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## A BLOCKCHAIN-BASED TRACEABILITY SYSTEM FOR WASTE MANAGEMENT IN SMART CITIES

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#### **ABSTRACT**

Waste tracking is becoming an important concern for developed countries as well as developing regions, where municipalities aim to assure proper waste management considering environmental economic objectives. Waste tracking is important not only for a transparent reporting system compatible with environmental regulations but also for economically viable waste collection and recovery solutions. In this paper, a waste tracking system based on the blockchain technology is introduced where different entities involved in the system will be able to retrieve required data from the platform and decide on their level of contributions. The conventional technologies do not provide a sufficient level of transparency and coordination among different entities. With the introduction of blockchain as a tamper-proof technology, municipalities can enhance the efficiency of their waste management efforts. The proposed blockchain technology can connect proper stakeholders towards collaboration and sharing information. The concept of a smart contract for waste management is discussed and further, a decisionmaking framework is developed to guide users of the system select proper services available to them,

depending on the level of data sharing, cost, reliability, and the security level that they expect from the system.

**Keywords:** waste management, blockchain, service systems

#### 1. INTRODUCTION

Municipalities have often been looking for innovative strategies to enhance their waste management efficiency. Despite all previous efforts, the waste disposal pattern continues to be a major challenge in the urban setting [1]. The concept of zero waste city is one example in which the objective is to process all sorts of waste through proper recycling of materials. However, in practice, this may be difficult to achieve due to various reasons ranging from uncertain waste generation rate to the lack of sufficient coordination among different entities in the system. Waste management constitutes of different stakeholders with different social, political, environmental, and technological viewpoints [2].

Modernizing the waste management system in today's consumption-driven society is very complex [3]. Still, due to the changing habits and lifestyles of consumers, there is a constant pressure on governments to improve the existing practices towards a more efficient system.

According to a study conducted in Nigeria, the composition of solid waste is mainly from households (55-80%), markets (10-20 %), and commercial areas (10-20%) [4]. The waste can contain any toxic material available in the market, where the portion left unattended can cause health and environmental hazards. The hazards associated with the collection, storage, transportation, and final disposal techniques are a major concern in cities [5].

The waste is difficult to track and there is no accountability of wastes being processed. Proper guidelines and infrastructure are needed to encourage better disposal behavior. Any misbehavior by entities involved in SWM can spoil a well-designed waste management solution. The current scenario of waste disposal lacks the traceability capability to track the EOL of solid wastes.

In this paper, the concept of Blockchain for waste management is discussed. The aim is to propose a decision-making framework to guide users on the type of objectives they need to consider, and the type of services offered on such Blockchain platforms towards developing a proper service-based waste management system.

#### 2. THEORETICAL REVIEW

With the introduction of industry 4.0, the capabilities offered by cyber-physical systems, Blockchain, and IoT (Internet of Things) help build smarter cities [6] as well as more efficient waste management systems. For example, previous researchers have discussed how waste management systems can employ RFID tags to better handle waste collection and recovery operations [7], [8]. Besides, the value of product tracking and information sharing in smart and sustainable cities has been highlighted in the literature [9].

Among the most recent technologies, blockchain has several key characteristics that make it stand out from other technologies [10]. It has a unique data structure that builds blocks together for every transaction processed [11]. The characteristics of blockchain vary depending on the type of protocol behind the system. For example, in public blockchains, a high level of reliability and security is needed since the platforms are open to the public and unanimous users [12]. On the other hand, private blockchains are open to known users operating under a validator who controls the operations [13]. The blockchain consensus protocol is an important aspect to consider when designing the platform [14]. Depending on the scale and the project requirement they can be private or public. The decision about the type of protocol behind the Blockchain platform can be made by considering factors such as cost and security. Gopalakrishnan et al. proposed a framework to choose the best protocol based on these two attributes [15].

The use of Blockchain for waste management has already been discussed in the literature. Kouhizadeh et al. worked on use cases and shortcomings of promoting green supply chains using Blockchain technology [16]. Lamminchane et al. [17] worked on developing a smart contract using IoT and Blockchain for a smart waste management system. They developed a telegram-based TAG architecture that can be used for waste management. Guido et.al [18] also worked on a Blockchain-based smart contract for waste management.

Previous researchers have worked on the issues arising by the sharing of the data [19], [20]. Pan et al. [21] worked on different aspects of the data stored in the cloud platform, they performed a variety of operations like prediction models on citizen behavior, social relation among individuals, resident behaviors and dynamics of city evolution. Citizens' decisions influence the waste management system, and the infrastructure of the entire system influences their behavior. This was a core motive for proposing a customer wallet system that rewards customers based on their waste disposal behavior [22]. Gupta et al. worked on a smart contract for the e-waste disposal pattern [23]. The aim of this paper is to propose a decision-making framework to guide users of the Blockchain platform on the type of objectives they need to consider and the type of services offered to them on such platforms towards developing a proper service-based waste management system.

#### 2.1. Waste Management in Smart Cities

Waste management involves the collection, storage, transportation, and final disposal of waste. It relies on a set of integrated resources and processes involved in managing and proper disposal of these wastes. This involves the proper sorting of wastes, maintenance of disposal trucks, dumping facilities, and designing a system compatible with environmental regulations. The entire management system should be designed such that it ensures proper disposal of waste while preventing health hazards and protecting the environment [24]. Waste disposal patterns may differ from one region to others as different regions are required to follow laws and environmental regulations put forward by their governments.

As shown in Figure 1, the major aspects of the cloud-based waste management system are municipality services, trucks (low and high capacity as per need), smart bins, recyclable facilities, incinerators, landfills, GPS, a smartphone navigation system, dynamic scheduling, and routing.



**FIGURE 1:** WASTE MANAGEMENT IN SMART CITIES [25]

The current process of waste disposal involves the disposal of trash in the bins nearby. The trash is collected at regular intervals by the municipality and sent to collection centers. It is then sent out for sorting and further recycling. This method proves to be effective but there are certain disadvantages. The bins are not expected to be full always, there might be bins that are underfilled and some may be overfilled. Some that are overfilled create unhygienic conditions. For ones that are underfilled, there is not a need for removal. Therefore, an optimized truck service is required. Newer methodologies are needed to increase the efficiency of this system [26].

Several studies have tried to solve the vehicle routing problem to optimize waste collection in smart cities considering the capabilities of sensor-based technologies. The smart waste management system can increase the efficiency of recycling and sorting mechanism. A smart waste management system involves components of IoT, a sensor, cloud storage, and other entities like a truck, GPS, and software to process it [27]–[30]. The sensors used here are mostly ultrasonic that measures the distance. These are kept on the top of the bin, once the level is reached it sends out an alert through the cloud and the truck can be immediately routed to pick up the trash [31].

These have their own set of disadvantages especially with the ultrasonic sensor efficiency, there might be times when the bin is not uniformly filled, the sensor simply measures the distance. There are high possibilities of vandalism, the sensors might be stolen or damaged. Another biggest gap is the way of recycling this waste and sorting them properly. There is no proper evidence or record of what happens to the wastes disposed of after the sorting facility. There is no proper tracking system in place. Some of these research gaps can be better addressed with the introduction of the Blockchain framework.

In terms of the waste classification, municipal solid wastes consist of so many items disposed of.

Residential, industrial, commercial, institutional, construction, municipal services, process, and agriculture form the major sectors contributing to the wastes in cities [32]. Table 1 provides a simple classification of waste.

The disposal pattern of each category of waste is different and the time they take to degenerate varies over time. Organic wastes can be dumped in landfills and they decompose over time. But other categories of waste cause a potential threat to the environment and human health. These wastes need to be properly handled and treated before disposal.

**TABLE 1:** WASTE CATEGORY AND SPECIFIC WASTE TYPES [33].

Category	Types
Organic waste	kitchen waste, vegetables,
(Landfill)	flowers, leaves, fruits
Toxic waste (needs	old medicines, paints,
proper treatment	chemicals, bulbs, spray
before disposal)	cans, fertilizer and
	pesticide containers,
	batteries, shoe polish
Recyclable (proper	paper, glass, metals,
recycling and	plastics
incineration)	
Soiled (treatment	hospital waste
before disposal,	
might contain	
infections)	

### 2.2. Blockchain Versus Traditional Database

Blockchain so-called distributed ledger technology is the technology that enables users to implement smart contracts and store information in different nodes in a decentralized way. The information can be further added or verified once the consensus is reached among different nodes of the network based on the smart contract behind the platform. Smart contracts are self-executing computer codes that take specified actions when certain conditions are met in practice. All transactions stored in the ledger are permanent and irreversible. Blockchain provides new opportunities for information sharing in different supply chain domains. Blockchain is robust and thrust worthy, it is not in favor of traditional database [34]

The advantage of Blockchain over the traditional method are summarized in Table 2.

**TABLE 2:** ADVANTAGES OF BLOCKCHAIN OVER TRADITIONAL DATABASE

Blockchain Database	Traditional Database
Self-validation of	Third-party required to
transactions	validate transactions
Involves multiple nodes	Mostly works on a
	single node
Transparent	Information is not
information to all users	transparent
Data stored in multiple	Data stored in a single
locations	location
Low risk of failure	High risks of failure

## 3. THE PROPOSED DECISION-MAKING FRAMEWORK

The proposed decision-making framework is based on this assumption that a Blockchain platform will be developed and made available to different users involved in the waste management system ranging from households to recycling companies based on service contracts or subscription-based business models. The framework helps different users with the selection of the level of service they require from the system and the type of attributes they need to consider while selecting their contract. The framework aims to guide users on finding the best possible way of obtaining the data as a service from the Blockchain platform stored in the cloud (node hosting method). The decision process is based on four main factors: processing time, cost, security, and the reliability of the platform.

The decision-making framework for service selection can be applied to any supply chain applications.

Let us assume that we have a set of data available in the Blockchain platform for selling to users. Depending on the level of service and the level of information, cost, processing time, reliability, and security of the platform would be different.

Let the available data sets in a Blockchain be defined as:

$$BD = \{B1, B2, B3, \dots, Bi\}$$
 (1)

The number of available services is defined as:

$$S = \{S1, S2, S3, \dots, Sj\}$$
 (2)

The Blockchain platform service flow can be defined as a function of both Blockchain dataset and the services offered:

$$BF = (BD, S) \tag{3}$$

Where.

BD: Blockchain datasets

S: Services offered

n: Total number of services

BF: Blockchain platform service flow

Let us define a set of constraints based on the abovementioned factors: cost, reliability, security, and response time [35]. The users can define an acceptable threshold for each attribute.

 $S_i$ : Service offered

t: Time

r: Reliability

c: Cost

s: Security

Response time constraint defines the minimum response time by which the data need to be obtained.

$$BF(time) = \sum_{j=0}^{n} S_j * t \le Min_{Response\ Time}$$
 (4)

Reliability constraint defines the minimum reliability required for the data obtained from the Blockchain service platform.

$$BF(reliability = \underset{1 \le j \le n}{\overset{Min}{S_j}} s_j * r \ge Min_{Reliability}$$
 (5)

Cost constraint defines the maximum budget available for purchasing the Blockchain service.

$$BF(cost) = \sum_{j=0}^{n} S_j * c * demand \le Budget$$
 (6)

Security constraint determines the minimum security required for the service. It may be defined based on the consensus protocol adopted by the user, depending on the sensitivity level required.

$$BF(security) = \underset{1 \le j \le n}{\text{Min}} S_j * s \ge Min_{Security}$$
 (7)

The tradeoff between choosing the dataset and their corresponding service is done using the above-mentioned four factors. These four factors are calculated similarly to the work performed by Zheng et. al for calculating reliability [36]. The number of requests is kept as a base for all the constraints and they are expressed as a function of the factors they depend on.

## 3.1. Response Time

The response time for the Blockchain may be defined based on the number of transactions happening in a block. This is based on the block size, average transaction size, transactions per block, and response time based on previous use cases.

Each request can be defined as Ri and the response can be defined as Pj.

Response time = Transaction per block/ Total number of requests

Transaction per block = Block size/ Average transaction size.

Response time may be defined as a function of

RT = f (Right block, Right height, Round trip time)

#### 3.2. Reliability

The reliability of a Blockchain platform can be defined based on three factors based on the block and time.

Each request can be defined as Ri and the response can be defined as Pj

Successful requests are named as Si,j

Failure request can be named as Fi,j

Total request can be named as TR<sub>i,j</sub>

Success rate  $SR_{i,j} = S_{i,j} / TR_{i,j}$ 

The success rate is given as a function of choosing the correct block, block height is correct, i.e. (it can take the request from the user and the block has the space to store it) and the round trip for the request to peer is less than the max response time (time tolerance preset by the user).

SR<sub>i,j</sub> = f (Right block, Right height, Round trip time)

#### 3.3. Cost

The cost associated with data storage is based on the following factors. The size of the data, the sensitivity of the data, technology used to process data, and the space required for a request.

The cost function is associated with different aspects of Blockchain implementation. With technology advancements and use of AI in supply chain platforms, the blockchain cost is associated with the Business layer, IoT layer, and the actual white paper cost. With more features like prototype, third party service, smart contracts (technology), and the number of transactions per day (more transactions need more storage) contribute to the increase in cost. We are extending this work where all the cost aspects related to the implementation of blockchain is clearly explained with use cases.

The storage cost exponentially increases with technology and storage. This is expressed as a function of time.

$$C(t) = Ae^{-k.t} (8)$$

C(t) is the cost over time

K is the rate at which the cost is defined

A is the assigned cost for a fixed amount of data

t is the time of service.

Cost of storage = Total data required based on storage, technology, time / Total number of requests.

#### 3.4. Data Security

The security of data is defined based on the consistency of the Blockchain ledger used. The integrity of the transactions and ease of access to the data available in the cloud. The level of confidentiality of the data also plays a major factor in accessing the security.

We define the security with certain factors using the probability of each events occurring

Where threat may be defined as the potential source of the attack and the vulnerability can be defined as the exposure of the technology to this threat. Table 3 provides the formulation for calculating the proposed constraints as per the number of requests.

We have defined the Blockchain platform service flow may be defined as a function of Blockchain dataset and services offered

$$BF = (BD, S)$$
 from (3)

This decision-making framework aims to develop a tradeoff between the services offered and the data available with constraints mentioned in Table 3. Based on these constraints the user can choose from the available datasets and the services compatible with them. The combination of some datasets with services may not be feasible. The matrix T can be used to represent different combinations of BiSj.

$$T = \begin{pmatrix} T_{11} T_{12} & \cdots & T_{1y} \\ \vdots & \ddots & \vdots \\ T_{x1} T_{x2} & \cdots & T_{xy} \end{pmatrix}$$
(9)

 $T_{ij=1}$ , means that the dataset is offered in the service level j.

**TABLE 3:** CONSTRAINTS FOR SELECTING THE BLOCKCHAIN PLATFORM

Constraints	Defined as a function of factors	Formulation
Response time	<ul> <li>Block size</li> <li>Average transaction time</li> <li>Transaction per block</li> <li>Use cases</li> </ul>	$Response\ time = \frac{Transaction\ per\ block}{Total\ number\ of\ request}$
Reliability	<ul><li>Returns right block</li><li>Returns recent block height</li><li>Returns in time</li></ul>	$Success \ Rate = \frac{Successful \ request}{\text{Total number of request}}$
Cost	<ul> <li>Size of data</li> <li>Sensitivity of data</li> <li>Technology used</li> <li>Space requirement for storage</li> </ul>	$Cost = \frac{Data(storage, technolgy, time)}{Total number of request}$
Security	<ul> <li>Consistency of ledger</li> <li>Integrity of transactions</li> <li>Accessibility of data</li> <li>Confidentiality</li> </ul>	$Security = \frac{Data(Threat, Vulnerability, cost)}{Total \text{ number of request}}$

The data starting from B1 to Bm is based on the availability of different data, starting from the customer input data to the data from different sorting facilities. Similarly, the service level is based on the requirements of the company. A company may be able to select a bundle of dataset and service level to satisfy their requirements. Therefore, a set of BiSj can be selected by companies as part of their service contract from the platform.

The dataset of Blockchain is based on the size of the dataset, with B1 being the least size of the dataset and Bm being the dataset with most data in terms of size.

The service level offered ranges from one service for S1, two for S2 and so on.

Let us assume a numerical example to clearly show how this combination works

We have eight **datasets** available as follow:

B1 is of size 16 MB (1000 transactions)	B2 is of size 100 MB
B3 is of size 1 GB	B4 is of size 10 GB
B5 is of size 100 GB	B6 is of size 1000 GB
B7 is of size 120,000 GB	B8 is of size 420,000 GB

The three different **services** offered are:

S1 is the service providing data for the amount
S2 is the service providing data and a storage
S3 is the service providing data, public Blockchain
platform and cloud storage.
S4 is the service providing data, private Blockchain
platform and cloud storage.

#### Let the constraints be:

Data sold separately ≤ 10 GB	
Cloud Storage requirement ≥ 100 GB	
100 GB≤ Public Blockchain platform ≤ 120,000 GB	
Private Blockchain with cloud storage ≥ 120,000 GB	

Figure 2 represents the decision tree to choose the service and the datasets available. There is a clear tradeoff between both. This can be adjusted as per the requirement of the protocol in place. Based on the constraints the possible combinations are:

{B1S1, B2S1, B3S1} {B4S2, B5S2} {B5S3, B6S3} {B7S4, B8S4}

#### 4. THE CONCEPT OF A WALLET SYSTEM

In addition to the services offered to recyclers and municipalities, the Blockchain platform offered incentives to households and end-users to encourage them to contribute to providing information on the platform. The proposed concept is a customer reward system implemented to encourage customers for proper disposal of waste and thereby encouraging them with rewards. The system is a part of the developed framework for data sharing, this mainly focuses on encouraging customers to dispose of the waste properly. The aim here is to make the customer bring their recyclable wastes to facilities nearby for proper disposal.

Each customer needs to enroll themselves in the system, this involves a mobile application that calculates the value of waste the customer disposes of in the facility. The first step is linking a photo ID of

the customer to the system. When the customer comes to the facility, the app generates a QR code that the customer needs to scan for starting the process. The machine provides different categories of wastes that are available for recycling, the customer can choose to dump the items that fall into the category. Based on the waste disposed of, the system generates a QR code. The customer needs to scan the code using the app, based on the waste recycled the system calculates the number of points. The QR code changes for every category of products disposed of. If the customer is not sure about the category of produced recycled the system automatically assigns the lowest value of the product. Figure 3 shows the various aspects involved in the customer reward system.

Finally, the customer can use these points to redeem rewards on the app. This entire system is run by the government and the advantage here is the system eliminated the sorting process which is considered to be the most time-consuming in the entire waste disposal system. The government needs to have collaborations with some companies to sell their products on their platform by offering perks like tax benefits.

## 5. DATA SHARING FRAMEWORK-GOVERNMENT CONTROLLED SWM BASED BLOCKCHAIN PLATFORM

In addition to end-users and households, other entities also should contribute to the Blockchain platforms. The proposed framework is shown in Figures 4 and 5. Various stakeholders and different types of data shared on Blockchain are shown. The platform discusses the need for stakeholder's contribution to the Blockchain system in order to be successful. Also, the benefits of each entity are discussed. With the adoption of the customer reward system and this data sharing methodology, the SWM can be more regulated and better monitored thereby benefiting each stakeholder involved.

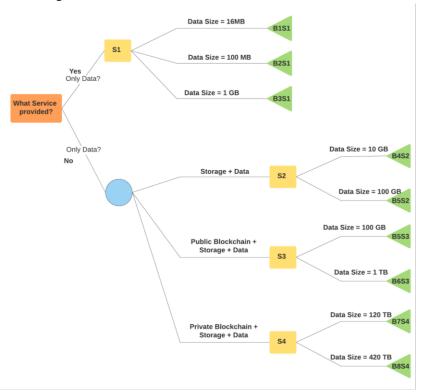


FIGURE 2: DECISION TREE FOR THE NUMERICAL EXAMPLE

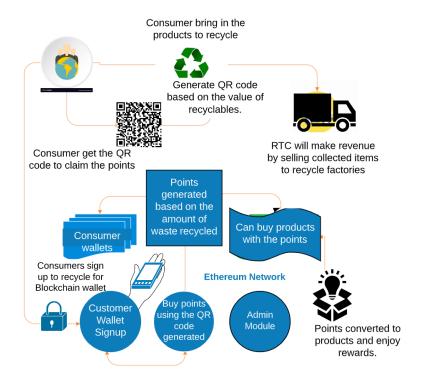


FIGURE 3: CUSTOMER REWARD SYSTEM FOR WASTE DISPOSAL PATTERN

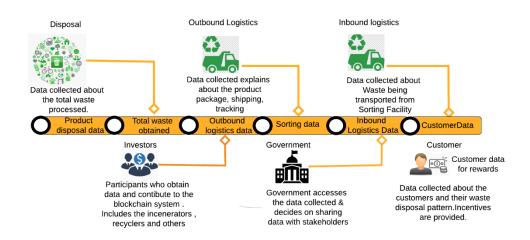


FIGURE 4: TYPE OF DATA SHARED IN THIS PLATFORM

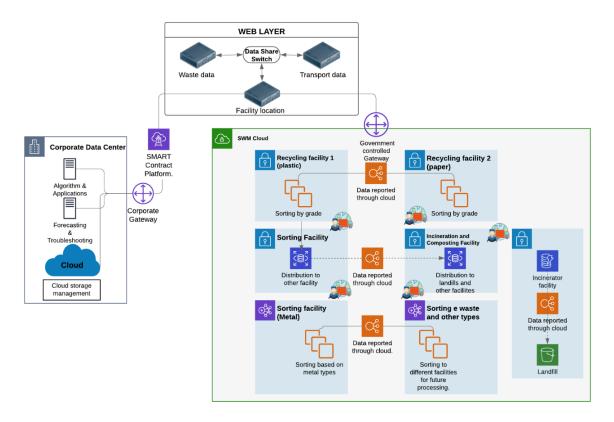


FIGURE 5: DATA SHARING BLOCKCHAIN PLATFORM FOR SOLID WASTE MANAGEMENT

The entire system is controlled by the corporate data center, the Blockchain platform is owned by the government. The corporate center offers a variety of datasets and services for the stakeholder. Depending on the requirements of the stakeholder, the services are built by the data center. Various factors like cloud storage, smart contract, and consensus protocols are designed for a set of requirements.

Figure 4 shows different elements of the system:

- Different types of data shared
- Different parties involved
- Parties contribute to the contract
- Investors (entities) need to pay for it (All stakeholders benefit from it)

## Data storage

- Stores assets, such as waste handling facilities (e.g. landfills, repositories) involved
- Stores local waste types and translations of waste types

Data and main attributes can be automatically or manually monitored in each waste handling facility

Waste volume in cubic meters or weight in tons

- Number of stops
- Waste transportation source and destination
- Percentage of recycling ability
- Percentage of waste disposal
- Waste type name including the corresponding identification number
- Incineration facilities: Percentage of waste incineration

Different types of stakeholders are the sorting facility, recycling facilities (based on the grade of materials), metal sorting facility, e-waste and other types of chemical wastes sorting facility, incinerator facility, and landfill facility. The facilities get their data from the corporate center and buy the wastes based on their requirement. All transactions go through the Blockchain platform. The stakeholder is entitled to provide information about the waste they process. The services here include providing smart contracts based on their requirement, provide software for forecasting troubleshooting and data services. stakeholders obtain the information about the raw data available and they can equip with the ability to process the waste. The advantage of this system is that the data is transparent throughout, starting from the collection facility to sorting until the final stage of disposal. This makes the system tamper-proof thereby preventing

any fraudulent activity from happening. This system can be highly instrumental in a smart city to eliminate the problems faced for tracking the waste. The customer gets clarity on the waste disposal pattern. Other services can be included in the Blockchain platform like customer service. The customer can place a request to obtain service for a locality, file complaints, and provide feedback on the Blockchain platform which is accessible to all officials in the government. A more efficient and transparent system can be maintained.

Data mismatch in the following domains can be prevented. These will be a major advantage of the proposed platform.

- Facility handling volume mismatches
- Impossible storage volumes
- An unusually high number of exceptional termination reasons
- Impossibly fast transportation
- Export fraud
- Dumping waste at non-disposal sites
- Impossible weight of waste
- Impossible routes or GPS coordinates

The framework can be adapted to any SWM systems. Depending on the scale of the project, the Blockchain platform and the features can be selected. Blockchain provides users with a tamper-free system, which is important for waste management. With growing concern over the wastes ending up in oceans, proper traceability with regulation for entities involved can help in achieving an efficient SWM system. The use of Blockchain in waste management has been adapted in a few places at a small scale and is proven to be effective. The proposed framework might be effective in smart cities where people are looking for higher living standards.

### 6. CONCLUSION

As Blockchain technology is emerging to the market, the waste management system can benefit from the capabilities of this technology in terms of both product tracking as well as data sharing and controlling waste management behavior of households. For instance, a blockchain platform and its distributed ledger capabilities keep all records tamper-proof and make it easier for the stakeholders to track waste shipments. This also helps recyclers and incinerator facilities prepare themselves to accommodate and process these wastes properly.

This paper develops a decision-making framework in form of a decision tree to help different users of blockchain platforms with the selection of a proper set of datasets and service levels considering factors such as cost, security, reliability, and processing time. In addition to the decision-making framework, the paper discusses the process of collecting information on the platform by proposing a wallet system in which users are rewarded based on the level of contributions in proper waste sorting and collection. Further, we have worked on the cost aspects of implementing the process by using use cases to show how the model can be used in a real-life scenario.

The future scope of this work involves exploring other aspects of Blockchain such as involving consensus protocols at the level of individual users. The Blockchain platform can be augmented with economic models to determine what would be the optimal level of incentives offered to each entity to maximize their contributions. Also, the current waste management platform is defined as a public platform, however, the scalability issues of public blockchains may hamper the large-scale implementation of such systems. Finally, the proposed system can be integrated into other sustainability systems that reward green behavior of customers to facilitate the collection and recovery of waste as well as waste reduction at the upstream.

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