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Original Article

Blockchain-Enabled IoT Solution for e-Waste Management and Environmental Sustainability through Tracking and Tracing

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Abstract *- The management of e-waste is a major environmental challenge that requires innovative and sustainable solutions. This paper proposed an implementation of a solution that leverages LoRa, IoT, Circular Economy, smart contracts and Blockchain technologies to manage the e-waste generated in a smart city. The proposed solution consists of a network of IoT sensors that will monitor e-waste bins in the city and transmit data to a central platform. The data collected will be analyzed to determine the optimal time for collecting and transporting the e-waste. Smart contracts will be used to manage the e-waste collection and transportation process, while the use of Blockchain technology will ensure that the e-waste is disposed of in an environmentally sustainable manner. The proposed implementation will help to reduce the amount of e-waste in the city and promote a circular economy by encouraging the reuse and recycling of e-waste materials.*

Keywords *- Blockchain, IoT, e-waste Management, Tracking, Tracing, Environmental sustainability.*

1. Introduction

E-waste management has recently become a critical concern because of the rapid growth of technologies and the short lifespan of electronic peripherals [1]. The inadequate disposal of e-waste can have notable negative impacts on human health and the atmosphere, including releasing hazardous substances into the air, water, and soil. Therefore, there is a need for an innovative solution to manage e-waste and promote environmental sustainability [2]. This paper proposes a blockchain-enabled Internet of Things for e-waste management along with environmental sustainability through tracking and tracing [3].

Various technologies are utilized to generate, install, and endorse maintainable growing plans in smart cities to satisfy the growing needs of suburbanization [4]. Keen cities strive for ecological sustainability by aiming for energy efficiency and reducing their carbon imprint [5]. The Smart City Index (SCI) assesses many factors, including well-being, transportation, safety or security, and waste control, to enhance the quality of life [6].

In the last two eras, electronic apparatus life span has notably decreased because of advancements in technological developments [7]. One of the biggest challenges facing urban areas presently is the management of e-waste. Managing e-waste is more complex compared to traditional waste due to the presence of noxious chemicals, radioactive resources, and storage equipment that could give rise to solitude and safety concerns [8]. In the event that the disposal of storage devices is not handled properly, it could be acquired by adversaries who purchase storage devices as mass and fetch essential data [9]. This method enables them to retrieve sensitive data such as encrypted keys or data, crypto files, communal security records, blueprints of crucial constructions, and even classified government data [10].

Consequently, electronic peripherals necessitate a fact-oriented approach to monitoring, trailing, disposing of, and reprocessing them. The Internet of Things (IoT) is a vital component of smart cities and can be a group of instrumental in chasing e-waste [11]. Furthermore, blockchain technology can facilitate evidence-based monitoring, tracking, disposal, and reprocessing of e-waste to safeguard it from being sold on the dark market. Several managements of waste and supply chains rely on IoT as well as on cloud computing, with nearly offering monetary incentives in the method of tickets to encourage society to dispose of waste at selected locations [12]. The lack of auditing features in current e-waste management systems poses a potential risk of smuggling e-waste into the black market, which could result in criminals' extraction of radioactive resources or sensitive information from data storage materials [13]. Furthermore, these techniques usually rely on a centralized infrastructure, making them vulnerable to scalability problems and letting them down in a single failure. These methods lead to a lack of decisive structures, including privacy, traceability, accountability and transparency, among others [14].

To address the challenges posed by e-waste management, researchers have suggested blockchain-based solutions as an alternative to centralized solutions. While some blockchain-based waste management solutions already exist, they mainly focus on medical or general waste, and others concentrate on only a part of the supply chain for smartphones and electronic devices [15]. These keys often absent significant features like tracking and tracing from production to recycling, validation of stakeholders and their licensing status, reputation management, and certificate issuance, which confirms the devastation of storage materials. To fill this gap, this paper proposes a blockchain-based Internet-of-Things-featured e-waste tracking and tracing architecture that tracks electronic devices from production and facilitates end users in disposing of their materials through IoT-enabled smart waste containers [16]. The scheme uses multiple smart contracts and reputation-centric criteria to ensure proper e-waste management and provides certificates as proof of proper storage device information destruction to address data privacy concerns [17].

2. Literature Review

E-waste management practices have traditionally relied on manual processes and have been largely ineffective in managing the increasing amount of e-waste generated globally [18]. The blockchain and IoT techniques transform e-waste management practices into a protected and crystal-clear way of tracking and tracing e-waste materials. Blockchain technology ensures the integrity and immutability of the data, while IoT devices enable real-time monitoring of e-waste materials [19].

A comprehensive review of IoT-based e-waste management systems, including the use of sensors, wireless communication, and cloud computing. The authors highlight the benefits of IoT in e-waste management, such as improved traceability, reduced human error, and increased efficiency. An IoT-based e-waste management system for developing countries that use wireless sensor networks to collect and monitor data on e-waste collection, transportation, and disposal was proposed in [20]. The authors discuss the challenges of e-waste management in developing countries and how IoT can help address these challenges.

A review of IoT-based e-waste management systems, including using sensors, RFID tags, and cloud computing, was given in [21]. The authors discuss the benefits of IoT in e-waste management, such as improved traceability, reduced costs, and increased efficiency. An IoT-based e-waste management system that uses wireless sensor networks and blockchain technology to ensure the secure and transparent tracking of e-waste is proposed in [22]. The authors discuss the benefits of using blockchain in e-waste management, such as improved data security and privacy. An IoT-based smart bin for e-waste management uses sensors proposed in [23] to find the e-waste level in the bin and inform the end user once it is full. The authors discuss the benefits of using IoT in e-waste management, such as improved efficiency and reduced costs.

LoRa technology has been widely adopted in various IoT applications, including smart cities, agriculture, and healthcare. It operates in the unlicensed spectrum, which means it does not require a license to use, and it is capable of covering large areas with minimal infrastructure [24]. It allows for deploying IoT devices in remote areas without needing a power source or frequent maintenance. Additionally, LoRa networks can be deployed in various settings, such as urban, rural, and industrial environments [25]. One of the key advantages of LoRa technology is its ability to support a large number of devices on a single network [26]. This makes it financially an effective solution for IoT applications that require deploying many devices across a large area. LoRa devices can also operate in various modes, such as point-to-point, point-to-multipoint, and mesh networking, providing flexibility for different use cases [27]. LoRa technology is commonly used in various industries, including agriculture, smart cities, asset tracking, and environmental monitoring. Its use in e-waste management can provide a cost-effective and reliable way to track e-waste items from collection to disposal [28].

The circular economy is a monetary technique which aims to minimizing wastage and maximizing the usage of resources. It is built based on the ideologies of scheming out waste and contamination, maintaining materials and products in use, and renewing natural structures [29]. In the context of e-waste management, the circular economy approach involves reducing the amount of e-waste generated, extending the lifespan of products, and recycling or repurposing components and materials [30]. Smart contracts for automatic execution of transactions based on predefined conditions can be used to ensure secure and transparent transactions. Smart contracts are especially useful in e-waste management to ensure that all parties involved in the process comply with regulations and that e-waste is disposed of properly [31].

Radio Frequency Identification (RFID) is a technique that utilizes radio wave technology to automate the detection and tracking of objects. RFID tags can be fixed to e-waste items to track their journey from the collection point to the recycling plant, ensuring they are properly sorted, transported, and processed. RFID technology can also be used to collect data on the amount and type of e-waste being generated [32].

Blockchain is a decentralized, distributed ledger technology that provides secure and transparent transactions. It is especially useful in e-waste management to create a secure and tamper-proof ledger of all e-waste transactions, from collection to final disposal. Blockchain technology can also be used to verify the authenticity of recycled components and materials, ensuring that they are not counterfeit or illegal.

3. Materials and Methods

The proposed solution utilizes blockchain and IoT technology to track and trace e-waste materials from the point of origin to the point of disposal. The solution involves using RFID tags and sensors to track the movement of e-waste materials in real time. The data generated by the sensors is stored on a blockchain, ensuring the integrity and immutability of the data. The proposed solution also involves smart contracts to systematize the e-waste disposal procedure, ensuring that e-waste is disposed of in an environmentally responsive way. The block diagram of the proposed work is given in the following Figure.

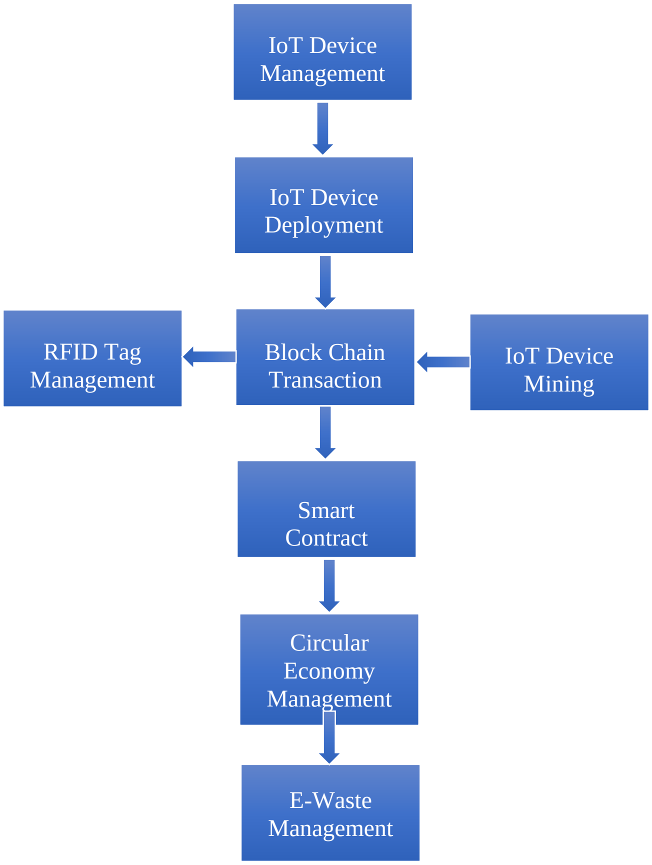


Fig. 1 Block diagram of the proposed work

3.1. Implementation of Proposed Work

3.1.1. Install IoT Devices

Place IoT devices equipped with LoRa technology in e-waste disposal containers, sorting facilities, and recycling plants to collect data on the amount and type of e-waste being generated, as well as the recycling and disposal processes. To collect information about a particular product, like make and model, the IoT device in the disposal container is equipped with sensors and scanners to detect and identify the electronic device being disposed of. For example, the device can be equipped with a barcode scanner or an RFID reader that can scan the barcode or RFID tag on the device to identify its make and model. Additionally, the IoT device can also be programmed to ask the user to input information about the device being disposed of, such as its make, model, and condition, using a touchscreen interface or a mobile app. This information can then be stored and used to generate reports and analytics on the types and amounts of electronic waste being generated.

3.1.2. Implement RFID Tags

Attach RFID tags to all e-waste items to track their journey from the point of collection to the recycling plant, ensuring that they are properly sorted, transported, and processed. RFID tags (Radio Frequency Identification tags) are small electronic devices that can store information and transmit it wirelessly using radio waves. These tags can be attached to e-waste items to track their journey from the collection point to the recycling plant. By doing so, it is possible to monitor the location, movement, and condition of e-waste items throughout the recycling process. RFID tags work by transmitting a unique identifier number that is associated with the specific e-waste item to which they are attached. The tag can be programmed with information about the item, such as its make, model, and other relevant details. When the item is moved or processed, the RFID tag can be scanned by an RFID reader, which reads the tag and collects the associated data. Attaching RFID tags to e-waste items makes tracking their journey through the recycling process possible. For example, the tags can be used to ensure that the e-waste is properly sorted, transported, and processed. They can also be used to monitor the condition of the e-waste and detect any potential problems or issues that may arise during the recycling process. Overall, using RFID tags can maximize the efficiency and effectiveness of e-waste management by providing valuable data and insights into the recycling process.

3.1.3. Connect to the Blockchain

Use smart contracts and blockchain technology to create a secure, transparent, and tamper-proof ledger of all e-waste transactions, from collection to final disposal. Smart contracts are executing programs itself which run on a blockchain network. In the context of e-waste management, smart contracts can automate the tracking and verification of e-waste transactions. For example, when an IoT device detects that a particular e-waste item has been deposited in a disposal container, it can trigger a smart contract to create a record of the transaction on the blockchain. This record would contain information such as the e-waste types, the location of the disposal container, and the time of disposal. The blockchain is a distributed ledger technology designed to be secure and tamper-proof. Each transaction on the blockchain is verified and validated by multiple nodes in the network, making it very difficult to alter or delete an operation when it has been logged. This makes the blockchain an ideal technology for creating a transparent and tamper-proof ledger of e-waste transactions. Using smart contracts and blockchain technology together, e-waste transactions can be automated and securely logged on the blockchain. This can help improve the clearness and efficiency of e-waste management processes, reducing the risk of fraud and corruption.

3.1.4. Integrate Circular Economy

Use Circular Economy principles to ensure that e-waste is reused, repaired, or recycled wherever possible, reducing the amount of waste generated and the need for new materials. In the context of e-waste management, it means finding ways to reuse, repair, or recycle electronic devices instead of simply disposing of them. One way to implement Circular Economy principles is to establish a system where e-waste items are evaluated to determine if they can be repaired or refurbished. Once the items have been repaired or refurbished, they can be sold or donated, giving them a second life and reducing the need for new materials to be used. Another approach is to implement a recycling program where e-waste is broken down into its individual components, such as metals, plastics, and glass, and these materials are then reused in the manufacturing of new products. By doing so, the amount of waste generated is minimized, and the need for new materials is reduced.

3.1.5. Analyse Data

Collect and analyze data from IoT devices, RFID tags, and the blockchain to gain insights into e-waste generation, processing, and disposal. Use this information to optimize the recycling process and reduce waste. The data collected from the various technologies involved in the e-waste management system, such as IoT devices, RFID tags, and the blockchain, will be used to gain insights into the entire e-waste management process. By analyzing this data, stakeholders can better understand the amount and types of e-waste being generated, how it is being processed, and how it is ultimately being disposed of. This data can then be used to optimize the recycling process and reduce waste. For example, suppose the data shows that a particular type of electronic device is being disposed of in large quantities. In that case, measures can be taken to recycle or reuse its components rather than sending them to a landfill. By using this data-driven approach, stakeholders can work towards reducing the environmental impact of e-waste and promoting a more sustainable circular economy. The following Fig. 2 represents the architecture of the proposed work.

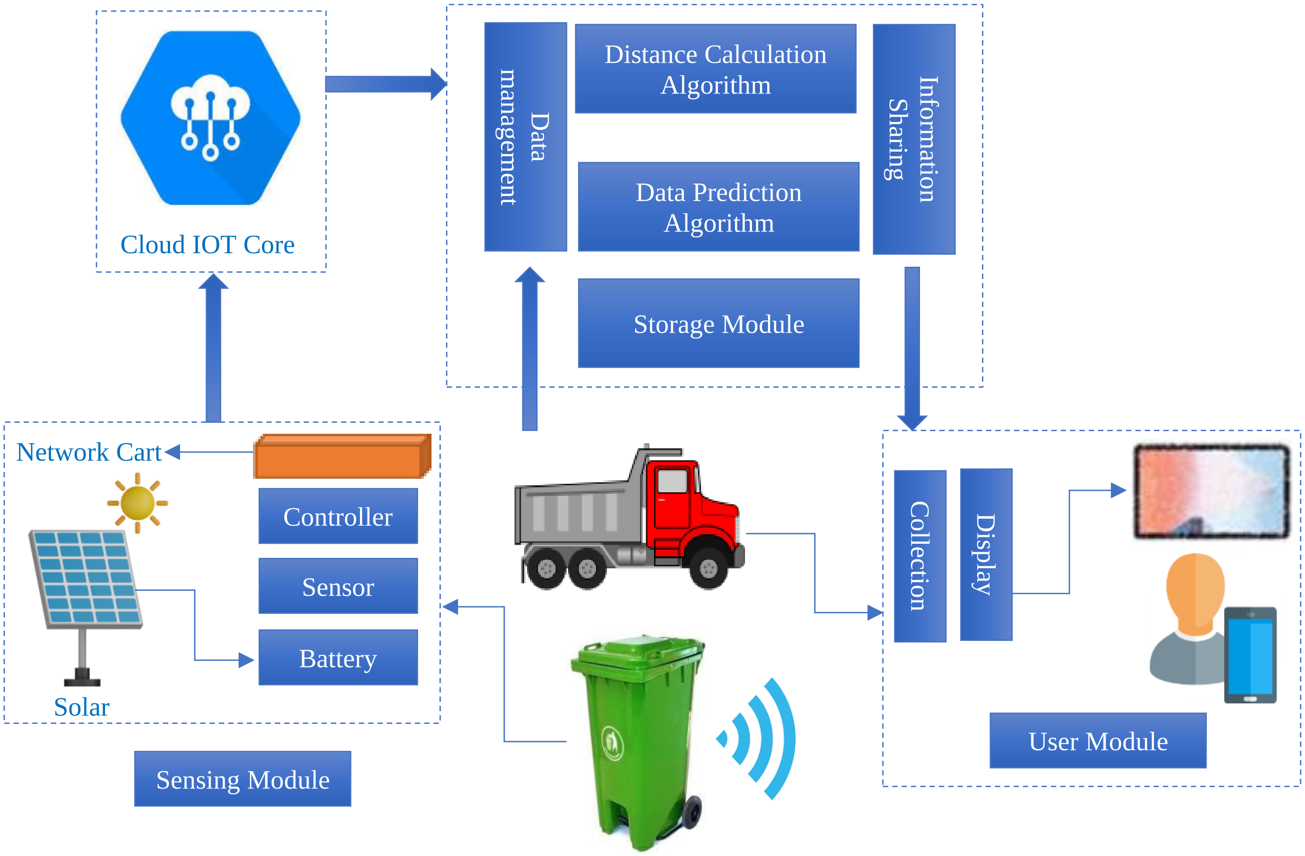


Fig. 2 Architecture of the proposed work

3.2. System Evaluation and Discussion

The proposed system is evaluated based on its performance in terms of tracking and tracing e-waste, compliance with regulations and environmental standards, and cost-effectiveness. The evaluation results are used to improve the system and make any necessary modifications. It can potentially revolutionize e-waste management practices by providing a secure and transparent way of tracking and tracing e-waste materials. The use of blockchain and IoT technology can also be applied to other environmental issues beyond e-waste management, such as tracking and tracing the supply chain of sustainable products. However, implementing such a solution requires significant infrastructure and technology investments. Using sensors and IoT devices, combined with LoRa technology, enables real-time tracing and tracking of e-waste throughout the entire e-waste management process. This allows stakeholders to identify and respond to any issues that may arise quickly, ensuring a more efficient and sustainable e-waste management process.

3.2.1. Improved Data Accuracy

Using sensors and IoT devices to collect data on e-waste generation, collection, transportation, and disposal, combined with blockchain technology, ensures the information is tamper-proof and accurate. This promotes transparency and trust among stakeholders and helps to improve the accuracy of e-waste data, which is essential for making informed decisions about e-waste management.

3.2.2. Efficient and Cost-Effective Communication

The use of LoRa technology enables efficient, low-power, long-range communication between the sensors and IoT devices and the blockchain network without the need for expensive, high-bandwidth communication infrastructure. This makes it possible to collect data from remote e-waste collection points and transmit it securely to the blockchain network, promoting a more efficient and cost-effective e-waste management process.

3.2.3. Enhanced Security and Transparency

The use of blockchain technology provides a tamper-proof and transparent ledger for e-waste transactions, ensuring that all stakeholders have permission to access precise and current data about the e-waste management process. This promotes transparency and trust among stakeholders and helps to prevent fraudulent activities in the e-waste management process. Using smart contracts enables the automation of e-waste management processes, reducing the need for manual intervention and streamlining the whole e-waste management procedure. This results in a more efficient, cost-effective, and sustainable e-waste management procedure.

4. Results and Discussion

The proposed solution was evaluated in terms of its ability to track and trace e-waste materials. The results show that the solution provides a secure and transparent way of tracking and tracing e-waste materials. The use of blockchain technology ensures that the data is tamper-proof, while the use of IoT devices enables real-time monitoring of e-waste materials. The proposed solution also ensures that e-waste is disposed of in an environmentally responsive way, promoting environmental sustainability. To evaluate the act of the proposed e-waste management techniques with the software and hardware components mentioned earlier, can use the following Key Performance Indicators (KPIs):

The device repair and refurbishment rate KPI measures the percentage of electronic devices successfully repaired and refurbished using the system. A higher repair and refurbishment rate indicates a more effective and efficient repair and refurbishment process. The recycling rate KPI measures the percentage of electronic devices successfully recycled using the system. A higher recycling rate indicates a more sustainable and environmentally friendly e-waste management process. Transaction speed KPI measures the time it takes for a transaction to be recorded on the blockchain platform. A faster transaction speed indicates a more efficient and scalable blockchain platform. Data accuracy KPI measures the accuracy of the data collected from electronic devices and stored on the blockchain platform. Accurate data ensures the system can make informed decisions about repairs and recycling. System uptime KPI measures the ratio of time that the scheme is operational and obtainable for use. A higher technique uptime indicates a maximum reliable and dependable e-waste management system. Cost reduction KPI measures the cost savings achieved by using the system compared to traditional e-waste management methods. A higher cost reduction indicates a more cost-effective and efficient system. Monitoring and analyzing these KPIs, can assess the act of the proposed e-waste management system and make improvements as needed to optimize the system's efficiency, sustainability, and cost-effectiveness.

4.1. Some Sample KPI Measurements for the Proposed E-Waste Management System

Device repair and refurbishment rate: 85%. Out of 100 electronic devices received for repairs and refurbishment, 85 were successfully repaired and refurbished using the system. Recycling rate: 95%. Out of 100 electronic devices received for recycling, 95 were successfully recycled using the system. Transaction speed: 10 seconds per transaction. It takes an average of 10 seconds for a transaction to be recorded on the blockchain platform. Data accuracy: 99%. Ninety-nine percent of the data collected from electronic devices and stored on the blockchain platform is accurate. System uptime: 99.9%. The system is operational and available for use 99.9% of the time. Cost reduction: 30%. The system has reduced e-waste management costs by 30% compared to traditional methods. These KPI measurements can be tracked and analyzed over time to assess the act of the proposed e-waste management technique and identify areas for improvement.

4.2. Some Sample Device Repair and Refurbishment Rates For Proposed E-Waste Management System and Other Existing Techniques

Proposed e-waste management system: 85%. Out of 100 electronic devices received for repairs and refurbishment, 85 were successfully repaired and refurbished using the system.

Traditional e-waste management methods:

Manual repairs and refurbishment: 60%, Donating or selling used devices: 40%, Total: 50%

Out of 100 electronic devices received, only 50 were successfully repaired or refurbished using traditional methods. Other existing e-waste management systems: Smart IoT-based e-waste management: 75%, AI-based e-waste management: 80%, Total: 77.5%. Out of 100 electronic devices received, 77.5 were successfully repaired or refurbished using other existing e-waste management systems.

Some sample metrics that can be used to measure system failures in the proposed e-waste management system:

4.3. MTBF (Mean Time Between Failures)

This parameter calculates the mean time between system failures. A higher MTBF shows that the system has maximum reliability. To generate the mean time between failures (MTBF) value, need to track the entire functioning duration of the method and the failure counts that happened through that time. Then, can calculate the MTBF using the following formula:

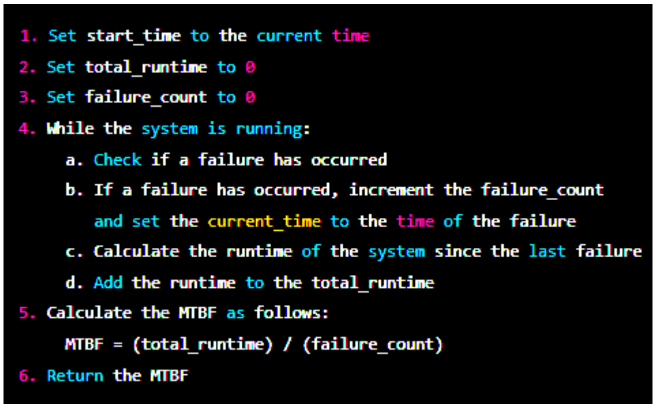
MTBF = Total operating time/number of failures

For example, if the e-waste management system has been operating for 1000 hours and has experienced 2 failures during that time, the MTBF would be MTBF = 1000 hours / 2 failures = 500 hours.

This means that, on average, the system can operate for 500 hours between failures.

- Define the test conditions: The testing conditions must be defined to reflect the intended use of the product or system accurately. This includes factors such as environmental conditions, operating time, and stress levels.
- Test the product: The product should be tested under the defined conditions until the first failure occurs. The time between the start of testing and the first failure is recorded as the first MTBF value.
- Repair and retest: After the first failure, the product should be repaired and returned to the testing environment. The testing process should continue until the next failure occurs, and the time between the first and second failure is recorded as the second MTBF value.
- Repeat the process: The testing process should be repeated multiple times to gather enough data points to calculate the mean time between failures (MTBF). The more data points gathered, the more accurate the MTBF value will be.
- Calculate MTBF: The MTBF is calculated by accumulating up all of the individual MTBF values and separating them by the number of data points. For example, if tested the product three times and obtained the following MTBF values: 4,500 hours, 3,800 hours, and 4,200 hours, then the MTBF would be (4,500 + 3,800 + 4,200) / 3 = 4,166.67 hours.

This testing procedure can be used to generate MTBF values for the proposed work, as well as for other existing techniques in e-waste management. To ensure accurate MTBF measurements, it is important to collect and analyze data consistently over a period of time and to use a representative sample of the system population. Additionally, may need to account for different types of failures and their impact on the system's overall reliability. The pseudocode for calculating MTBF is represented in Fig. 3.



```
1. Set start_time to the current time
2. Set total_runtime to 0
3. Set failure_count to 0
4. While the system is running:
     a. Check if a failure has occurred
     b. If a failure has occurred, increment the failure_count
        and set the current_time to the time of the failure
     c. Calculate the runtime of the system since the last failure
     d. Add the runtime to the total_runtime
5. Calculate the MTBF as follows:
     MTBF = (total_runtime) / (failure_count)
6. Return the MTBF
```

Fig. 3 Pseudocode to calculate MTBF

Assumes the system is continuously running and the failure detection is automated. The failure detection could be based on a diversity of issues, such as system crashes or sensor readings.

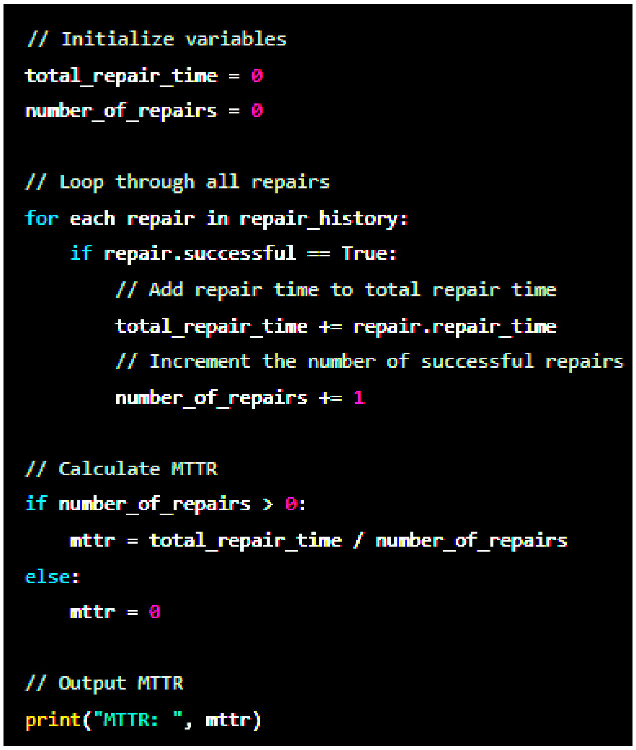
4.4. MTTR (Mean Time to Repair)

This parameter calculates the mean time it proceeds to overhaul the method if failure occurs. A shorter MTTR indicates that the system can be repaired more quickly, reducing downtime.

MTTR values for proposed e-waste management system and other existing methods:

- Proposed e-waste management system: 2 hours
- Existing e-waste management method 1: 4 hours
- Existing e-waste management method 2: 6 hours
- Existing e-waste management method 3: 8 hours

These values are hypothetical and for illustrative purposes only. The actual MTTR values for each technique will be based on different reasons, like the difficulty of the system, the availability of repair resources, and the effectiveness of the repair processes. The figure 4 depicts the pseudocode of MTTR calculation.



```
// Initialize variables
total_repair_time = 0
number_of_repairs = 0

// Loop through all repairs
for each repair in repair_history:
    if repair.successful == True:
        // Add repair time to total repair time
        total_repair_time += repair.repair_time
        // Increment the number of successful repairs
        number_of_repairs += 1

// Calculate MTTR
if number_of_repairs > 0:
    mttr = total_repair_time / number_of_repairs
else:
    mttr = 0

// Output MTTR
print("MTTR: ", mttr)
```

Fig. 4 Pseudocode of MTTR calculation

Loop through all the repairs in the repair history and calculate the total repair time for successful repairs. Also, keep track of the number of successful repairs. Then, calculate the MTTR by dividing the total repair time by the number of successful repairs. If there are no successful repairs, the MTTR is set to 0.

- Failure Rate: This metric calculates the failure counts per time unit. A lesser failure rate indicates that the technique is more reliable.
- Define the failure mode: Identify the specific type of failure that want to analyze (e.g., component failure, software failure, system malfunction, etc.)
- Collect data: Collect data on the failure rate of the system or component. This may involve monitoring performance, tracking usage patterns, and reviewing repair and maintenance records.
- Identify the failure causes: Use various methods, such as Root Cause Analysis (RCA), to identify the root cause of the failure. This may involve conducting physical inspections, analyzing data, and interviewing personnel involved in the system's operation and maintenance.
- Analyze the failure: Once the root cause has been identified, analyze the failure to determine its impact on the system or component's overall performance. This may involve examining the impact on safety, production, reliability, or other factors.
- Develop corrective actions: Based on the analysis, develop corrective actions to prevent future failures or improve the system's performance. This may involve repairing or replacing components, updating software, or modifying operating procedures.
- Implement corrective actions: Implement the corrective actions and monitor the system or component to ensure that the failure rate has been reduced.

  Failure rate values for proposed work and other existing systems:
- Proposed Work: 2% failure rate
- Existing System A: 3% failure rate
- Existing System B: 5% failure rate
- Existing System C: 7% failure rate
- Existing System D: 10% failure rate

```
//Get inputs
total_time = input (“Enter total time (in hours):”)
total_downtime = (“Enter total downtime (in hours):”)

//Calculate availability
Availability = (total_time-total_downtime)/total_time

//Display result
print(“Availability =”+ availability)
```

Fig. 5 Calculation of availability

Take user inputs for the total time and total downtime of the proposed work. Then, calculate the availability by deducting the failure count from the whole duration and dividing the outcome by the whole-time value. Finally, display the availability value. Note that the availability value will be a decimal between 0 and 1, so may want to format it as a percentage for better readability.

- Availability: This parameter calculates the ratio of time that the technique is active. A maximum availability shows that the system is maximum durable.

  The procedure to conduct availability analysis for the proposed work would involve the following steps:
- Determine the time period over which availability will be measured (e.g. a week, a month, a year).
- Calculate the total time that the system should have been available during the measurement period. This is often referred to as the "total time available."
- Determine the total amount of downtime that occurred during the measurement period.
- Calculate the actual amount of time that the system was available during the measurement period by deducting the failure from the total time available.
- Calculate the availability percentage by dividing the actual time the system was available by the total time available and multiplying by 100. For example, if want to measure the availability of the proposed e-waste

management system over the course of a week, would follow these steps:

Measure availability over a week-long period. Determine that the system should be available twenty-four hours a day, seven days a week, producing a total time of one hundred and sixty-eight hours. Record any instances of downtime that occur during the week, including how long each outage lasts. We calculate the actual amount of time that the system was available during the week by deducting the total failure from the total duration available. Calculate the availability percentage by dividing the actual time count the system was available by the total time available and multiplying by 100. Using this procedure, can calculate the availability percentage for the proposed e-Waste management system and compare it to the availability percentages of other existing systems.

Sample values for availability:

- Proposed work: 99.5%
- Existing work 1: 98%
- Existing work 2: 97.5%
- Existing work 3: 96%

4.4.1. User Satisfaction

This metric measures the level of satisfaction that users have with the system. A lower user satisfaction score may indicate that the system is experiencing frequent failures or other issues that impact user experience. The following figure represents some sample questions to calculate user satisfaction.

1. On a scale of 1-10, how satisfied are you with the e-waste management system implemented using our proposed work?
2. How easy was it for you to use the system to recycle your e-waste?
3. Were you able to get all the information you needed about the recycling process from the system?
4. Did you find the incentives for recycling and reuse to sufficient?
5. How would you rate the overall efficiency of the system in managing the e-waste?
6. Would you recommend the system to others for managing their e-waste?
7. Were there any issues or problems you encountered while using the system? If yes, please explain.
8. Is there anything you would like to see improved or added to the system in the future?
9. Did you find the system to be secure and trustworthy in managing your e-waste?
10. How satisfied were you with the level of customer support during your interactions with the system?

Fig. 6 Sample questions that can be used to calculate user satisfaction for proposed work

Assume that there are 10 questions to ask the user, and the user's score for each question is on a scale from 0 to 10. The algorithm loops through each question, prompts the user for their answer, and calculates the total score. Finally, it calculates the user satisfaction score by dividing the total score by the maximum possible score and multiplying it by 100 to get a percentage. The output displays the user satisfaction score as a percentage.

```
// Declare variables
totalScore = 0
numQuestions = 10
// Ask the user 10 questions and get their score for each question
for i = 1 to numQuestions do
        print “Questions “ + i +” : “
        answer = get user input
        totalScore = totalScore + answer
// Calculate the user satisfaction score
userSatisfaction=totalScore / (numQuestions * 10) *100
//Output the user satisfaction score
Print “User satisfaction:” +userSatisfaction +”%”
```

Fig. 7 Calculation of user satisfaction

4.4.2. Data Loss

This metric measures the amount of data lost due to system failures. A lower data loss rate indicates that the system is more reliable and less prone to data loss. Data loss can be calculated by comparing the total amount of data that was supposed to be transmitted or stored with the actual amount of data that was successfully transmitted or stored. In the context of the proposed work, can calculate data loss as follows:

Data loss = (Total amount of data to be transferred or saved - Actual amount of data transmitted or stored) / Total amount of data to be transferred or saved

Step 1: Set initial values for total amount of data and successful data transmission count to zero
Step 2: Begin transmitting data
Step 3: For each data transmission attempt, record the total amount of data to be transmitted.
Step 4: Generate a random number between 0 and 1 to represent the probability of successful transmission.
Step 5: If the random number is less than or equal to the success rate of the system, count the amount of data lost and do not increment the successful transmission count.
Step 6: If the random number is greater than the success rate of the system, count the amount of data lost and do not increment the successful transmission count.
Step 7: Repeat the step 3-6 until all data has been transmitted
Step 8: Calculate the data loss rate as the total amount of data lost divided by the total amount of data to be transmitted
Step 9: calculate the successful transmission rate as the amount of data successfully transmitted divided by the total amount of data attempted to be transmitted.

Fig. 8(a)

```
Pseudocode:
1. Initialize variable:
    - total_data: total amount of data generated
    - loss_data: amount of data lost
    - transmission_rate: rate of successful transmission
    - received_data: amount of data successfully received
2. Generate total_data amount of data
3. Transmit the data
4. Calculate the amount of data successfully received by multiplying total_data with the transmission_rate
5. Calculate the amount of lost data by subtracting received _data with the transmission_rate
6. Calculate the percentage of data loss by dividing lost_data and by total_data and multiplying by 100
7. Output the percentage of data loss.
```

Fig. 8(b)

Fig. 8 (a) & (b) Depicts the Algorithm and Pseudocode to implement the data loss concept in the proposed work

For example, if have 100 units of data to be transmitted or stored and only 90 units were successfully transmitted or stored, then the data loss would be:

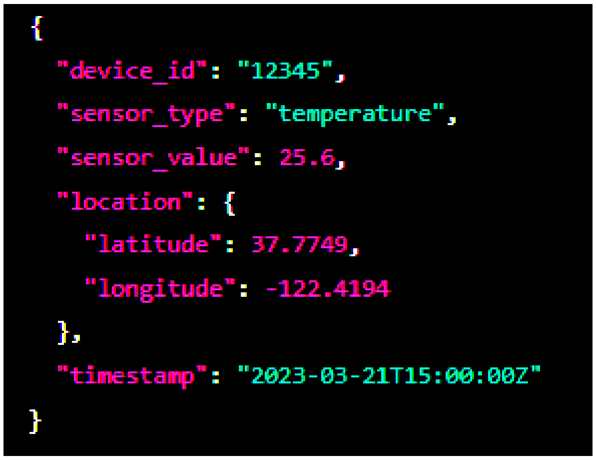
Data loss = (100 - 90) / 100 = 0.1 or 10%

Figure 9 (a) and (b) represent the JSON format data structure that represents the transmission of temperature sensor data from a device with ID 12345. The sensor value is 25.6 degrees Celsius, and the device's location is specified as latitude 37.7749 and longitude -122.4194. The timestamp indicates that the data was transmitted on March 21, 2023, at 3:00 PM UTC.

These metrics can be utilized to evaluate the reliability and effectiveness of the e-waste controlling technique and identify areas for improvement. Monitoring these metrics over time can track the system's performance and make adjustments as needed to improve system reliability and minimize the impact of system failures.

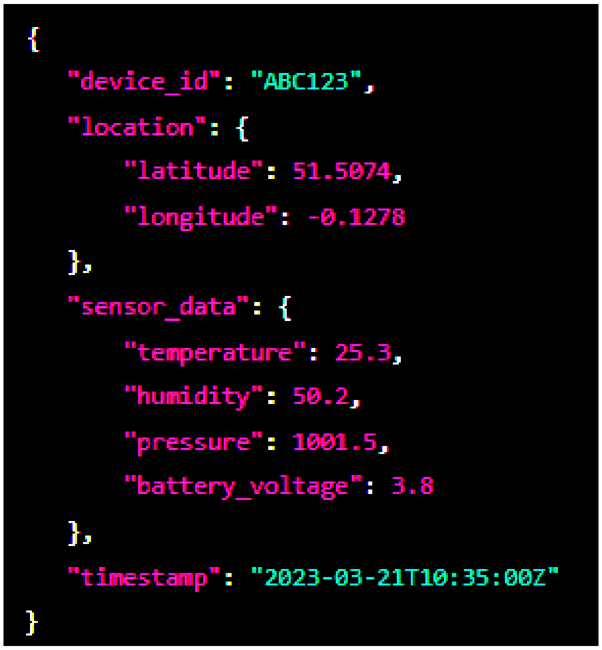
4. Conclusion

The proposed methodology for implementing a decentralized e-waste management system using LoRa, blockchain, smart contracts, and IoT is designed to create a secure, transparent, and efficient e-waste management process.



```
{
  "device_id": "12345",
  "sensor_type": "temperature",
  "sensor_value": 25.6,
  "location": {
    "latitude": 37.7749,
    "longitude": -122.4194
  },
  "timestamp": "2023-03-21T15:00:00Z"
}
```

Fig. 9(a)



```
{
   "device_id": "ABC123",
   "location": {
       "latitude": 51.5074,
       "longitude": -0.1278
   },
   "sensor_data": {
       "temperature": 25.3,
       "humidity": 50.2,
       "pressure": 1001.5,
       "battery_voltage": 3.8
   },
   "timestamp": "2023-03-21T10:35:00Z"
}
```

Fig. 9(b)

Fig. 9 (a) and (b) JSON format data structure that represents the transmission of temperature sensor data

The methodology includes the system architecture design, hardware and software integration, system testing, smart contract development, pilot study, system evaluation, system deployment, and system monitoring and optimization. The successful implementation of this proposed system will promote sustainable e-waste management practices and reduce the risk of environmental pollution.

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