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RESEARCH ARTICLE

# A Blockchain-Based IoT-Enabled E-Waste Tracking and Tracing System for Smart Cities

**ATTA UR REHMAN KHAN, (Senior Member, IEEE), AND RAJA WASIM AHMAD**
College of Engineering and Information Technology, Ajman University, Ajman, United Arab Emirates

Corresponding author: Atta Ur Rehman Khan (dr@attaurrehman.com)

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**ABSTRACT** Recycling of electronic waste is a rapidly growing global issue that requires proper monitoring and tracing of electronic devices and the business transactions between the stakeholders. The majority of current systems that manage electronic devices throughout their supply chain stages are centralized and lack data transparency, immutability, and security. Specifically, such systems are incapable of handling problems like comprehensive coverage of the life cycle of e-products, access control for maintaining data security, reputation-aware selection of stakeholders, and large amounts of data generated during various stages of the supply chain processes. In this paper, we propose a blockchain-based IoT-enabled system for monitoring all post-production business processes, activities, and operations performed on an electronic device. The system is supported by five smart contracts that record the actions of users on the immutable distributed ledger that aid in ensuring that the business processes carried out by the participants are transparent, traceable, and secure. To store large files, such as images of e-waste materials, products, and licenses for stakeholders, we have integrated our system with a distributed storage system. The proposed system is tested on Ethereum blockchain to check the gas consumption of the functions of the smart contracts. The cost and security analysis shows that the proposed system is viable.

**INDEX TERMS** Blockchain, smart cities, security, e-waste, traceability, IoT, Ethereum.

## I. INTRODUCTION

Smart cities rely on multiple technologies to create, deploy, and promote sustainable development strategies to meet the increasing demands of urbanization. For smart cities to be sustainable, they try to be energy efficient and have a small carbon footprint. In order to improve quality of life, the Smart City Index (SCI) examines many factors, such as health, mobility, safety, and waste management. Population growth, urbanization, and economic growth have all led to a rise in waste generation. Considering the impact of waste on public health, environment, and climate, modern waste disposal and treatment methods, such as bioremediation, incineration, and plasma gasification, are utilized.

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In the last two decades, the life span of electronic equipment has reduced substantially due to rapid technical advancements. Managing e-waste is currently one of the major challenges of the urban cities. E-waste is more difficult to manage than conventional waste since it contains toxic chemicals, radioactive materials, and storage devices that might lead to privacy and security issues. If the storage devices are not disposed appropriately, they may fall into the hands of adversaries who acquire storage devices in bulk and scan them for sensitive information. Through this process, they can extract important data, such as encryption keys, crypto wallets, social security numbers, blueprints of important buildings, and even classified information of the governments [1], [2]. Therefore, electronic devices require evidence-based tracking, tracing, destruction, and recycling. Internet of Things (IoT) is one of the building blocks of smart cities and can play a crucial role in the collection and tracking of e-waste. Moreover, blockchain can allow us undertake evidence-backed tracking, tracing, destruction, and recycling of e-waste to prevent e-waste from entering the black market.

Many of the existing solutions for supply chain and waste management are based on IoT and cloud computing. Some of these solutions also offer financial incentives in the form of tokens to motivate people to deposit waste in the designated places. Due to the absence of auditing features, there is always a risk that e-waste may enter the black market, where criminals can extract radioactive materials or confidential data from the storage devices. Moreover, these systems are typically centralized and have scalability and single point of failure issues. Moreover, these solutions often lack essential features, such as transparency, traceability, accountability, and privacy etc.

Considering the issues of the centralized solutions, researchers have emphasized the usage of blockchain-based solutions for numerous applications [3], [4], [5], including waste management. Hence, along with the centralized solutions, there also exist some blockchain based solutions for the waste management. However, these solutions are mainly designed for medical waste or general waste management. There also exist some blockchain based solutions proposed for smartphones and electronic devices, however, they focus on a particular portion of the forward supply chain [6]. These solutions lack many important features, such as tracking and tracing from the time of manufacturing to the time of recycling, validation of the involved stake holders and their license status, reputation management of the stack holders, and issuance of certificates confirming the destruction of storage devices.

In this paper, we present a blockchain based IoT-enabled e-waste tracking and tracing system. The proposed system keeps track of the electronic devices from the time of its manufacturing and facilitates the consumers in depositing their used electronic devices through IoT-enabed smart waste bins. This proposed system is implemented on blockchain and uses multiple smart contracts to ensure proper handling of the e-waste. It uses reputation-centric criteria to minimize frauds in supply chain operations. In addition, to cater to the data privacy issues of the storage devices, it issues certificates as a proof that the storage device data is destroyed properly.

The main contributions of this work are as follows:

- Blockchain based system for tracking and tracing of electronic devices (e-waste) after their production.
- Reputation-centric criteria for stakeholders selection to minimize frauds in supply chain operations.
- Certificate issuance for proof of destruction of the storage devices data.
- Testing and implementation of the proposed system on Ethereum blockchain.
- Security and cost analysis of the proposed system to confirm its viability.

The rest of paper is organized as follows. Section II presents the related work. Section III presents the proposed system and its sequence diagram, showing interactions between the stakeholders. Section IV presents the implementation details. Section V presents testing and validation. Section VI presents discussions on the cost and security analysis. Section VII presents conclusions and future work.

## II. RELATED WORK

When it comes to waste management, smart cities are increasingly focusing on the design and development of waste management solutions that are based on advance technologies, such as Internet of Things (IoT), Cloud Computing, AI, and blockchain. There are various solutions for waste management in which the consumers or stakeholders are given incentives for recyclable goods. For example, in [7] and [8], the consumers are rewarded coins/tokens for depositing their recyclable goods. In [8], the researchers highlight some of advantages of the blockchain technology and the main challenges in adopting blockchain based waste management systems.

In [9], the researchers present a blockchain based reward system for solid waste management. In this system, LoRa based sensors are attached to waste-bins to monitor the garbage level. This data is uploaded to the cloud on runtime and also written on the blockchain. The individuals who dispose their waste in the bins are automatically rewarded based on the quantity of the waste. In this work, there are no special considerations for the e-waste.

In [10], the researchers present a smart trash control system for universities to reduce cost of waste collection. Similar to the previous technique, they use multiple LoRa based sensors to monitor the garbage level in the waste-bins. In addition, they use ML technique to predict the filling time of the waste-bins and graph theory based optimization solution to compute paths and schedule for waste collection. Similar to the previous work, there are no special considerations for the e-waste.

In [6], the researchers present a blockchain-based solution for COVID-19 medical equipment waste management. This system uses Ethereum blockchain with Interplanetary File System (IPFS) [11] for the management of COVID-19 medical equipment data. The positive aspect of this system is that the interaction rules for the management and handling of COVID-19 waste are defined. In addition, relevant entities are penalized for violations in case of mishandling of the medical waste. This work only deals with the COVID-19 waste and has no special considerations for the e-waste.

In [12], the researchers present a smart waste management system that uses pricing estimation model to charge waste producers based on the quantity of the waste that they produce. This system utilizes IoT for monitoring waste in the waste-bins. Also, it uses blockchain for micropayments between the involved stakeholders. The main drawback of this work is that it has no special considerations for e-waste.

In [13], the researchers present an electronic waste management system with an objective to assure compliance with the guidelines for Electrical and Electronic Equipment (EEE). This system uses smart contracts to keep record of the EEE waste and provide incentives to the consumers who return their old electronic items. In this system, the producers are penalized if they fail to collect EEE waste from the retailers. This system has no bidding mechanism and does not provide certificates to confirm destruction of data on the electronic devices.

In [14], the researchers present an Ethereum blockchain based system for tracking of electric equipment throughout their lifetime. They use smart contracts between different stakeholders and provide incentives to the consumers who dispose their e-waste in e-waste facilities. In this work, stakeholders are also bound to deposit some amount which is returned once the e-waste reaches the e-waste facility, and it is ensured that the stakeholders are in compliance with the defined e-waste management rules. However, the role of the data destruction unit has not been considered in the proposed research. In addition, the researchers ignored the significance of the stakeholders' reputations in supply chain operations.

In [15], the researchers present an Ethereum blockchain based system for secure disposal of confidential e-waste, such as hard drives that can contain secret/confidential data. This system uses smart contracts to allow authorities to perform audits and verify different activities related to secure disposal of e-waste. This system also ignore the stakeholders' reputation and does not provide certificates for destruction of data on the electronic devices.

In [16], the researchers present a smart e-waste management system that uses online interactive maps. With the help of the interactive maps, the consumers can request for collection of e-waste from their locations to the enterprise recycling units. In this work, the researchers propose utilization of the available delivery services to deliver the e-waste to the respective recycling units without deviating from the planned route. The main motive for doing so is to reduce the emission of $CO2$ incurred by the e-waste delivery vehicles. Similar to the previous techniques, this system has no mechanism for stakeholders reputation, bidding, or data destruction certificate issuance.

In [17], the researchers present a distributed trustless solution for reverse logistics activities related to e-equipment, especially the smartphones. The main contribution of this work is the use of blockchain for smartphone refurbishment, with a particular emphasis on the privacy of user data kept on the devices, in order to increase consumer confidence in refurbished smartphones. This solution has no bidding mechanism and does not provide certificate for destruction of data that is stored on the electronic devices.

In summary, existing research has ignored the role of the data destruction unit in e-waste management, putting data security at risk. In addition, the participants' reputation scores were not considered in the aforementioned works. As a result, participating entities may engage in unethical activities, and electronic device and e-waste trading frauds may occur. To prevent such frauds, in our proposed system, only participants with impeccable reputations are permitted to trade electronic devices and their waste. Moreover, our solution provides a certificate for data destruction on the electronic devices.

## III. PROPOSED IoT-ENABLED BLOCKCHAIN-BASED SOLUTION

In this section, we present the high-level design of the IoT-enabled blockchain-based solution for tracking and tracing electronic devices and their waste in smart cities. It highlights the stakeholders, as well as, the operations carried out on an electronic device after its manufacturing. The system users, their roles and operations, system components, and direction of data flow between various entities of the proposed blockchain-based system are highlighted in figure 1. The role and duties of users in the proposed system are discussed further in the following section.

### A. SYSTEM PARTICIPANTS AND COMPONENTS

This section outlines the responsibilities of each stakeholder involved in tracking and tracing of electronic devices and their waste in smart cities. It also highlights the key system components that ensure that electronic devices and e-waste disposal-related activities are carried out in a secure, trusted, reliable, transparent, and verifiable manner. The main components and system participants of our proposed system are discussed as follows:

#### 1) MANUFACTURERS

Manufacturers are responsible to manufacture the electronic devices for sale. They sells the electronic products to distributors and retailers. Before manufacturing any electrical equipment, the manufacturer undertakes market research to ensure that supply and demand are balanced. In our proposed system, the manufacturer creates a lot that is identified by a unique identity and publishes facts about the manufactured devices to the blockchain. The manufacturers record all important information on the blockchain, such as device name, type, production date, design, and type of raw material used in manufacturing process. The system also keeps track of the certificates granted by the authorities to ensure that the manufacturers have a valid manufacturing license.

#### 2) RETAILERS

The retailers role is to buy electrical devices from the manufacturer or distributor and resale them in small quantities to the general public. They ensure that all of the customer's purchase requirements are addressed as quickly as possible. When the retailers buy electrical devices from distributors/manufacturers, they create lots of the bought items on the blockchain (referenced by unique identities) and allows consumers to buy electronic devices from them. They are also responsible of coordinating shipments for the delivery of the consumer orders. They also make their trading license public on the blockchain, ensuring the validity of the license.

#### 3) CONSUMERS

Consumers purchase the electronic equipment from retailers. In order to place a buy or sell request, consumers must be

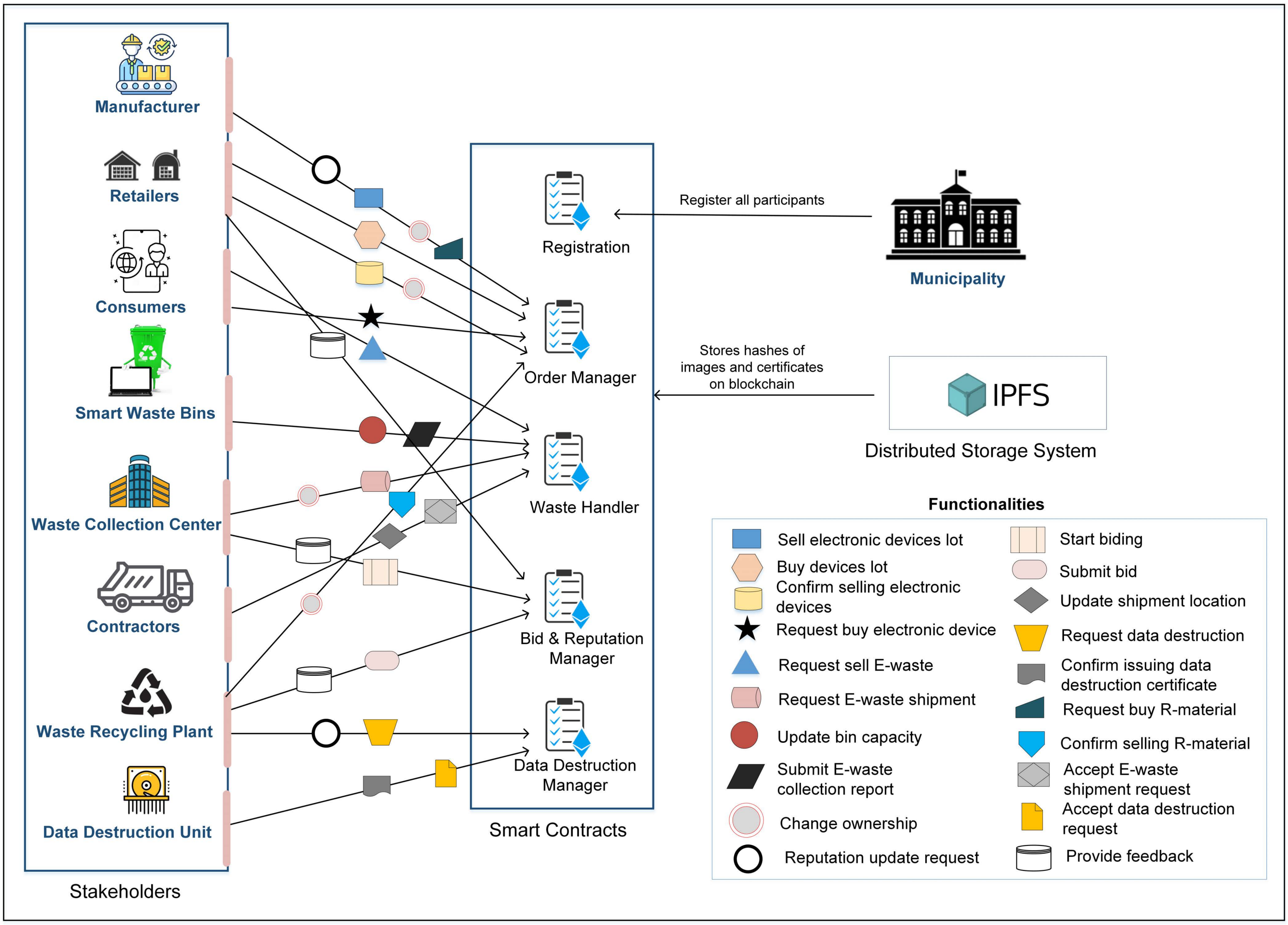


**FIGURE 1.** An overview of the proposed blockchain-based IoT-enabled e-waste management system in smart cities.

registered on the blockchain. Consumers deposit coins electronically into the retailers wallet after successful delivery of the placed order. After the usage, when the consumers want to dispose off their electronic devices, they deposit their devices in the nearby smart waste bins. The consumers may search for nearby waste bins that are registered on the blockchain by utilizing smart contracts stored on the blockchain. Ethers are automatically credited to the consumers wallets based on the type and weight of the e-waste following the disposal of e-waste into the smart waste bins.

### 4) SMART WASTE BINS

Using sensors and image recognition technologies, smart waste bins are able to differentiate between different types of waste. They are also capable of determining the weight of the e-waste that is being dumped in the containers. In our proposed system, it is assumed that IoT-enabled smart waste bins are deployed across a smart city. These bins are managed, owned, and controlled by the waste collection centers/facilities. When a waste bin reaches its maximum capacity, the server associated with the container triggers a transaction on the blockchain and requests waste shipment. In addition, it generates and sends a report about the e-waste depositor. Payments to waste depositors are based on this report.

### 5) WASTE COLLECTION CENTER

The e-waste collection bins are situated throughout the smart city and are managed by the waste collection center. Waste collection center also arranges transportation service provides (contractors) for the collection of e-waste and are responsible for controlling overflow of the waste bins. Waste collection center chooses contractors based on the bids that prospective contractors submit. While announcing the bid on the blockchain, the center specifies the terms and conditions (e.g., delivery time, route, and safety limits), and the applicant with best match to the defined terms and conditions is selected. The consumers who dump electronic waste are identified by the smart waste bins, and waste collection center is notified by triggering a blockchain-based event. In response, the waste collection center pays money in the form of cryptocurrency to the e-waste depositors. The center eventually

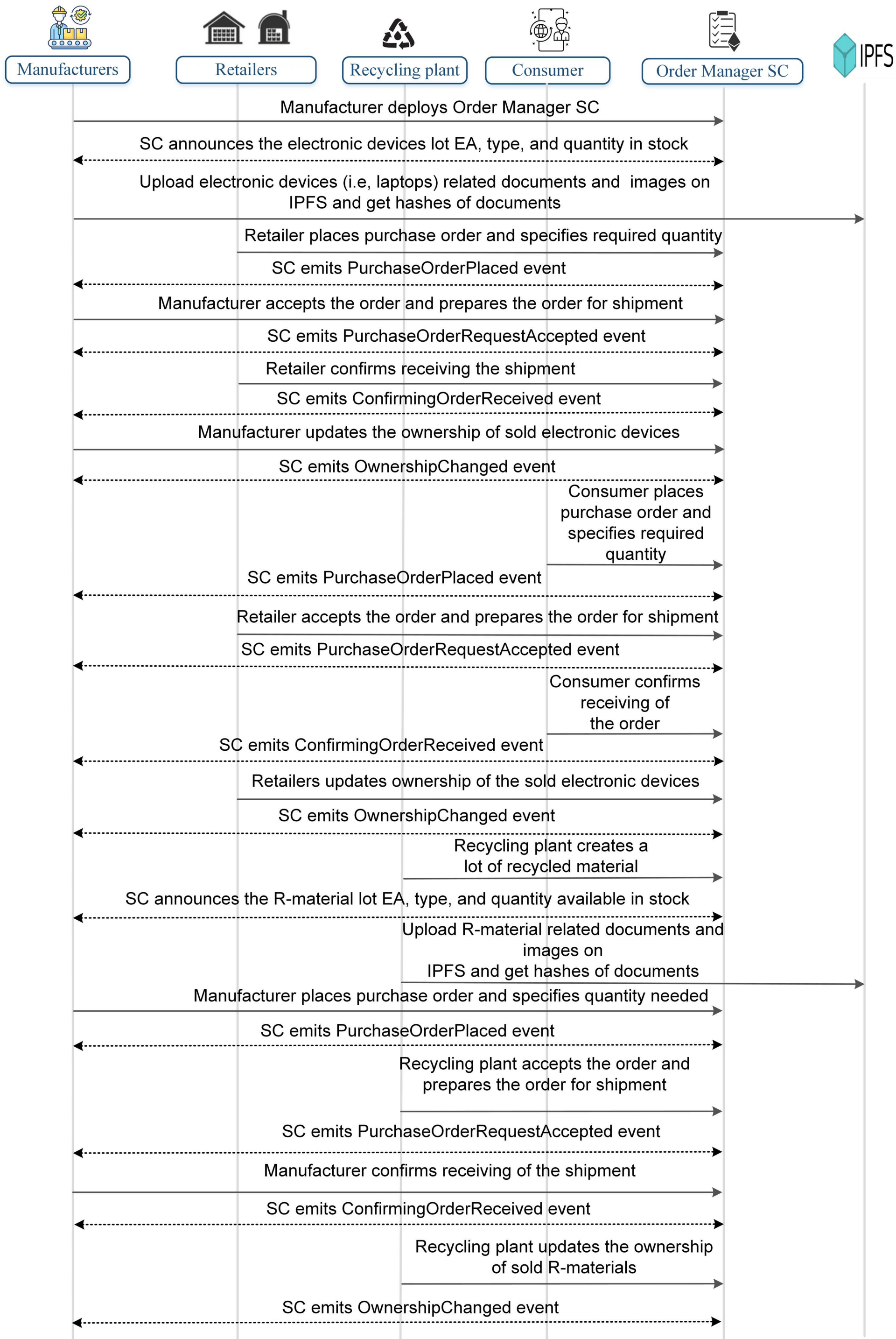


**FIGURE 2.** **Detailed sequence diagram illustrating how the Order manager smart contract can be used to regulate business operations between participants.**

sells the e-waste it collects from customers to the recycling centers.

### 6) CONTRACTORS

Contractors are responsible for collecting and transporting electronic waste from the waste collection center to the recycling facility. During e-waste shipment and handling, the contractor adheres to all government-issued guidelines and rules for handling and managing e-waste. Contractors are obligated to deliver e-waste to the agreed-upon location in a timely and secure manner. In addition, the contractor periodically updates the involved parties on the shipment current location, route, and estimated time of arrival. In our proposed system, the waste collection facility hires and pays the contractors after using their services. In addition, only registered contractors can be hired to transport the e-waste to their destination.

#### 7) WASTE RECYCLING PLANT

This facility's main purpose is to ensure that all waste is recycled. The e-waste is transported to the recycling facilities by contractors engaged by a waste collection facility. To improve public health, the environment, and the climate, processes such as incineration, bioremediation, and plasma gasification are performed on e-waste when it is delivered. Furthermore, the recycling plant identifies IT data storage devices during the e-waste segregation phase and delivers them to a data destruction facility for data destruction. The electronic devices are scrambled and r-material (recycled material) is collected and sold to the producer. After this, r-material is used to construct new electronic equipment.

#### 8) DATA DESTRUCTION FACILITY

The data destruction facility's principal goal is to erase data from the storage devices it receives. This facility uses cutting-edge data destruction procedures to ensure that data privacy is maintained during data erasing process. A certificate is issued to the waste recycling unit when the data is successfully destroyed. This certificate serves as verification that data was safely and securely erased before the electronic data storage device was recycled.

#### 9) SMART CONTRACTS

Smart contracts are computer programs that execute themselves and reduce the need for mediators while ensuring the administration of rules as agreed upon by the parties. As part of our research, we developed five primary smart contracts, namely registration, order manager, waste handler, bid handler, and data destruction manager. The smart contracts implement functions that are called when a certain event incurs relating to the management of electronic waste.

#### 10) DISTRIBUTED STORAGE

Blockchain technology faces scalability issues, especially when massive files and data are to be stored on the blockchain. Distributed storage solutions (e.g., IPFS) allow stakeholders, such as manufacturers, merchants, waste recycling plants, and contractors to store huge size photos and files in a reliable and secure way without worrying about the scalability issues. In our proposed system, IPFS is used to store huge files and photos related to manufactured or recycled materials, as well as, user licenses. It is not worthy that only hashes of the files are stored on the blockchain.

### B. SEQUENCE OF OPERATIONS

This section presents the sequence diagrams for our proposed system. These diagrams show the function calls and events that occur on the blockchain when a function is called.

Figure 2 shows a sequence diagram that highlights the user's interaction with the system. All system users must be registered on the blockchain and must have valid licenses in order to transact on the blockchain. The presented sequence diagram shows the business operations carried out by the Order Manager smart contract. Order manager smart contract allows participants to place, reject, deny, and accept requests of buying or selling the electronic devices or waste. This smart contract is deployed on the blockchain by the manufacturer. The manufacturer registers information about the manufactured electronic devices on the blockchain, as well as, their images on IPFS. Retailer places a purchase order request using Order Manager smart contract to show the willingness in purchasing the electronic equipment. In response, manufacturer accepts or rejects the request based on factors, such as available stock, retailer reputation, and any other factors that are negotiated off-chain. When the buy order request is accepted, blockchain emits *PurchaseOrderAccepted* event to inform the related participants about occurrence of this transaction on the blockchain. The retailer invokes *ConfirmReceiving* function to confirm receipt of the shipped order and emits *ConfirmedOrderReceived* event to notify the participants of the delivery.

In our proposed system, the consumer is an entity that purchases electronic items only from the registered retailers. Consumer submits a buy request by invoking the Order Manager smart contract's *PlaceBuyRequest* function. In response, retailer approves or rejects consumer's request after verifying the available inventory. If the order is accepted, the retailer will organize shipment and notify the consumer about the shipment by triggering an event on the blockchain. Using the *ConfirmingOrderRequest* function of Order Manager smart contract, the consumer notifies the retailer that order has been delivered. After receiving the package, the retailer calls the *ChangeOwnership* function to update the ownership of the electronic devices. Consequently, the consumer's status of the electronic device is updated as a new owner. The Order Manager Smart contract also allows the manufacturer of electronic devices to buy r-material from the waste recycling plant. The waste recycling facility generates the r-material and registers it on the distributed ledger. By invoking the *PurchaseOrderPlace* function, a licensed manufacturer places a request to buy r-material. The waste recycling plant can accept or reject the order request based on the criteria mentioned in the smart contract. The manufacturer notifies the waste recycling facility that the r-material has been received by calling the *ConfirmingOrderReceived* function, which emits the *ConfirmingOrderReceived* event.

Figure 3 highlights the user's interaction with the system using a sequence diagram. In shown in the figure, the business operations between waste recycling plant, waste collection center, data destruction unit, waste contractors, and smart waste bins are implemented using functions defined in Bid Manager, Waste Manager, and Data Destruction Manager smart contracts. The Waste Manager smart contract is responsible to implement waste handling, storing, processing, and

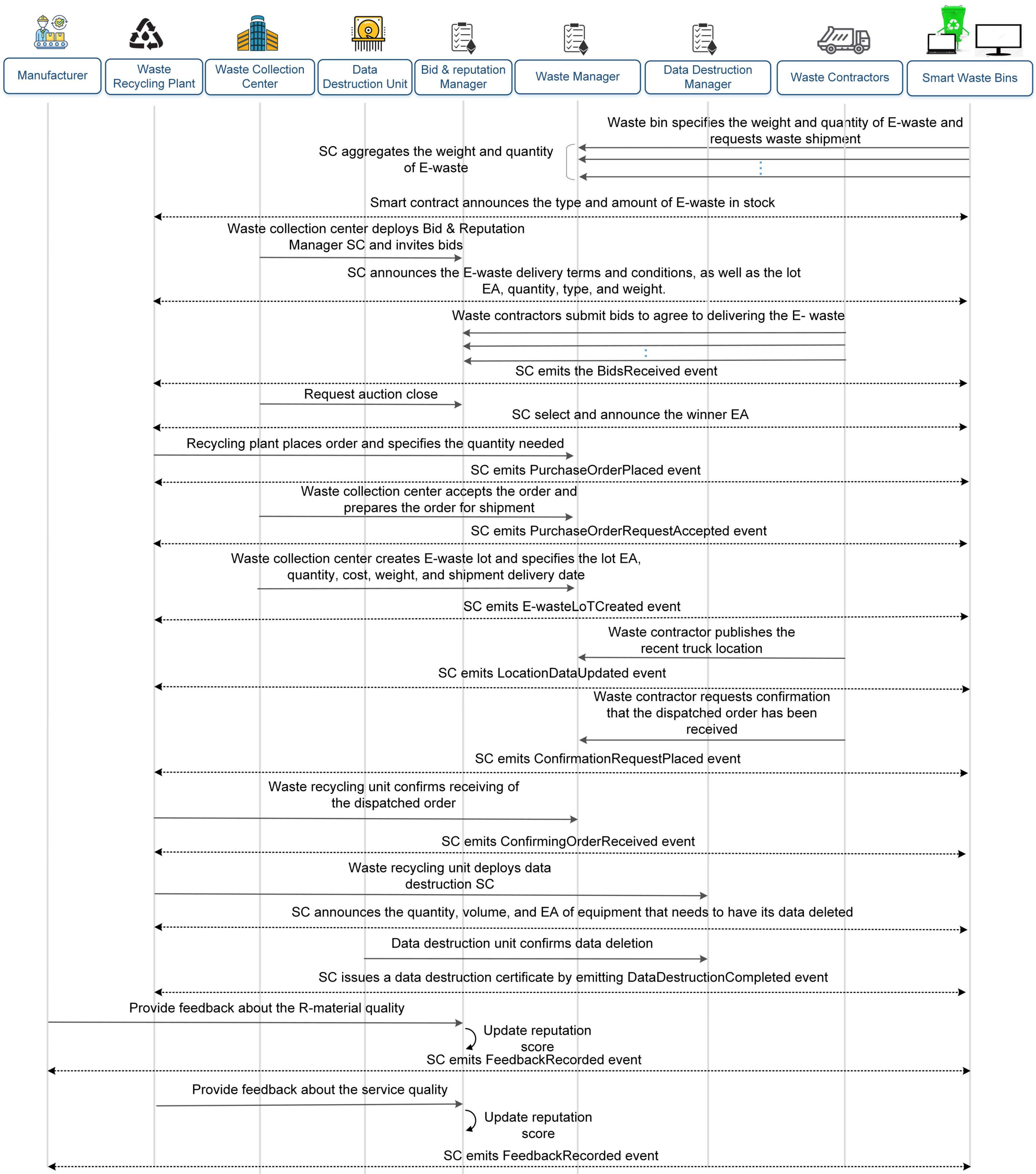


**FIGURE 3. Detailed sequence diagram illustrating how the bids & reputation manager, waste manager, and data destruction manager smart contracts can be employed to regulate business operations between participants.**

transportation services. Customers deposit waste in smart waste bins, which is equipped with sensors that compute the type and weight of e-waste. When the waste containers are full, they publish this information on blockchain by calling *UpdateCapacity* function. The smart contract calculates the total weight of the e-waste that is reported by consumers and requests the waste collection facility of the e-waste to collect it. Bid and reputation manager smart contract is used by the waste collection center to select contractors for e-waste shipment in a certain area. All contracts submit bids and the smart contract selects the contractors whose offers most closely fit to the waste collection center's specifications. Contractors inform the participants about the current location of shipment by using the waste manager smart contract's *UpdateLocation* function.

The Waste Manager smart contract is used by the e-waste recycling plant to purchase e-waste from waste collection centers. When the shipped order that carries e-waste is successfully received from the contractors, the waste recycling plant notifies the involved entities by triggering the

**Algorithm 1** Placing a Request to Buy Electronic Devices From Manufacturer

```
Input: Electronic device EA, shipment delivery due
  date, quantity, and type
Output: Emit PurchaseOrderPlaced Event
if Retailer is not a registered user then
    The request is rejected due to an unverifiable
      Ethereum address.
end
else
    if Order placing entity is a Retailer AND
      QuantityRequested < Lot.GetLOTQuantity() AND
      QuantityRequested >
      Lot.MinimumOrder_threshold AND Trade_licence
      != Expired AND Manufacturer.GetReputationScore
      ( ) > Minimum_Threshold then
        Set request status to 'Waiting'.
        Create an order ID.
        Inform the stakeholders by emitting an event
          reporting the successful placing of a request for
          electronic devices using the retailer EA,
          amount requested, and electronic device EA.
    end
    else
        Display an error message and return the smart
          contract to its initial state.
    end
end
```

**Algorithm 2** Submitting Bids to Confirm Delivering e-Waste in a Particular Region

```
Input: Waste contractor EA, bid
Output: Emit ContractorsSelected Event
if Waste contractor is not a registered user then
    The request is rejected due to an unverifiable
      Ethereum address.
end
else
    if WasteContractor has a valid permit to ship
      e-waste AND Bidscount ! = Threshold_limit AND
      biding. status = = Open AND Biding_Value <
      MaximumThreshold AND Reputation_Score
      >Minimum_value then
        Register the bid.
        Create Bid submission ID.
        Set bidding status to "Submitted".
        Bidscount+=1.
        Inform the stakeholders by emitting an event
          reporting the successful placing of a bid for
          shipping electronic waste in a particular region
          using the Waste contractor EA, biding values,
          biding ID, and status.
    end
    else
        Display an error message and return the smart
          contract to its initial state.
    end
end
```

*ConfirmigOrderReceived* function. The waste is separated in the waste recycling plant. Data storage devices, such as hard drives, are separated from e-waste during the waste segregation process. The waste recycling plant then uses Data Destruction Manager smart contract to ask the data destruction unit to erase the data from such devices. The data destruction unit accepts or rejects the waste recycling unit's request. After successful data erasure from storage devices, it issues a certificate of data destruction to the waste recycling unit. The waste recycling plant can destroy and recycle these storage devices after acquiring the certificate.

## IV. IMPLEMENTATION DETAILS

The smart contracts are written, compiled, and tested in the Remix IDE for system evaluation. We designed multiple smart contracts, namely Registration, Order Manager, Waste Manager, Bid & Reputation Manager, and Data Destruction Manager to implement services relevant to operations performed on the electronic products by the stakeholders; after they are manufactured.

Electronic device manufacturers manufacture a large number of electronic gadgets, which they then publish on the blockchain. Important details about the created lot are published on the blockchain, which includes total quantity, price, and minimum and maximum order thresholds information. Following the public release of such information, retailers can place purchase orders for electronic devices. Algorithm 1 shows procedure of how an order for electronic devices can be placed and verified on the blockchain. For the algorithm to work successfully, the caller must supply information, such as the electronic device EA, shipment delivery date, amount, and type of the electronic device. It is note worthy that only a register retailer can make a request for electronic devices. It also validates that the requested quantity is less than the available quantity and larger than the minimum order threshold, as well as that the retailer has a valid license. Using the Keccak 256 algorithm, our algorithm generates a unique identifier. In addition, it changes the status of the order to "Waiting". By emitting a *purchaseorderplaced* event, it notifies the participating entities that a new order has been placed.

Following the successful triggering of event from Algorithm 1, the manufacturer creates the electrical devices lot and prepares it for shipment, as shown in Figure 2. The manufacturer changes the ownership of the electronic items by naming the retailer as the new owner of the sold lot. The consumers buys electronic devices from the registered retailers and become their new owners. After using an electronic item, the users can dispose of their devices in smart waste bins managed by the waste collection center. The waste

**Algorithm 3** Placing a Request for Data Destruction Unit to Perform Data Erasing

**Input**: Quantity, type, service time, device EA
**Output**: Emit *DataDestructionRequestPlaced* Event
**if** *Caller is not a registered user* **then**
    This service cannot be granted due to unverifiable Ethereum address.
**end**
**else**
    **if** *Caller is WasteRecylingPlant AND Permit.GetPermitofDataDestructionUnit ( )!= Expired AND Reputation_Score > Minimum_Value AND Device.Type = = Storage* **then**
        Generate an identifier to uniquely identify the order.
        Update status of the order to 'Submitted'.
        Emit an event for the entities participating to let them know that the data destruction request was successfully placed using the waste recycling unit EA, the device EA, and the data destruction unit EA.
    **end**
    **else**
        Display an error and restore the smart contract to its initial state.
    **end**
**end**

**Algorithm 4** Issuing Data Destruction Certificate of the Storage Devices

**Input**: Waste recycling unit EA, order ID, payment status
**Output**: Emit *DataDestructioncertificateIssued* Event
**if** *Data destruction unit is not a registered user* **then**
    The request is rejected due to an unverifiable Ethereum address.
**end**
**else**
    **if** *Order.status==submitted AND Payment_Status== 'Yes' AND Reputation_Score > Satisfactory* **then**
        Store certificate on IPFS.
        Set status to "Completed".
        Store IPFS hash on blockchain.
        Set shipment.status= TRUE.
        Inform the stakeholders by emitting an event reporting the successful issuing of a certificate for electronic waste using the Waste recycling unit EA, data destruction unit EA, Shipper EA, and order ID.
    **end**
    **else**
        Display an error message and return the smart contract to its initial state.
    **end**
**end**

collection center arranges for e-waste to be transported from the waste collection center to the waste recycling facility via a transportation service. The waste collection center creates a bid on the blockchain, requesting that the waste be sent to the waste recycling facility by approved and registered waste contractors. On the blockchain, the waste collection center registers its requirements in terms of the earliest pick-up time, price, and safety measures (e.g., no opening of e-waste during shipment). In response, the bids are submitted to the blockchain by the retailers using procedure mentioned in Algorithm 2. It ensures that bidders are registered and approved, that bidding is open, and that the submitted bid value is more than the minimal threshold value. It also ensures that no one else can create, register, and start auctioning except the waste contractor. When twenty bids are received, the algorithm ends the bidding. The *BidsReceived* event is emitted by the algorithm to notify the participants. These submitted bids are analyzed by an algorithm operating on an edge server, which selects the contractors whose proposals are most closely aligned to the registered specifications. The winners of the bids are announced by a smart contract stored on the blockchain.

The e-waste is delivered to the waste recycling center by the waste contractors. The e-waste is separated at a waste recycling center, and data storage devices are isolated from the e-waste as such devices require data erasing before performing recycling to preserve data confidentiality. Algorithm 3 highlights procedures that are used to request data erasure from data storage devices by the data destruction unit. Quantity, device type, expected service duration, and device EAs are provided as inputs to Algorithm 3. This algorithm assures that this procedure/ service can only be invoked by a waste recycling center. In addition, it assures that the order is approved only if the data destruction unit has a valid license, is approved, and the device type is storage. The algorithm generates an order with a unique identifier and sends an event called *DatadestructionRequested* to all participating entities informing them of the order. The procedure for obtaining a data destruction certificate from a waste data destruction unit is shown in Algorithm 4. It guarantees that certificates can only be issued by the data destruction unit. The algorithm ensures that a certificate can only be provided if payment has been received and a certificate request has been made. The issued certificate is stored on IPFS, and the hash of the certificate is shared with the waste recycling center in order for it to be accessed securely. The event is broadcast to notify participants of the issuance of a certificate of data deletion.

## V. SYSTEM TESTING AND VALIDATION

This section discusses system testing and validation details. The smart contracts are written, compiled, and tested in the

**TABLE 1. Ethereum addresses for participants.**

| Stakeholder Name | Ethereum Address |
|---|---|
| Waste Collection Center | 0xAb8483F64d9C6d1EcF9b849Ae677dD3315835cb2 |
| Consumer | 0x4B20993Bc481177ec7E8f571ceCaE8A9e22C02db |
| Contractors | 0x78731D3Ca6b7E34aC0F824c42a7cC18A495cabaB |
| Data Destruction Unit | 0x617F2E2fD72FD9D5503197092aC168c91465E7f2 |
| Manufacturer | 0x17F6AD8Ef982297579C203069C1DbfFE4348c372 |
| Retailer | 0x5c6B0f7Bf3E7ce046039Bd8FABdfD3f9F5021678 |
| Smart Waste Bin | 0x03C6FcED478cBbC9a4FAB34eF9f40767739D1Ff7 |
| Waste Recycling Plant | 0x1aE0EA34a72D944a8C7603FfB3eC30a6669E454C |
| Owner/Municipality | 0x5B38Da6a701c568545dCfcB03FcB875f56beddC4 |

**FIGURE 4.** Function call result indicating that the waste collection center was successfully registered.

Remix IDE for system evaluation. Moreover, the smart contract functions are written in Solidity language.

As a part of the forward and reverse supply chain of electronic devices in smart cities, five smart contracts are proposed to implement the services performed by participants. We rigorously tested the proposed smart contracts to ensure that no supply chain violations occur during forward and reverse operations in IoT-enabled smart cities. We added modifiers to the functions to ensure that only authorized, registered, and valid participants can perform certain tasks. If an unauthorized access is made, the smart contract generates an error and notifies the participants. Events are implemented within functions and are emitted automatically to transparently record transaction logs. Traceability services benefit from such logs. Furthermore, system participants are assigned Ethereum addresses, which serve as unique identifiers. Table 1 shows the Ethereum addresses that have been assigned to users of our proposed system.

Figure 4 shows successful registration of the participant when the Registration smart contract's *Register_CollectionCenter* function is run. Using the function modifier of this function, the system guarantees that the entity invoking this function is the owner/municipality. After that, the system successfully registers the waste collection center's valid and unique Ethereum address and license number on the blockchain. Smart contract ensures that the participant is only registered once. The registration smart contract also implements other supporting functions, such as *WasteCollectioncenterExist* and *WasteCollectionCenterLicencesisValid*, which assist to govern access control policies in smart cities.

Once all entities are successfully registered on the blockchain, the participants can perform business transactions among them. Figure 5 shows result of the executing

**FIGURE 5.** Log showing the successful placement of order for electronic devices by Retailer.

**FIGURE 6.** Function call result showing the initial reputation score assignment to contractors.

**FIGURE 7.** Log showing the user's updated reputation score based on the feedback submitted by service user.

*PlaceOrderRequest* function by the retailer. This function is implemented in Order Manager smart contract, and can be called only by the retailer and consumers entities. It receives the order receiver EA, the device ID, the lot size, the orderer EA, and the time of shipment as inputs. On successful execution of this function, the *OrderPlaced* event is emitted to notify the participants about occurrence of the transaction. The same function can be used by customers to purchase electrical devices from stores. Consumers sell the used electronic items to the waste collection center by dumping them in a nearby smart waste bin.

The Bid and Reputation Manager smart contract is in charge of providing feedback to the participants, as well as, calculating and updating their reputation scores. Figure 6 shows result of the function that assigns reputation score to the new participants. The waste collection center assigns

**FIGURE 8.** Log showing the bid announcement by waste collection center.

**FIGURE 9.** The user is not allowed to participate in the bidding process due to an insufficient reputation score.

**FIGURE 10.** Log showing the result of bid closing by the waste collection center.

**FIGURE 11.** Log showing the issuance of data destruction certificate to the waste recycling unit.

the waste contractors a reputation score as shown in the diagram. The initial score assigned to each participant is 80. This function's access modifier ensures that only authorized stakeholders can provide a reputation score to an entity. The service consumers use the *GiveEntityFeedback* function to submit feedback to the system about the provider's service. The input (feedback) submitted by the participants should be 1 or 0. If the submitted feedback is 1, the algorithm will enhance the participant's reputation score by a factor of four [18]. Otherwise, the participant's reputation score will be reduced by a factor of four. The result of executing the *CalculateEntityRepScore* function to update the users' reputation scores depending on the feedback supplied is shown in Figure 7. Being the service consumer, the waste collection center or the waste recycling unit can use this function to update the reputation score of service providers. This function cannot be called by other participants because of the rules implemented by the function access modifier. Because the feedback supplied in the above figure was 1, the user's new reputation score has raised to 84.

The outcome of running the *startBidingRequest* function is shown in figure 8. The access modifier implemented by this function ensures that only the waste collection center can call the function. The waste collection center leverages this function and announces its specifications (e.g., minimum reputation score of bidder and maximum cost for e-waste shipment) and asks highly reputable contractors to submit bids. Following successful execution, an event named *AuctionStarted* is triggered, informing bidders that bidding is now open. As a result, the participants participate in the bidding process, and if they are permitted users, they will be allowed to submit their bids. The result of executing the *SubmitBid* function is shown in figure 9. The smart contract prevents the bidder from submitting a bid since the bidder's reputation score is lower than the minimum reputation score threshold. Figure 10 shows the result on executing the *CloseBidandAnnounceWinner* function of bids and reputation manager smart contract. This function can only be called by the waste collecting center. The waste collection center uses this function to choose and announce the bidders who submitted the best bids in terms of pricing and other shipment parameters.

Using the *PlaceEwasteRequest* function, the waste recycling unit submits an e-waste purchase request to the waste collection center. By executing the *LocationUpdateSending* and *RequestConfirmWasteReceiving* functions, the contractor starts the e-waste shipment and acknowledges the e-waste receiving. By executing the *PlaceDataRemovalRequest* function, the waste recycling unit sends a request to the data destruction unit for the destruction of storage devices. In response, the data destruction unit destroys the data of the storage devices and transports them to the waste recycling unit. The outcome of invoking the *RequestCertificateIssue* function is shown in figure 11. The IPFS hash of the certificate is sent to the blockchain when this function is run. Through the blockchain network, this hash is securely communicated with the waste recycling unit. The waste recycling unit can demolish the storage devices after acquiring this certificate in order to manufacture new electronic devices.

## VI. DISCUSSION

This section presents the cost and security analysis of the proposed solution.

**TABLE 2. Gas consumption of various functions in smart contracts.**

| Function Name | Gas Consumption (Gwei) | Caller |
|---|---|---|
| Deploy Registration SC | 1995307 | Owner |
| Deploy OrderManager SC | 2196657 | Manufacturer |
| Deploy DataDestructionManager SC | 1579368 | Waste Recycling Unit |
| Deploy BidsandReputationManager SC | 1257753 | Waste Collection Center |
| Deploy WasteHandler SC | 1752812 | Waste Collection Center |
| Register_COllectionCenter | 68757 | Owner |
| Register_Consumer | 46384 | Owner |
| register_Contractors | 68792 | Owner |
| Register_DataDestructionFacility | 68835 | Owner |
| Register_Manufacturer | 68822 | Owner |
| Register_Retailer | 68756 | Owner |
| Register_WasteBins | 46471 | Waste Collection Center |
| Register_WasteRecyclingPlant | 68845 | Owner |
| PlaceOrderRequest | 226723 | Retailers and Consumers |
| ConfirmOrder | 71527 | Manufacturers and Retailers |
| ConfirmReceived | 41796 | Retailers and Consumers |
| StartBidingRequest | 165105 | Waste Collection Center |
| SubmitBid | 79904 | Contractors |
| BidCloseandAnnounceWinner | 28332 | Waste Collection Center |
| AddEntityRepScore | 46219 | Waste Recycling Unit and Waste Collection Center |
| GiveEntityFeedback | 66930 | Waste Collection Center and Waste Recycling Plant |
| CalculateEntityRepScore | 31444 | Waste Collection Center and Waste Recycling Plant |
| PlaceDataRemovalRequest | 216472 | Waste Recycling Plant |
| PlaceDataRemovalRequest | 216472 | Waste Recycling Plant |
| ConfirmDataRemovalRequest | 63694 | Data Destruction Unit |
| ConfirmReceivingCertificate | 40342 | Waste Recyling Plant |
| RequestCertificateIssue | 65586 | Data Destruction Unit |
| PublishSensorNotificationResult | 32412 | Smart Waste Bin |
| Location UpdateSending | 44231 | Contractors |
| RequestConfirmWasteReceiving | 61529 | Contractor |
| PlaceEwasteRequest | 224437 | Waste Recycling Unit |

### A. COST ANALYSIS

Gas is an Ethereum-specific unit of measurement that quantifies the computing work necessary to execute transactions or smart contracts. To successfully execute a transaction on the Ethereum platform, the user must first specify a gas limit. Each action of an Ethereum Virtual Machine (EVM) needs a specific quantity of gas. Data storage variables, repetitive statements (loops), decision making statement (if-else-if structure), mappings, and manipulations all consume a significant amount of gas in smart contracts [6], [19]. Gas is a virtual element that cannot be possessed by a system user. The value of each unit of gas is instead expressed in Ethers. For example, 100x units of gas consumed during an EVM operation may be equivalent to 0.003Y Ethers. Ethereum blockchain platform enables the customers to customize the amount of gas usage based on their needs using slow or fast transaction execution mode. As a result, consumers can provide higher gas prices to encourage the miners to execute their transactions quickly [20]. The transaction costs which is referred to as Gwei is calculated and stored by the Remix IDE in the transaction execution details. Gwei is the most well-known ether unit.

In Table 2, we show the total number of gas units that are consumed by each function of the proposed smart contracts; when run in the Remix IDE. It also lists the stakeholders who have permission to call these functions. From Table 2, it can be seen that the functions which deals with deploying smart contracts need most tokens to work. Similarly, *PlaceDataRemovalRequest* needs more units of gas to run on EVM. This is mostly because this function has used a lot of global variables, local variables, structures, mappings, and modifiers to ensure that business operations are performed by authorized stakeholders. More specifically, the modifier for this function ensures; (i) both the participant placing the order and the organization receiving it have valid licenses, (ii) all participants are registered, (iii) the number of items they want is more than what is available, and (iv) sending the items they want does not break any rules. It also uses structures to store data about the people who place orders and other details about orders, such as shipment date, quantity, timestamp, and shipper credentials. Minimum quantity of Ethers are required to execute functions that do not perform a lot of work.

### B. SECURITY ANALYSIS

This sections presents a rigorous security analysis of the proposed blockchain-based IoT-enabled solution for electronic devices and their waste management in smart cities. It has been briefly discussed how the proposed system offers high security, transparency, privacy, resilience, and robustness. The following is a brief overview of how our system addresses the most significant security, fault tolerance, integrity, and privacy challenges of the existing electronic devices and their waste management systems. The security of the proposed smart contracts is also verified using a security analysis tool for smart contracts.

#### 1) INTEGRITY

Our proposed system for electronic devices and e-waste management in smart cities stores transactions, data, and metadata on the immutable distributed ledger using an event-based technique. Through cryptographic techniques, the blockchain preserves the integrity of data [6], [18], [21]. Moreover, the access modifiers in smart contracts aid in the protection of user data. Since our system is based on blockchain technology, the data will always maintain their integrity.

#### 2) AVAILABILITY

Blockchain is a distributed system that is resilient against multiple internal and external threats. More specifically, the system functionalities, including order placing, bid management, and reputation score calculation will be accessible even if a portion of the blockchain network is under attack [17], [18], [22]. Since our proposed system is implemented on blockchain, it will be always accessible regardless of any internal or external blockchain threats.

#### 3) NON-REPUDIATION

Digital signatures, which are routinely used to authenticate the legitimacy of a transaction, are based on mathematical techniques [6], [10], [22]. In our proposed system, digital signatures guarantee non-repudiation and ensure that no party may deny a committed transaction. The waste contractor, for instance, cannot deny the submitted bid because the transaction is digitally signed with his private key. Due to blockchain's immutability, this transaction cannot be altered or deleted.

#### 4) CONFIDENTIALITY

The confidentiality feature ensures that the participants' privacy and data access rights are safeguarded [23]. Our approach uses modifiers with the functions to restrict access to just authorized users. In addition, the registration contract assures that only authorized users can join the network and engage in business operations.

#### 5) SMART CONTRACTS VULNERABILITIES

To prevent smart contracts from being exploited for malevolent purposes, it is strongly suggested that they be carefully drafted. There are numerous tools available that can be helpful to analyze the functions in smart contracts and provides guidelines to improve the security of smart contracts. We have utilized the SmartCheck tool to uncover probable problems in our code during the investigation [6], [24]. Based on the outcome of code analysis using SmartCheck, we modified our code and ensured that our smart contracts do not contain vulnerabilities, such as race conditions, infinite loops, integer divisions, or locked transfers.

## VII. CONCLUSION

In this research, we presented an IoT-enabled blockchain-based system for tracking and tracing of electrical devices and their waste. Using the Ethereum blockchain-platform, we designed a system that enables stakeholders to perform their business processes in a completely decentralized, secure, transparent, and auditable manner. The proposed system enables the authorities to ensure that electronic devices are purchased and supplied from licensed, reputed, and trustworthy users, disposed of appropriately, and managed by the participants in a safe and privacy-preserving manner. We resolved the scalability issues of the existing blockchain solutions by storing big data sets pertaining to electronic devices, e-waste, and participants on the IPFS server. Moreover, we conducted the cost and security analysis of the proposed solution and found that our solution is practical, secure, viable, and highly dependable. The proposed system is generic and with small iterations it can be implemented for various other use case scenarios, such as domestic waste management, water waste management and other scenarios where traceability is required. In the future, we aim to incorporate additional types of waste into our system, such as wastewater, organic wastes, and food waste. Moreover, we will propose a mechanism for rewarding consumers for the deposited electronic devices.

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**ATTA UR REHMAN KHAN** (Senior Member, IEEE) is currently an Associate Professor at the College of Engineering and Information Technology, Ajman University, United Arab Emirates. In the past, he has worked as a Postgraduate Program Coordinator at Sohar University, the Director of the National Cybercrime Forensics Laboratory, Pakistan, and the Head of the Air University Cybersecurity Center. He also serves as a domain expert for multiple international research funding bodies and has received multiple awards, fellowships, and research grants. His research interests include cybersecurity, mobile cloud computing, *ad-hoc* networks, and the IoT. He is a Senior Member of ACM and a steering committee member/track chair/technical program committee (TPC) member of over 85 international conferences. He is serving as an Associate Editor for IEEE Access and *Journal of Network and Computer Applications* (Elsevier), an Associate Technical Editor for *IEEE Communications Magazine*, and an Editor for *Cluster Computing* (Springer), *The Computer Journal* (Oxford), IEEE Software Defined Networks Newsletter, *KSII Transactions on Internet and Information Systems*, and *Ad-Hoc and Sensor Wireless Networks* journal. For more updated information, visit his website (www.attaurrehman.com).

**RAJA WASIM AHMAD** received the master's degree in computer science from COMSATS University Islamabad (CUI), Abbottabad Campus, in 2011, and the Ph.D. degree in computer science from the Center for Mobile Cloud Computing Research (C4MCCR), Faculty of Computer Science and Information Technology (FSKTM), University of Malaya, Malaysia. He is currently working as an Assistant Professor at the College of Engineering and IT, Ajman University, United Arab Emirates. He has published several research papers in leading journals and conferences. Most of his research contributions are published in top-cited journals, such as IEEE Transactions on Emerging Topics in Computing, IEEE Systems Journal, IEEE Access, *Journal of Network and Computer Applications*, *Journal of Grid Computing*, *Cluster Computing*, the *International Journal of Communication Systems*, the *International Journal of Information Management*, *Journal of Systems and Software*, *The Journal of Supercomputing*, *IET Intelligent Transport Systems*, and *Renewable and Sustainable Energy Reviews*. His research work is well acknowledged in national and international conferences. One of his research articles has received an award of the Best Paper in SPECTS Symposium held in France, in 2018. He is serving as a reviewer for several journals and conferences.