommitmentDetails",
		"args": {
			"0":
"0x78731D3Ca6b7E34aC0F824c42a7cC18A495cabaB",
			"1":
"0xa131AD247055FD2e2aA8b156A11bdEc81b9eAD95",
			"2": "70",
			"hospital":
"0x78731D3Ca6b7E34aC0F824c42a7cC18A495cabaB",
			"_LotEA":
"0xa131AD247055FD2e2aA8b156A11bdEc81b9eAD95",
			"_placedorder": "70"
		}
	}
]
```


FIGURE 8. Logs displaying the successful placing of bids by hospital A.

```
[vm] from: 0x787...cabaB to: LotProductionCommitment.PlaceBid(uint256) 0xA83...5B

transact to LotProductionCommitment.PlaceBid errored: VM error: revert.

revert
	The transaction has been reverted to the initial state.
Reason provided by the contract: "This hospital has already placed a bid before".
Debug the transaction to get more information.
```

FIGURE 9. Error message showing that the bidder cannot place order twice.


```
	{
		"from":
"0xa131AD247055FD2e2aA8b156A11bdEc81b9eAD95",
		"topic":
"0xc631510aef7d9d5aa6504cdc9c84f7a8902aa6f515
d54f46dbdfbb3b9c76f7d7",
		"event":
"ProductionApproved",
		"args": {
			"0":
"0x50726f64756374696f6e20697320617070726f7665
640000000000000000000000",
			"1": "100",
			"2":
"0xa131AD247055FD2e2aA8b156A11bdEc81b9eAD95",
			"_approved":
"0x50726f64756374696f6e20697320617070726f7665
640000000000000000000000",
			"_currentbids":
"100",
			"_vaccineLotEA":
"0xa131AD247055FD2e2aA8b156A11bdEc81b9eAD95"
		}
	}
]
```


FIGURE 10. Logs displaying the successful updating of the total current bids.

stored on an immutable ledger, allowing users to trace the commitment, production, delivery, and consumption phases one by one. For instance, any distributor committed to delivering the lot or any hospital placing bids is recorded in the form of events to confirm that the manufacturer is informed of the handled and needed amount. Moreover, *data privacy* is available in our proposed solution because no personal information is stored permanently on chain; consequently, all participants are recognized by an Ethereum Address rather than their actual identities. Any private information is kept private and is not accessible to the public.

The decentralized feature of blockchain technology has made it immensely popular, as opposed to centralized systems. Decentralization ensures that the system is accessible to all entities securely. As a result, denial of service (DoS) attacks are practically impossible. Our system's functions are always secure and *available* to the involved entities since it is built on the Ethereum blockchain. Besides, actors need to be accountable for their actions, so they can do them in a secure and trustworthy manner. The "Modifier" feature in the Solidity language is useful for *accountability* and non-repudiation metric. In our proposed solution, the involved actors are held accountable for their actions and cannot deny their respective transactions as all transactions are stored permanently on an immutable ledger.

Additionally, a ledger transaction requires the sender's private key signature, preventing attackers from tampering with the blockchain and reducing the risk of *man in the middle attacks*. For example, only people who are trusted can get information and use our blockchain-based medical waste assessment solution.

Furthermore, smart contracts can have vulnerabilities and bugs, affecting the performance of any blockchain system. Hence, we carry out the security analysis using the Oyente tool to ensure that our smart contract codes were free of any vulnerability. Oyente is an auto-auditing tool that analyzes smart contracts and reports possible bug attacks on them. Figure 11 shows the output of the Oyente tool execution. It indicates that the designed smart contracts have no existing vulnerabilities. Therefore, we can state that they are robust and highly secured against common vulnerabilities. Moreover, the EVM code coverage is 99.9% for the registration smart contract, 83.9% for the lot production commitment

TABLE 2. Comparison between our solution and existing blockchain-based solutions.

	[17]	[18]	[19]	[20]	[21]	Our Solution
Blockchain Platform	Hyper-ledger Besu	NA	Ethereum	Ethereum	Ethereum	Ethereum
Mode of Operation	Private	NA	NA	Private	Public	Private
Off-Chain Data Storage	No	NA	Yes	No	Yes	Yes
Traceability	Yes	Yes	Yes	Yes	Yes	Yes
Waste Assessment	No	No	No	No	No	Yes
Implemen-tation	No	No	Yes	Yes	Yes	Yes

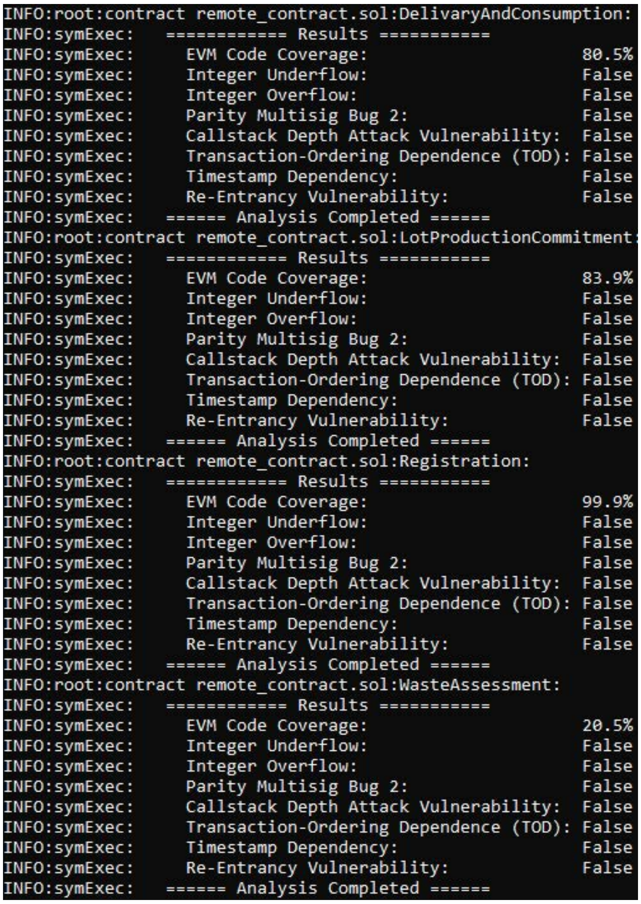

FIGURE 11. Smart contracts vulnerability analysis using Oyente.

smart contract, 80.5% for the delivery and consumption smart contract, and 20.5% for the waste assessment smart contract.

B. COMPARISON WITH THE EXISTING SOLUTIONS

Table 2 shows how our solution is different from other blockchain-based solutions in terms of a number of design factors. These factors include the platform where the blockchain solution is based; the mode of operation, either public or private; offering off-chain storage for large-sized data files; offering traceability where the origin of waste can be identified, including a waste assessment phase where commitment violations can be captured; and offering an implementation for the suggested solution. Overall, all the blockchain-based solutions provide a traceability feature. The solutions proposed in [19]–[21], and our solution used the Ethereum network, while [17] used the Hyperledger Besu [21] that was implemented in a public mode, while our solution and [17], [20] were implemented in a private mode. In addition to that, off-chain data storage is only offered by our solution, [19], and [21]. On the other hand, none of the other solutions implemented the commitment smart contract, where each participant needs to commit to demands and be held accountable for any violations through the assessment smart contract. Overall, identifying entities that are not fulfilling their commitments to reduce medical waste is what distinguishes our solution from other existing solutions. The waste assessment phase identifies which one is behind the waste, as any commitment violations will be captured and announced during it.

Table 3 shows a performance and security comparison between our solution and the existing blockchain-based solutions. Data Confidentiality deals with preventing information disclosure by ensuring that access to data is restricted to those who are permitted. In [21], anyone can participate in the network; therefore, transactions can be viewed, while in [17], [20], and our solution, only authorized entities can participate. Moreover, as the mode of operation in [21] is public; more energy is consumed than in other solutions.

TABLE 3. Performance and security comparison between our solution and the existing blockchain-based solutions.

	[17]	[20]	[21]	Our Solution
Confidentiality Of Data	Yes	Yes	No	Yes
Throughput	High	High	Low	High
Energy Consumption	Low	Low	High	Low
Scalability	Low	Low	High	Low

With public blockchains, transaction speed enhances scalability challenges. The more users on a blockchain, the more it burdens the network with more transactions. When it comes to the number of transactions per second, private blockchains outperform public blockchains. Since private blockchains have a limited number of authorized participants, they may handle thousands of transactions per second. However, because public blockchains have more nodes, they are considered more secure than private blockchains. Our solution, [17], and [20], have high throughput and low levels of scalability issues.

VII. CONCLUSION

In this paper, we proposed a blockchain-based solution to mitigate the medical supplies waste caused by their overproduction and underconsumption in a manner that is decentralized, accountable, auditable, traceable, secure, and trustworthy. We developed four smart contracts that automatically record events, maintain data provenance, and ensure integrity. We presented five algorithms that describe the logic behind our developed smart contracts. Each phase of the proposed solution is discussed in detail, including implementation details, testing, and validation. We presented how our solution ensures data integrity, privacy, availability, accountability, and resistance against middle man attacks. We performed the security analysis to show our developed smart contracts are highly secure against common vulnerabilities and attacks. Our proposed solution is general and can be used in many applications in healthcare and other industries with minimal modifications. In the future, we aim to deploy and test our proposed solution on the real Ethereum network and build an end-to-end DApp.

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