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Cost analysis and optimization of Blockchain-based solid waste management traceability system

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ABSTRACT

As global concerns over End-of-Life (EoL) wastes released to the environment is rising, the need for enhancing the transparency of recycling systems is growing. To address the waste traceability issue, technologies such as Blockchain can be instrumental in the proper disposal and handling of wastes. In this paper, we propose a Blockchain-based Solid Waste Management (SWM) model that can help municipalities enhance the efficiency of their waste management efforts. A Blockchain framework owned and controlled by a municipality is proposed in which customer companies pay to join the platform to avail services from the suppliers managed by the municipality. The cost burdens to both supplier and consumer companies have been discussed. In addition, an optimization model is developed to determine the optimal quantity of waste that can be traded between supplier and consumer companies in order to maximize their profit based on parameters such as the number of suppliers, consumer companies, and the processing capacity of customer companies and several constraints including maximum storing capacity, storage, and transportation constraints. Further, the cost aspects associated with Blockchain implementation are estimated from several use cases obtained from companies providing Blockchain solutions.

1. Introduction

Growing populations, advanced technological improvements, changing policy requirements, and new sustainability goals have prompted a movement towards "smart cities" to manage solid waste efficiently (Su et al., 2011).

Smart cities produce an enormous amount of waste (Chourabi et al., 2012). For example, San Francisco, one of the biggest Smart cities in the USA, produce about 1.8 million tons of waste every year (sfenvironment, 2006). Zero waste city is a popular concept in smart cities to curb all wastes through proper recycling of materials. However, the concept is challenging to achieve since it requires joint efforts among all stakeholders with different social, environmental, political, and technological viewpoints (Zaman and Lehmann, 2011). The biggest hurdle faced by municipalities is the lack of coordination among the SWM participants (Ahmed and Ali, 2006).

In this paper, we will discuss the importance of Blockchain technology for enhancing the coordination among different participants in SWM systems. The use of Blockchain for waste management has already been the point of attention in the literature (Ojo and Adebayo, 2017). Blockchain simplifies the supply chain and creates a more efficient, transparent, and trustworthy system (Casado-Vara et al., 2018). One major problem with using this platform is the cost associated with its implementation. As high-tech companies start offering Blockchain as a service (Baas) concept, the costs have become nominal and more companies started adopting the technology.

The objective of this paper is to analyze different aspects of costs associated with implementing Blockchain for the SWM system. We have proposed a Blockchain platform in which the municipality and stakeholders working together to achieve a transparent system. There are two cost aspects dealt with in this paper; the first part deals with the cost of implementing Blockchain framework into the SWM process. The second cost involves the total amount spent by customer companies to adapt to the existing Blockchain platform. Further, we have proposed an optimization model to define the optimal waste flows among entities, thereby increasing the profits of suppliers.

We have demonstrated the application of the proposed method with several numerical examples and sensitivity analyses.

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The rest of this paper is organized as follows. Section 2 presents the state of the art and the problems associated with SWM. Section 3 describes the Blockchain-based SWM model. Section 4 discusses the optimization model for adopting the platform. Section 5 discusses a numerical example to describe the data analysis and optimization model further. Finally, Section 6 concludes the paper.

2. Review of literature

2.1. New technologies for waste management

A range of activities, including collection, storage, transportation, and final disposal of waste define the SWM operations. The success of SWM operations depends on the coordination of all entities involved in the process. Municipalities often aim to increase the efficiency of waste management processes by adopting new approaches. Some cities have implemented a cloud-based SWM practice using trucks, smart bins, recyclable facilities, GPS, a smartphone navigation system, dynamic scheduling, and routing (Abdoli, 2009).

Wastes come from different sources such as nondurable goods, durable goods, packaging, and food waste, where they need to be appropriately treated. They must be sorted and allocated to different facilities for processing, which is not an easy task as it may involve different handling protocols, disposal alternatives, and treatment possibilities (Nema and Gupta, 1999). With new software technologies and diffusion of the internet over the years, it has led to compact, reliable, and cheap hardware products, thereby creating efficient integrated systems for SWM (Rada et al., 2013). Such integrated technologies are highly adopted for the optimization process of SWM. For instance, Web-GIS systems with RFID tags are used for waste capturing, storing, integrating, analyzing, and obtaining the data related to location or users (Rada et al., 2010).

Handling various waste (domestic, industrial, hospital, and chemical) leads to higher costs for collection and transportation (Amponsah and Salhi, 2004). Optimization techniques have been widely used in the literature to reduce the collection cost. For example, the shortest path method has been used to reduce the cost of collection and transportation (Das and Bhattacharyya, 2015) or even more complex problems that consider aspects such as routing, dispatching, maintenance, and management. Also, optimization models have been integrated with other tools to make waste management more efficient. For instance, Komly et al. combined life cycle assessment with genetic algorithms (Komly et al., 2012). Najm and El-Fadel developed a computer-based interface for an integrated solid waste management optimization model, making it user-friendly (Najm and El-Fadel, 2004).

Artificial Intelligence (AI) techniques have gained momentum in offering alternative computational approaches to solve SWM problems. Abdallah et al. have performed a detailed literature review on articles that used AI for SWM applications (Abdallah et al., 2020). The capabilities of cyber-physical systems, IoT, and Blockchain provide additional insights towards building an efficient waste management system (Bharadwaj et al., 2016). Chowdury and Chowdhury developed a multi-layer waste management system architecture for the design of an RFID, sensor-based real-time automatic waste identity, weight, and stolen bins identification system. Using this system, waste management service providers have a chance to track a waste identity, weight, missing, stolen bins quickly and accurately without human intervention (Chowdhury and Chowdhury, 2007). Jiang et al. developed a data-driven analytical framework to analyze household waste-dumping behavior and facilitated policy regulations by using IoT and data mining technologies (Jiang et al., 2020). Esmaeilian et al. discussed the importance of using tracking and data sharing technologies for investigating waste management issues. They proposed an IoT-enabled waste management framework for connecting waste management practices to the whole product lifecycle (Esmaeilian et al., 2018).

Among the recent technologies, Blockchain stands out as it has several key characteristics that can help optimize the waste management system (Kainuma and Tawara, 2006). Blockchain is a time-stamped series of immutable records of data stored in a distributed ledger using cryptographic principles (Nakamoto, 2019). Blockchain, initially used by financial institutions for storing transactions, stores information permanently as blocks in which anyone who is a member of the network has a copy of the ledger. With advancements in Blockchain, the concept of distributed ledger is now being used for any type of data and in different business applications beyond just financial transactions (Nguyen, 2016). This opened up opportunities to use Blockchain for other sectors like banking, food, healthcare, logistics, and other supply chains (Crosby et al., 2016). Blockchain simplifies the supply chain and creates a more efficient, transparent system that helps in tracking the waste with more accountability on the stakeholders of the system (Zheng et al., 2017).

Blockchain solutions offer a unique collaborative approach enabling governments, regulatory bodies, and businesses to work together towards better-organized waste management without fewer inconsistencies. Waste tracking ensures that recyclables do not turn up in the landfills (Pilkington, 2016). Depending on the complexity of the projects and security levels, the platform is generally classified as public or private. Pongnumkul et al. have discussed factors for choosing between two platforms and conducted a performance analysis in varying workloads to decide the applicability of each platform in different supply chain applications (Pongnumkul et al., 2017).

Blockchain has been introduced in reverse logistics and SWM literature before (Saberi et al., 2019). For example, the Hashcash algorithm is used to register each recyclable item into an existing Blockchain platform. This shared ledger has access to all stored transactions on waste disposal, recyclables, and other related transactions accessible to all network participants. This system helps keep track of disposables and recyclables and minimizes the risk of any mix-up or manipulation of data (Newswire, 2019).

2.2. Current challenges with solid waste management

The solid waste disposal involves various entities working together in a coordinated way to achieve success. In this section, we discuss the significant problems facing municipalities in managing MSW.

Lack of traceability: There are about 251 million tons of wastes being generated in the US alone every year. Waste is mostly sent to landfills, composters, waste to energy plants, or recyclables (T. wang, 2019). The waste needs to go through transfer stations and material recovery centers before reaching the final destination (Dumbsters, 2020). Proper guidelines are often not followed by authorities to segregate wastes. There is no traceability system to track the EoL of waste. During transportation, there are high possibilities of wastes getting mixed up, and non-compatible wastes may lead to fire, explosion, toxic gas, and heat generation. Landfills can cause environmental pollution and health hazards to humans if they are dumped with undesirable wastes (Pichtel, 2005).

Loss of economic value of waste: SWM requires consideration of comparative costs of various options such as recycling for recovery of materials or energy. Solid waste incineration in the resource recovery plant for electricity generation forms the basis of determining the fossil-fuel equivalent. Three issues threaten the economic value of waste (Korzun, 1990). First, manufacturers still hold a deep concern about accessing secure resources at the right quality. The amount of material received is often less as they are not appropriately sorted for processing; this causes enormous loss to companies investing in such measures. Secondly, the legislative framework for waste is still confusing (guidelines vary in every state in the USA), disjointed (not all entities agree to the same protocol), and can act as a barrier (the involvement of informal waste collectors) to resource efficiency. The improper communication and tracking associated with the waste lead to more wastes being sent to landfills. Thirdly, the services offered to manufacturers need to be reformed. Proper waste sorting services and expert advice is the key to avoid losses (Baker, 2012).

Lack of control: The government or municipal authorities need to control waste processing entities. They set rules and regulations on the amount of waste processed each time period, taking into consideration environmental degradation. Improper control over the quantity of waste processed can lead to environmental pollutions (Vongdala et al., 2019) as well as social consequences that hinder improvements in sustainable development (Ferronato and Torretta, 2019).

Lack of mechanisms for policy implementation: Mechanisms such as the Resource Conservation and Recovery Act (RCRA) proposed by the US Environmental Protection Agency (EPA) create standard procedures for managing solid wastes from the cradle to the grave (Cheremisinoff, 2003). The wastes come from different sources and need to be sorted as per type and sent to different facilities for proper disposal. RCRA responds to changes in waste generation by constantly evolving to accommodate the challenges of highly toxic waste and growing populations. RCRA is committed to safeguarding communities by following different mitigation steps and material management approaches (EPA, 2019). To ensure RCRA procedures are appropriately followed, the agencies such as EPA can consider implementing Blockchain-based SWM through the RCRA. They have the authority to dictate terms in the Blockchain smart contract and play a significant role in facilitating commerce and enhance stakeholder's participation in SWM.

3. Blockchain-based Solid Waste Management

The concept of a smart contract as part of the Blockchain platform helps assign rules for tracking, sustainability terms, regulatory policies, and other enforcements by the deciding authority.

Blockchain in SWM has received attention in the recent literature. Lamichhane et al. developed a framework for integrating IoT and Blockchain. They consider features such as decentralized autonomous organizations, smart contracts, telegram bot, and creating their cryptocurrency (Lamichhane et al., 2017). Ongena et al. used the design science approach to apply Blockchain smart contracts for SWM. They identified and formulated problem areas and evaluated the applicableness of using a Blockchain solution to mitigate the problems in SWM (Ongena et al., 2018). Similar frameworks using Blockchain in SWM were developed for e-waste management (Gupta and Bedi, 2018) and small municipalities (França et al., 2020). Gopalakrishnan et al. developed a service-based waste management system using Blockchain in smart cities. They discussed a Blockchain-based decision-making framework for data sharing and a customer reward program for waste disposal behavior (Gopalakrishnan et al., 2020). Table 1a summarizes the advantages of implementing Blockchain-SWM over the traditional SWM.

Table 1b shows how the current work is different from previous studies. Overall, this paper considers the cost aspects of SWM and develops an optimization framework and a numerical example to show the effectiveness of the model, which has not been discussed in previous work.

3.1. Proposed Blockchain-based SWM model

In this section, we describe a Blockchain-based SWM system that can complement municipalities' efforts in processing the waste. We describe different entities that will be part of the platform and participate in the network. The corporate data center controls the operations of the entire system. The municipality funds the service. The suppliers, along with the municipality, form the basis of this chain. The corporate centers provide them with different services starting from white paper, smart contracts, cloud storage, consensus protocol, and other services. The corporate center offers services to the consumer companies as well, and they help in adding the number of users, storage, and node hoisting based on their requirements (Fig. 1). The node hoisting method refers to the chosen method for storing Blockchain platform and its ancillary technological requirements. Our model considers a cloud-based system for the storage of Blockchain data.

In this paper, we assume that a Blockchain platform is managed by a collision of the municipality and supplier companies with the help of corporate centers. The customer companies are added as members to this platform and are responsible for providing data for the waste they process. Supplier companies sort and sell the waste, and customer companies are those who purchase and process the waste. Customer companies can recycle, generate energy, or process the waste as compost to generate revenue. Each supplier company is interested in being part of the network to create a good scenario to track the EOL of waste. Consumer companies, on the other hand, are benefited from purchasing the sorted waste.

The most expensive task associated with waste processing is the collection and sorting of waste. Since the suppliers carry out these processes, consumer companies can pay more money to cut down their sorting costs. The assumption is that the municipality acts as the entity that owns and operates the suppliers. The reason for this assumption is to have a transparent system to trace the EOL of wastes. If we look at the current scenario, the municipality does not spend resources on the sorting of waste. They sell the waste based on the type o for recycling or energy conversion. The disadvantage here is the companies buy them at a significantly lower price and do not account for anything after purchase. So it becomes difficult to track the EOL of waste.

To avoid this situation and increase transparency, we incorporate suppliers as entities owned by the municipality to act as a bridge to sort wastes. The tradeoff here is to have the consumer companies buy the wastes as per grade at a nominal price and assure reporting the EOL data through the SWM-Blockchain system. This solution can highly reward the municipality's efforts to track the EOL of wastes. The key feature of this work is to suggest a platform that can benefit all entities involved. The suppliers, on the other hand, can compensate for the costs they spend on Blockchain, sorting, and transportation. The aim here is to encourage customer companies and reward them with incentives based on their responsible behavior. The customers are expected to report with the way they handle the waste that they purchase. The municipality controls this platform, and they dictate the terms for the users. The suppliers can make profits based on their investment costs within the clauses set by the municipality. The municipality decides the amount of waste that a supplier can sell on a given day. This might cause losses to the suppliers in specific scenarios when the sorting process is longer than expected, or the transportation cost is high. The municipality addresses such issues. The supply is not constant, and it may vary depending on the supplier location, and the profits based on the grade of material they sell. The decision on the implementation of this technology should be based on the availability of raw materials. Blockchain technology is expensive and proves to be effective when implemented on a large scale. So the assumption is that we have considered the economy of scale by implementing the system in a highly populated region or regions generating high volumes of waste. The optimization problem identifies the best way of sorting the wastes with the available number of suppliers and consumer companies. The user may add or remove the facilities based on their requirement, assessing the amount of waste generated in the locality.

We discuss two categories of costs, as presented in Table 2. These cost categories are described from the perspective of supplier and customer companies with a broader perspective to emphasize the importance and advantage of using the Blockchain system. The cost aspects may be different during actual implementation, depending on the local and regional factors.

The two cost aspects are the cost associated with setting up of Blockchain-based SWM platform and the total purchasing cost of the wastes by the customer companies. The setting up cost includes the transportation associated with the collection of waste, sorting costs, storage costs, and the Blockchain platform cost on the supplier side. The Blockchain platform costs are further divided into different phases, as described in Table 3. The second cost aspects are the cost associated with the total cost spent by customer companies for buying the wastes. This cost category

Table 1
Comparison study of current work.

(a) Advantages of Blockchain over traditional SWM model

Blockchain-SWM	Description	Traditional SWM	Description
Smart contracts	Terms and clauses are written as computer codes (enforcing tariffs, trade policies, compliance agreements), Fully automated	Manual contracts	Terms and clauses are written in paper and signed by individuals
Transaction and information data encrypted	Every data is encrypted with hash functions and stored permanently.	Database stores information data as logs	Modified, managed, and controlled by a single user called an administrator. Possibility of tampering or data loss
Self-validation	Algorithms in smart contracts verify every piece of information stored. Outliners will be disputed	Third-party validation	Manual entry must be validated to avoid discrepancies
Multiple nodes of information	Decentralized as information is stored across different nodes which are independent of each other	Single node for information sharing	Centralized and the information is stored in a single database
Transparent information to all users	All participants of the Blockchain system can access the information stored in the ledger	Information is not transparent	Only administrator can access and modify the information in the database
Prevents compliance violations	Any discrepancies will be immediately alerted to all users of the ledger	Compliance violations are hard to track	Only the administrator has access to the database
Reduces human error	Any changes go through all the users of the system, and the outliers are identified by the inbuilt algorithms	High risk of human error	Data is manually entered by the administrator
Low risk of failure	Transparent, controlled, and tamper-proof, Delegates work and give credit to entities for contribution	High risks of failure	Single storage, data can get corrupted or erased. Entities' efforts go unnoticed with the failure of some other entity

(b) Comparison between previous work in SWM-Blockchain and the current paper

Title	Framework	Decision Makers	Cost Aspects	Method
A smart waste management system using IoT and Blockchain technology (Lamichhane et al., 2017)	IOT and Blockchain based	Decentralized Autonomous Organization (Government)	Cost of service, user account, date, and amount of waste discussed as part of a generalized framework	Develop a generalized framework using the Proof of work concept to combine Blockchain and IoT. SWM is discussed as a case study
Blockchain-based Smart Contracts in Waste Management: A Silver Bullet? (Ongena et al., 2018)	Use case for cross border waste	The Human Environment and Transport Inspectorate (ILT)	Not discussed	Use a design science approach to formulate the waste management based on Blockchain solutions with ILT use case as an example
Proposing the use of Blockchain to improve the solid waste management in small municipalities (França et al., 2020)	Ethereum based digital architecture for SWM	Small Municipalities	Green coins-cryptocurrency introduced	Blockchain as a viable technology for an SWM with the use of digital social currency. Reward system to convert green coins to actual currency
A Blockchain-Based Traceability System for Waste Management in Smart Cities (Gopalakrishnan et al., 2020)	Decision making framework for service selection	Large municipalities (smart cities)	A constraint for the decision-making framework	Enhance the existing system with data sharing protocols and customer reward programs to reward green behavior
Cost analysis and optimization of Blockchain based SWM traceability system (Current work)	Municipality owned Blockchain Framework	Large Municipalities	Cost aspects of the model are defined and analyzed for a numerical example	Track the EOL of waste and optimize the waste flow across SWM supply chain Optimization of waste flow in supply chain using cost values

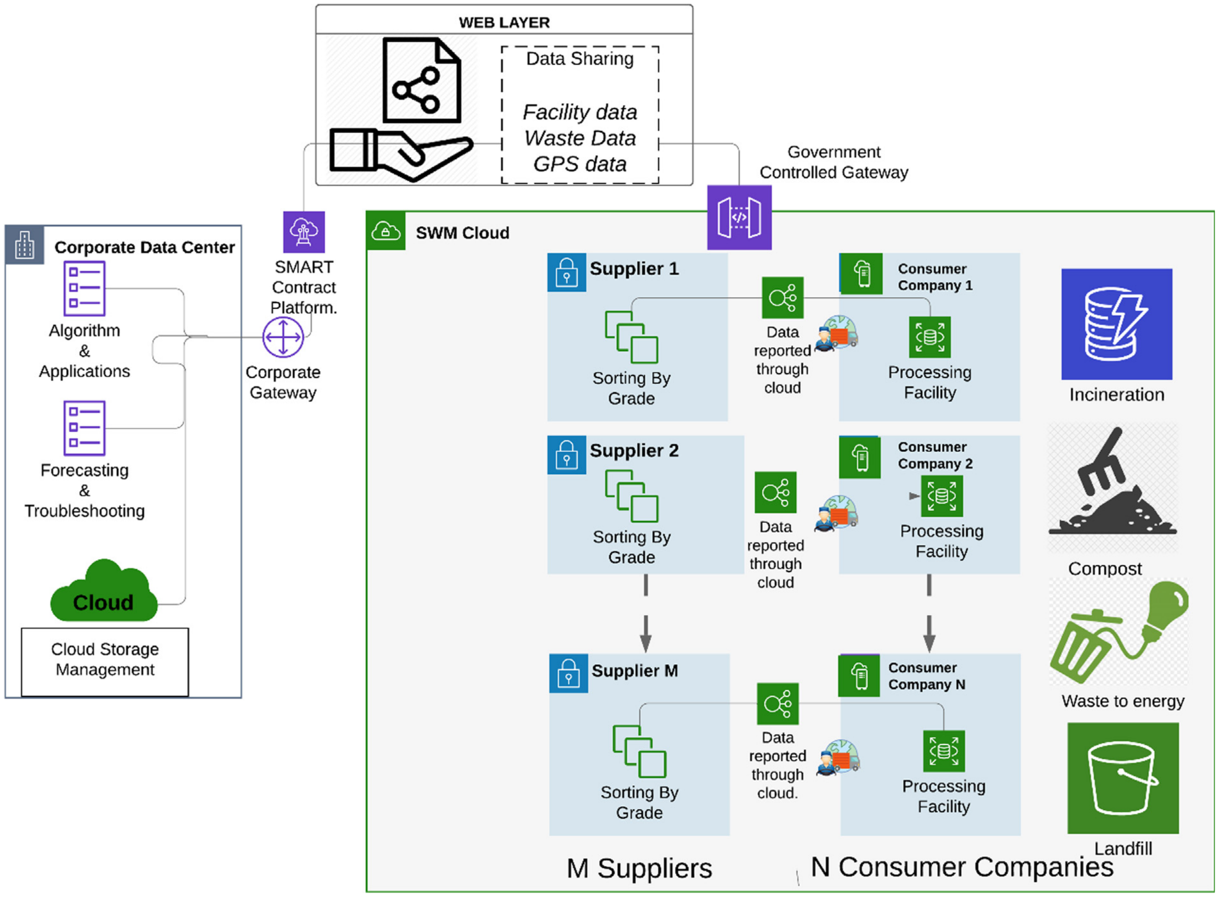

Fig. 1. Proposed supplier - consumer-based Blockchain -SWM model.

Table 2
Cost Aspects involved in the Blockchain-based SWM Framework.

Cost category	Parties involved	Cost elements
Cost 1 – Setup of Blockchain platform (Defined in Step 1 to Step 3 in Section 3.2)	Municipality, Suppliers, and corporate center	Blockchain cost associated with the creation of a framework and smart contract Waste collection and transportation cost in the supplier side Waste sorting and storage cost
Cost 2 – Purchasing cost of customer (Defined in Section 3.3)	Suppliers, customer companies, and corporate center	Transportation cost associated with transferring waste to customer companies Blockchain user and node hoisting cost (cloud-based for data storage) Product cost as per grade

includes transportation of wastes from supplier to consumer facilities, Blockchain user and node hoisting cost, and the product cost based on grade. The suppliers and the corresponding municipalities set up the Blockchain platform, and all consumer companies are expected to pay for their Blockchain user costs.

The data reported by the entities can be monitored using better designed smart contracts, which are computer codes written to authenticate the information entered in the ledger. Volume mismatches, facility handling excess, impossible fast transportation, weight mismatches, GPS coordinate mismatches, and other fraudulent activities can be easily detected and fixed using this service. Further, this platform is discussed from the perspective of the customer and a reward system to encourage waste disposal in our previous work (Gopalakrishnan et al., 2020). This work is an extension of our previous work showing more insights on the supplier- consumer company relationship and developing a cost model. Also, an optimization model is proposed to determine the optimal amount of waste that can be processed, maximize the amount of waste transferred optimally, and increase the profits for the suppliers. The suppliers can set profits within the clauses set by the municipality. The municipality sets the amount of waste a particular supplier can sell on a given day. This may lead to losses for specific suppliers; they are backed by municipality funding.

3.2. Cost elements for the supplier side

This section describes the supplier-customer company connection. It considers a group of suppliers run by the municipality that sells the wastes to the companies for processing. The information is presented in three different steps. Step 1 describes the characteristics of the supplier companies. Step 2 discusses three different cost elements for suppliers. Step 3 utilizes cost values from several use cases to formulate the supplier cost functions based on the categories described in Step 2 and provides a cost estimate for implementing the blockchain platform for four different scenarios.

If a private entity or a group of suppliers are interested in owning this platform, they can use the generalized cost formulations proposed in this section. The cost values can be defined based on their investments or budget. The cost elements discussed in this section give them the perspective of the cost involved in implementing the Blockchain platform. The cost elements discussed in the next section talk about the cost paid by consumer companies for transporting and obtaining wastes besides the platform cost. This paper considers the municipality funds the Blockchain, and customer companies are enrolled as members. However, a private entity can also have the Blockchain-SWM platform funded and managed by a collision of supplier and customer companies.

Nomenclature

S	Supplier
C	Costs associated with platform setup (cost 1)
B	Budget
D	Number of trips
T	Customer companies
U	Number of users of Blockchain
CS	Cloud storage capacity for data storage
Q	Quantity of waste
t	time

Step 1: Characteristics of the supplier network

The suppliers, along with the municipality, are entrusted with the responsibility of maintaining the SWM-Blockchain platform.

The cost of implementing the platform is defined based on the factors discussed in this step.

The set of suppliers is defined as

$$S = \{S1, S2, S3, \cdots\cdots\cdots\cdots\cdots\cdots..Si\}$$

Supplier i, Si, has the following characteristics:

$$Bi - Budget\ of\ the\ supplier$$

$$Mi - Storage\ capacity\ of\ the\ facility$$

$$Di - Maximum\ possible\ trips\ per\ day$$

$$Ui - Number\ of\ user\ space\ available\ in\ Blockchain\ platform$$

$$CSi - Cloud\ storage\ capacity\ for\ storing\ Blockchain\ data$$

The supplier budget refers to the overall investment of a particular supplier. This depends on the location, requirement in terms of transportation, storage, and a number of customer companies. The storage capacity is the space available in the facility for the storage of waste. The maximum number of trips depends on the number of trucks available on a given day, and the distance traveled. This distance is measured between the supplier and consumer companies. The user space availability and the cloud storage capacity depend on the size of the location and the number of customer companies that purchase waste for processing from Supplier i, Si.

Step 2: Three different cost elements

Waste generators or suppliers need to consider at least three different cost elements if they would like to handle their waste properly: Cost of collection and transportation of wastes, Cost of sorting and storage of wastes based on waste grade, and the Cost of utilizing Blockchain for SWM process.

These three cost elements mainly contribute to the supplier's efforts cost in implementing this platform.

C_{CT} is the cost associated with the collection and transportation of waste from different locations to Supplier i.

$$C_{CT}(i) = C_{collection} * Q_i + C_{trans} * Q_i * D_i$$

Where $C_{collection}$ refers to the unit collection cost per ton, and Q_i expresses the quantity of waste. C_{trans} is the unit transportation cost, and D_i is the number of trips for the collection of wastes from different locations.

C_{SS} is the cost of sorting and storage of waste.

$$C_{SS}(i) = C_{store} * Q_i * t_i + C_{sort} * Q_i$$

Where the storage cost is based on the unit storage cost, storage quantity, and time t_i. C_{sort} is the unit cost of sorting waste based on the type (landfill, recyclable, compost, or energy).

The utilization cost for Blockchain platform is expressed as,

$$C_{blockchain}(i) = C_{fixed} + C_{onboarding} * Q_i * U_i + Q_{trans,i} * Q_i * CS_i + C_{GPS} * D_i + C_{mc} * Q_i + C_{mo} * Q_i$$

The Blockchain cost is expressed as the initial fixed costC_{fixed} associated with the utilization of Blockchain (white paper cost). The onboarding cost is expressed as a function of $C_{onboarding}$, the quantity of waste dealt and the number of users U_i. The transaction cost is a function of the transaction cost per unit $Q_{trans,i}$, *the* quantity and cloud storage CS_i. The GPS cost is based on the unit C_{GPS} cost and the number of trips. Finally, the maintenance and monitoring cost is based on the unit maintenance C_{mc} and monitoring C_{mo} cost and the quantity of waste processed.

Step 3: Factors important in estimating blockchain cost

The above-mentioned cost function is further discussed in this section, with some numerical examples and cost estimates.

We estimate the sorting costs based on the national average collection costs per ton, which is between \$45 and \$80 per ton (depending on demographics, density, program design, degree of competition, and other variables). This phase of cost can vary depending on the complexity involved in the sorting of wastes. This value is an estimate and can vary with different scenarios. We consider that the trucks used for waste transportation are heavy loading trucks and can carry up to 2000 lb., which is approximated as 1 Ton. The storage cost can be summarized as \$15 per sq—foot per year. Based on the total storage requirement and the quantity of waste storage, the cost can be calculated accordingly. This cost might vary with the location of the facility and depends on the rent of the area.

The $C_{blockchain}(i)$ is estimated from certain assumptions and the data provided by Leeway cost estimator. We have considered four different scenarios of Blockchain implementation. The scenarios are drafted based on the primary criterion of whether we use an existing methodology for Blockchain or create a new platform from scratch. Further, other criteria, such as factors listed in Table 3a, can be used to estimate the budget needed for Blockchain.

Besides cost, other constraints such as reliability, security, and response time exist that Blockchain users need to consider when selecting a blockchain platform (Liu et al., 2011). If the municipalities decide to design and develop a Blockchain platform instead of using platforms available in the market, they need to consider five different phases as shown in Table 3b, including the consulting phase, design, development, quality assurance, and finally the monitoring and maintenance phase (Leewayhertz, 2019a).

The consulting phase refers to a range of services that ensure the successful deployment of Blockchain solutions. Consultants analyze the need of every customer and diligently work with them

Table 3
Factors and relevant Cost for Blockchain implementation.

(a) Blockchain selection criteria

Category	**Description**
Type of Blockchain	Public Private
Financial Transaction	Application requires Financial Transaction Application does not require Financial Transaction
Third-party Requirements	Cloud computing outside Blockchain network No cloud computation required
Product Interface	Web interface Mobile Apps Admin Interface
Proof of concept	Demo required Demo not required
Users	Different types of users involved Number of users based on consensus protocol

(b) Cost distribution as phases of Blockchain (Lielacher, 2019)(Tarasenko, 2019)(Analytics, 2019)(Btracking, 2018)(Leewayhertz, 2019a)

Phases of Blockchain implementation	**Cost Ranges**
Consulting Phase – **10%**	The consultant charges $200/hr. (min 10 hrs.)
Design phase– **15–20%**	White paper cost – $ 1500 – $ 50,000 Prototype development – $ 30,000
Development Phase – **50–60%**	Smart contract – $ 3000 – $ 30,000 Website development – $ 500 – $ 35,000 Cryptocurrency/Tokens (existing or new) – $10,000 – 50,000 GPS installation – $75/truck.
Quality Assurance – **20%– 25%**	Security (sales, cyber) – $ 60,000 Legal costs – $ 10,000 KYC (Know your customer) or AML (Anti-money laundering) – Variable depending on the agency. $ 6000 for an agency (estimated) $ 1170 for an individual (estimated)
Maintenance and Monitoring costs (yearly – **15–25%** of the total project value).	Third-party service Public Blockchain – $ 750 / Month Private Blockchain – $ 1500 /Month Tracking – $20 – $ 30 (Monthly) Per truck

(c) Different scenarios of cost for Blockchain platforms (Leewayhertz, 2019b, 2019a)

Scenario 1 – New Blockchain platform, Public, Requires Financial transaction, third party services in place (all 3), Proof of concept, and 4 different types of users
Development costs – $ 109,900 – 172,700 Estimated time – 31 Weeks Maintenance cost – 11,932–13,188 (per year, estimated) Third Party costs – $ 2355 (Monthly)
Scenario 2 – New Blockchain platform, Private, Requires Financial transaction, third party services in place (all 3), Proof of concept, and 4 different types of users
Development costs – $ 116,900 – 183,700 Estimated time – 33 Weeks Maintenance cost – 12,692–14,028 (per year, estimated) Third Party costs – $ 2505 (Monthly)
Scenario 3 – Integrate Blockchain to an existing platform, Private, Requires Financial transaction, third party services in place (all 3), Proof of concept and 4 different types of users
Development costs – $ 102,900 – 161,700 Estimated time – 29 Weeks Maintenance cost – 11,172–12,348 (per year, estimated) Third Party costs – $ 2205 (Monthly)
Scenario 4 – Integrate Blockchain to an existing platform, Public, No Financial transaction, third party service – Mobile Apps, Proof of concept not in place and 2 different types of users
Development costs – $ 60,200 – 94,600 Estimated time – 17 Weeks Maintenance cost – 6536–7224 (per year, estimated) Third Party costs – $ 1290 (Monthly)

on identifying their needs for developing the Blockchain framework. The average consultant cost is considered \$200/hr in Northern America (Petrashchuk, 2018). Consulting tasks might take anywhere between 10 hours to weeks, depending on the scale of the project.

The design phase involves the white paper cost associated with finding the best design solution for the platform. The prototype cost, which involves testing the model as a prototype before implementing it on the actual project, is part of the design cost.

The development phase involves developing and coding the platform and the cost of developing the smart contract, which reads the terms and conditions associated with the project. Also, the cost of using cryptocurrency or developing new tokens should be considered. The company can either choose an existing medium of exchange (e.g., token, cryptocurrency) or develop a new one depending on the scale of the project. The website or landing page is based on the need of the users. GPS cost involves the installation cost in trucks and sensors for tracking purposes. The cost of GPS is split as Installation - \$75/ per truck (one – time) and tracking - \$20-\$30 (Monthly) per truck depending on complexity. The charges may increase if there are sensors attached for process control purposes during transportation.

Quality assurance involves security and legal costs based on the requirement of the project. Also, options such as Know Your Customer (KYC) or Anti-Money Laundering (AML) analyses are used for authentication.

The maintenance and monitoring costs occur on a yearly basis and contribute to 15–25 percentage of the project value. It also involves the use of third-party services for mobile apps, admin and web interfaces, and tracking services for trucks.

Based on the costs in Table 3b, we assume four different scenarios (new Blockchain or existing platform). Table 3c gives the user an overview of costs associated with these four different scenarios for Blockchain implementation in SWM. The cost ranges are obtained from a private consulting firm providing Blockchain software solutions. The values used are from the quotes provided by the company based on the four scenarios discussed.

3.3. Cost elements for the customer side

This section defines the cost elements for the customer companies. The customer companies pay to suppliers for obtaining waste for processing. They are responsible for transporting waste from suppliers to their sites, paying Blockchain user costs, and the actual price of waste. The entire system is controlled and owned by the municipality. They set the clauses for customer and supplier companies. Suppliers make profits based on their efforts in processing the waste. They can set the product cost within the clauses determined by the municipality.

The consumer side cost is split into three elements.

Nomenclature

$\hat{C}$	Cost associated with the selling of product (cost 2)
C_j	Consumer company
D	Number of trips
n	Quantity of waste transported in tons per month
d_{ij}	Distance between the consumer company j, C_j, and supplier i,S_i
$\hat{C}_{\frac{rent}{trip}}$	Truck rent
$\hat{C}_{RTC}$	Real-time tracking cost per trip
$\hat{C}_{NHC}$	Node hosting cost per month
$\hat{C}_{CSC}$	Cloud storage cost per month
Uj	Number of users required by the customer
G_k	Cost of grade k
n_k	Quantity of grade k
$\hat{C}_{i,t}$	Profit per ton
$\hat{C}_{permile}$	Cost per mile

Transportation cost:

$$T(j) = \sum_{j=1}^{m} T_{cost}(j)$$

Product cost:

$$P(j) = \sum_{j=1}^{m} P_{cost}(j)$$

Blockchain cost:

$$B(j) = \sum_{j=1}^{m} B_{cost}(j)$$

The total cost burden to consumer companies includes three main elements: transportation, blockchain utilization, and souring the waste for processing:

$$\hat{C}_{total} = \hat{C}_{transport} + \hat{C}_{blockchain} + \hat{C}_{product}$$

Where

$\hat{C}_{total}$ – Total cost paid by the customer for obtaining the service (per month)

$\hat{C}_{transport}$ – Transportation cost paid by customer (per month)

$\hat{C}_{product}$ – Cost paid by the customer company for obtaining waste from supplier companies

$\hat{C}_{blockchain}$ – Cost paid by the customer for using Blockchain and cloud storage

The transportation cost is a function of the number of trips, the quantity transported, and the distance between the facilities.

$$\hat{C}_{transport} = n * (\hat{C}_{\frac{rent}{trip}} + \hat{C}_{per\ \ mile} * d_{ij})$$

We clarify these costs with some numerical values assumed as below:

$\hat{C}_{\frac{rent}{trip}}$ – Truck rent (\$75/trip)

$\hat{C}_{per\ \ mile}$ – Cost per mile - \$4.15 ($\leq$ 100 mile) \$ 2.5 (>100 mile)

We represent all three aspects of cost in terms of quantity n, and the cost is transported based on the cost per mile and a fixed truck rent every trip. Considering the assumed numbers, we have:

$$\hat{C}_{transport} = n * (75 + 4.15 * d_{ij}) \quad If \ \ dist \leq 100$$

$$\hat{C}_{transport} = n * (75 + 4.15 * d_{ij}) \quad If \ \ dist > 100$$

The Blockchain cost here is the cost that consumer companies pay to be a part of the platform. It depends on the number of users of the Blockchain platform, node hosting space (cloud storage), and GPS tracking for the trucks.

$$\hat{C}_{blockchain} = n * \hat{C}_{RTC} + Uj * (\hat{C}_{NHC} + \hat{C}_{CSC})$$

$$\begin{aligned}\hat{C}_{blockchain} = n * 20 + Uj * (&number\ \ of\ \ nodes\ \ per\ \ user \\ &* service\ \ cost\ \ per\ \ node\ \ per\ \ minute \\ &* number\ \ of\ \ minutes\ \ in\ \ a\ \ month \\ &+ number\ \ of\ \ nodes\ \ per\ \ user \\ &* cost\ \ per\ \ GB\ \ per\ \ month * total\ \ storage\ \ per\ \ month\end{aligned}$$

$$\hat{C}_{blockchain} = n * 20 + Uj * (3 * 0.0053 * 43,800 + 3 * 0.05 * 250)$$

$$\hat{C}_{blockchain} = 20n + 733.92Uj$$

The cost of Blockchain is defined in terms of quantity n and the number of Blockchain users *Uj*. We have made the following assumptions for the above formulation: Nodes per user is 3, Storage cost per GB for a month is $0.15 for a user, and the total storage per node for a user is 250 GB.

Nodes are used for storage of data; three nodes mean there are three copies of data. The storage cost is estimated based on the cloud cost. We have assigned 250 GB per node, accounting for 750 GB per user. The cost of selling the waste based on the grade is described in the flowchart. The wastes are the raw material source for the customer companies. The customer companies buy the wastes and convert them into commodities. The suppliers manage the collection, sorting, and transportation, and the processing facilities are the customer companies that convert them into revenue.

The product cost is expressed in terms of the quantity n and the cost G of k grade material sold by the suppliers sell.

$$\hat{C}_{product} = \sum_{k=1}^{4} n_k * G_k$$

Where

k – number of grades (4)
k = 1 Recyclables
k = 2 Landfill
k = 3 Compost
k = 4 Energy
G_k – Cost of grade k
n_k – Quantity of grade k

$$\hat{C}_{product} = n_1 * G_1 + n_2 * G_2 + n_3 * G_3 + n_4 * G_4$$

Where $n = n_1 + n_2 + n_3 + n_4$

The cost function for the total purchasing cost paid by the consumer companies for obtaining the waste is defined as

$$\hat{C}(j) = \hat{C}_{transport}(j) + \hat{C}_{blockchain}(j) + \hat{C}_{product}(j)$$

$$\hat{C}(j) = n * (75 + 4.15d) + 20n + 733.92Uj + \sum_{k=1}^{4} n_k * G_k$$

$$\hat{C}(j) = 95n + 733.92Uj + 4.15nd + \sum_{k=1}^{4} n_k * G_k$$

This equation is generalized in terms of quantity, the distance between the supplier and customer companies, the number of users of Blockchain, and the price based on grade. $\hat{C}(j)$ represents the total purchasing cost of the waste. The profit per ton of waste of the suppliers is defined as $\hat{C}_i$.

The transportation is provided through the suppliers; we assume that the customer companies pay all the three cost aspects defined in this section to the supplier.

4. The proposed optimization model

In this section, an optimization model is proposed for determining the quantity of waste traded between supplier and consumer companies. The municipality controls the optimization model and they dictate the terms for the users. The suppliers are responsible for sorting and selling the waste. The municipality decides the capacity or the amount of waste that a particular supplier can sell on a given day. The service provided by suppliers includes the collection, sorting, and transportation of waste. The municipality aims to process the maximum amount of waste based on consumer demands and maximize the suppliers' profit. Municipalities spend resources on sorting and organizing the wastes as per grade before they sell it through the suppliers. The model assumes that the customer companies will pay more for better quality goods and must provide data regarding the post-processing of waste. This can help the municipality's effort in regulating the proper disposal of waste.

The suppliers set is defined as,

$$S = \{S_1, S_2, \cdots\cdots.., S_i\}$$

The consumer companies set is defined as,

$$T = \{T_1, T_2, \cdots\cdots.., T_j\}$$

Objective function: The objective is to maximize the total profit for the collision of suppliers by determining the optimal quantity of waste traded between different entities. Where $\hat{C}_i$ is the profit per ton for the supplier and n_{ij} is the quantity of waste transferred from supplier i to consumer j. The product cost can be increased by factor *X* according to the efforts of the supplier.

$$Maximize \sum_{i \in S} \sum_{j \in T} \hat{C}_i n_{ij}$$

Subject to:

The quantity transported is less than the quantity available on the supplier side:

$$\sum_{j \in T} n_{ij} \le Q_i \quad \forall i \in S$$

The processing capacity P_j of customer j is more than the quantity transported:

$$\sum_{i \in S} n_{ij} \le P_j \quad \forall j \in T$$

The space capacity of the customer company V_j is more than the incoming waste. The v_i is the storage requirement for the waste per ton:

$$\sum_{i \in S} v_i n_{ij} \le V_j \quad \forall j \in T$$

This constraint is to balance the amount of waste going into the consumer processing facility. The proportion of the quantity sent should be in balance with the quantity processed. The ratio is defined as a constant *y* that should be greater than zero.

$$\frac{1}{P_j} \sum_{i \in S} n_{ij} = y \quad \forall j \in T$$

$$n_{ij} \ge 0, 0 < y \le 1$$

We assume there are *n* suppliers and *m* number of consumer companies, and they have a Blockchain platform in place. To clarify the proposed model, a numerical example is provided.

5. Numerical example

Based on the cost elements discussed in the previous section, a numerical example is provided, and the dataset is randomly generated using Python. The cost ranges are defined based on available estimates from online sources. The data values are normally distributed to cover a wide range of prices offered by different companies.

5.1. Dataset and model inputs

The initial consideration for the input dataset is 20 suppliers and 20 customers. Later in the paper, a sensitivity analysis is performed by varying the number of customers or suppliers. The dataset is generated randomly based on the following assumptions.

We assume i = 20 and j = 20. Suppliers have an existing Blockchain platform, and we add the customers to the platform. We assume every user needs three nodes. n is the quantity of waste transported. Every trip D carries 1 ton of waste. The maximum number of trips is based on the truck capacity (number of trucks on a given day) of the suppliers. The maximum distance between the supplier and customer is 300 miles. The processing capacity of the customer is between 50 and 100 tons per day. The storage capacity of customer facilities ranges from 45,000 to 80,000 cubic meters. The waste sent requires a storage capacity anywhere between 390 and 580 cubic meters per ton, depending on the grade of material. Furthermore, the profit per ton of waste based on the grade of material ranges between \$200 and \$3000.

The profit is calculated by considering the sorting, collection, and Blockchain user fee charged by the consumer companies. This value is an assumption for calculation purposes and given as input to the optimization model. This value can be modified depending on the profit margin.

Constraints:

The maximum number of trips for a month is restricted to 450, by limiting a maximum of 15 trucks servicing a customer per day.

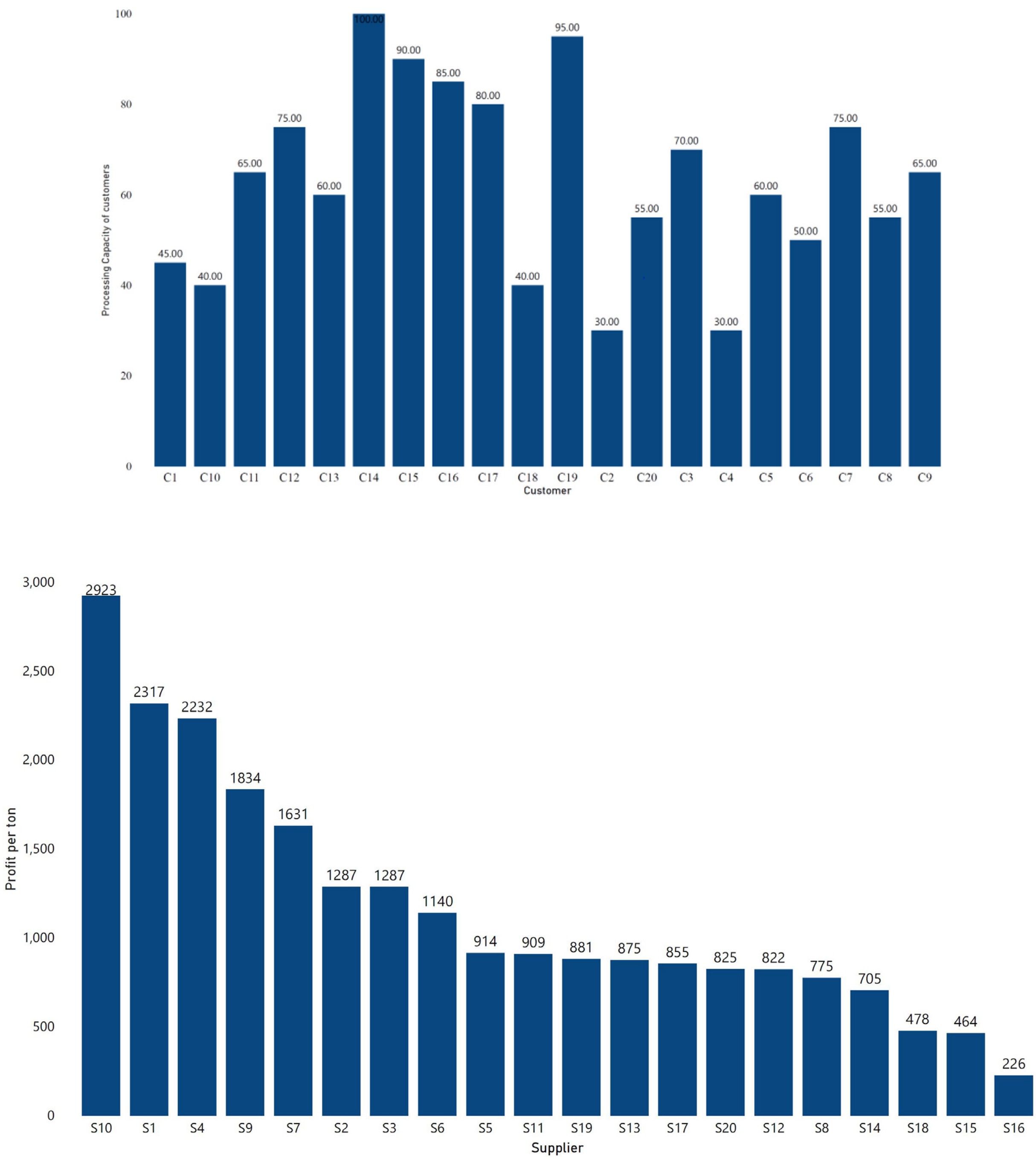

Fig. 2. (a) Processing capacity of different customer companies. (b) Profit per ton for different suppliers.

$1 \leq D \leq 450$

The number of users, m is the maximum capacity of users from each consumer company to join the Blockchain platform. As mentioned above, each user is assigned three nodes with 250 GB storage.

$1 \leq Uj \leq 4$

We assume that the distance n between the suppliers and companies is within 300 miles. This assumption is based on having this within a state. The user can modify these constraints based on their requirement.

$1 \leq d \leq 300$

The dataset consists of 200 rows and 21 columns of data. The 200 rows are based on the distance between the 20 suppliers and the 20 customer companies. The columns include the suppliers, customer companies, processing capabilities, quantities of each product and total (5 columns), 3 costs and total (4 columns), Average cost per ton, storage requirement per ton for consumers, and the storage capacity of the suppliers.

Fig. 2a shows the processing capacity of different consumers. They range from 30 to 100 tons.

The constraints for the dataset are assigned based on the processing quantity of consumer companies, the distance between supplier and the customer, maximum trips, processing capacity of customer companies, quantity transferred, and the storage capacity of the consumer company. The graphs summarize how the dataset is spaced out. Some of these parameters are used as input to our optimization model. Fig. 2b shows the profit per ton for different supplier companies. They range between $ 200 and $3000 per ton. This value varies based on the product and different grades of the material sold.

This optimization model uses the quantity sent, storage requirement/ton of product based on grade, profit per ton from the customer perspective and the processing capacity, maximum storage capacity from the customer perspective as parameters from this dataset. We can use other parameters such as distance, budget, and quality. depending on the requirement. Based on the formulation provided for the cost to supplier and customer, the values can be generated as needed. This optimization model is also generalized, and we can vary the parameters according to the requirement.

5.2. Numerical example

The inputs to the optimization model are the parameters obtained from the dataset. The constraints are defined based on the range of values given in the input dataset. We have not used all the parameters in the dataset. The following five parameters have been used as input to obtain the optimal quantity of waste that maximizes profit.

Table 4
Optimal distribution of wastes among different customer companies.

(a) Output obtained for Example 1 (i = 2 & j = 5) and Example 2 (i = 5 & j = 5)

Example 1 i = 2 & j = 5···Value of objective function – $456916.57 Total quantity processed- 235 tons $y-1$

Supplier/customer	**C1**	**C2**	**C3**	**C4**	**C5**
S1	45	0	45	0	60
S2	0	30	25	30	0

Example 2 i = 5 & j = 5···Value of objective function – $537240.51 Total quantity processed-235 Tons $y-1$

Supplier/Customer	**C1**	**C2**	**C3**	**C4**	**C5**
S1	0	20	70	0	60
S2	0	0	0	0	0
S3	0	0	0	0	0
S4	45	10	0	30	0
S5	0	0	0	0	0

(b) Optimization values for different scenarios of consumer companies

Scenario 1 – Consumer companies fixed as $j = 10$

Number of Suppliers	**Quantity processed/transferred**	**Maximum profit ($)**	***y***
$i = 2$	250	476,227.16	**0.48**
$i = 5$	480	940,978.99	1
$i = 10$	520	1,128,187.19	1
$i = 15$	520	1,128,187.19	1
$i = 20$	520	1,128,187.19	1

Scenario 2 –Consumer companies fixed as $j = 5$

Number of Suppliers	**Quantity processed/transferred**	**Maximum profit ($)**	***y***
$i = 2$	235	476,227.16	1
$i = 5$	235	940,978.99	1
$i = 10$	235	1,128,187.19	1
$i = 15$	235	580,776.62	1
$i = 20$	235	580,776.62	1

Scenario 3 –Consumer companies fixed as $j = 20$

Number of Suppliers	**Quantity processed/transferred**	**Maximum profit ($)**	***y***
$i = 2$	250	476,227.16	**0.2**
$i = 5$	617	1,029,647.18	**0.49**
$i = 10$	1164	1,946,535.32	**0.97**
$i = 15$	1235	1,994,688.89	1
$i = 20$	1235	1,996,398.07	1

Table 5
Optimization values for constant suppliers.

***(a)* Optimization value for 5 suppliers**

Suppliers fixed as $i = 5$

Example	Number of Customers	Quantity processed/transferred	Maximum profit ($)	y
Example 1	$j = 2$	75	173744.92	1
Example 2	$j = 5$	235	537240.52	1
Example 3	$j = 10$	520	940978.99	1
Example 4	$j = 15$	617	1029647.18	**0.68**
Example 5	$j = 20$	617	1029647.18	**0.49**

***(b)* Output obtained in different scenarios**

Example 1: 5 suppliers and 2 consumer companies

Suppliers	C1	C2	Total transfer per supplier
S1	45	30	75
S2	0	0	0
S3	0	0	0
S4	0	0	0
S5	0	0	0

Example 2: 5 suppliers and 5 consumer companies

Suppliers	C1	C2	C3	C4	C5	Total transfer per supplier
S1	0	20	70	0	60	150
S2	0	0	0	0	0	0
S3	0	0	0	0	0	0
S4	45	10	0	30	0	85
S5	0	0	0	0	0	0

Example 3: 5 suppliers and 10 consumer companies

Suppliers	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	Total transfer per supplier
S1	21.17	0	8.82	0	0	0	0	15	65	40	150
S2	0	0	0	0	0	0	60	40	0	0	100
S3	0	0	0	0	60	50	15	0	0	0	125
S4	8.82	30	61.17	30	0	0	0	0	0	0	130
S5	15	0	0	0	0	0	0	0	0	0	15

Example 4: 5 suppliers and 15 consumer companies

Suppliers	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	Total transfer
S1	3.7	0	0	16	0	0	0	0	0	27	44	51	0	8.5	0	150
S2	0	0	0	0	0	0	0	0	0	0	0	0	41	59	0	100
S3	0	0	0	0	0	0	0	19.9	44.1	0	0	0	0	0	61	125
S4	0	0	0	4.6	40.7	33.9	50.8	0	0	0	0	0	0	0	0	130
S5	26.8	20.3	47.5	0	0	0	0	17.4	0	0	0	0	0	0	0	112

Example 5: 5 suppliers and 20 consumer companies

Suppliers	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
S1	0	0	0	14.6	0	0	23.8	0	0	16.5
S2	0	0	0	0	0	0	0	0	31.7	0
S3	0	0	0	0	0	0	12.8	26.8	0	0
S4	0	0	0	0	0	0.8	24.2	0	0	0
S5	22	14.6	34.2	0	28.5	0	0	0	0	3.1

	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20
S1	31.7	36.6	0	0	0	0	0	0	0	26.8
S2	0	0	29.3	39	0	0	0	0	0	0
S3	0	0	0	0	43.9	41.5	0	0	0	0
S4	0	0	0	0	0	0	39	19.6	46.4	0
S5	0	0	0	9.7	0	0	0	0	0	0

For suppliers,
$390 \leq Storage\ \ requirement/ton \leq 580$ in cubic meters/ton
$100 \leq Quantity \leq 200$ in tons

$200 \leq Profit \leq 3000$

For customers,
$50 \leq Processing\ \ capacity \leq 100$ in tons
$45,000 \leq Space\ \ capacity \leq 80,000$ in cubic meters

The optimization model is run using the dataset from Section 5.1 as input. The dataset was further extended for 20 suppliers and 20 consumers with the same assumptions to run the optimization model for $i = 20$ and $j = 20$.

The problem shows how much waste is transferred between a particular supplier to a group of consumers. Let us take an example of (i = 2 & j = 5) and (When i = 5 & j = 5) to show how the results are obtained. This optimization model determines the quantity of waste being transferred from Supplier 1 to customers 1 to 5 and

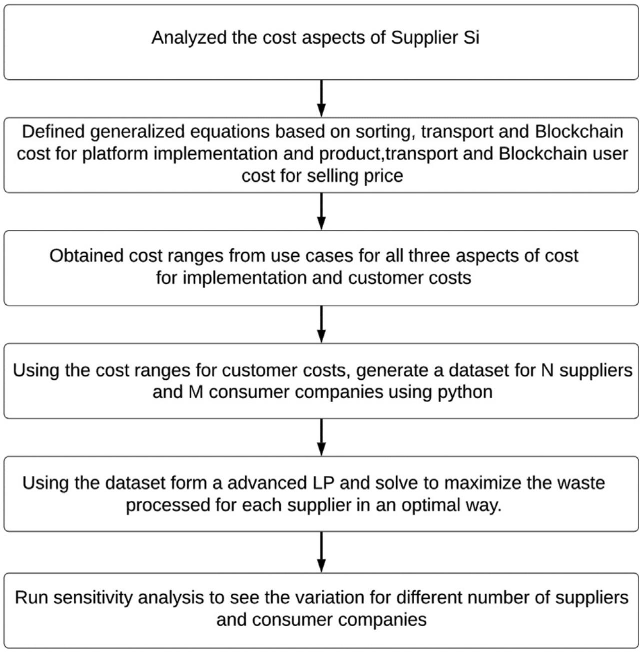

Fig. 3. Different steps of the proposed method.

supplier 2 to customers 1 to 5, and so on. Table 4 illustrates how the quantity is being distributed among different customer companies. The examples in Table 4a show us how the output is obtained for i suppliers and j customers.

Table 4b shows three different scenarios with a constant number of consumer companies. To make a comparative analysis, we have added up the total quantities processed by varying the number of suppliers and customers. The objective function is recorded in every case. The value y is the ratio between the quantity transferred and the processing capacity of the customer. If we look at Scenario 1, supplier 1 has the maximum profit per ton, so it tries to accommodate a maximum capacity of 150 tons and distribute it among the customer companies. Similarly, if we look at Scenario 2 the waste is transferred from supplier 4, who has more profit margin than the other suppliers. This model tries to obtain the maximum profit by utilizing the capacity of all consumer companies.

Table 4b shows the quantity transferred and the profit function in each case. Scenario 1 shows that the maximum capacity of the consumer companies is utilized, and the profit increases with more suppliers. In Scenario 2, the quantity is constant as the processing capacity is limited to 235 tons, but the profit is maximized by utilizing supplies from different suppliers. Scenario 3 is similar to Scenario 1, but we can see with 10 suppliers and 20 consumer companies, the quantity processed and the profit almost doubles. The value of y less than one indicates that there are not enough suppliers to serve the number of consumer companies.

Similarly, we can run this model with a constant number of suppliers and varying consumer companies and observe the trend. This model can be further explored with different parameters as well. Next, we analyze how the trend varies if we make the number of suppliers fixed.

The scenarios in Table 5a show how the costs can vary with a different number of customer companies with a constant number of suppliers. The optimal quantity processed is based on the consumer companies capacity; irrespective of the number of suppliers, the consumer companies, decide the capacity processed on a given day. If we look at the overall costs, the value increases with the number of customer companies. Our aim here is to maximize the profit for the suppliers and capitalize on the resources available in an optimal way to increase the amount of waste processed on a given day.

Further, Table 5b shows the distribution of wastes among different consumer companies. This is how the actual output is obtained for every scenario. We add it up to obtain the total value of quantity transferred. In the first three examples, the value of Y, which is the ratio of quantity transferred to processing capacity, remains 1. In Examples 4 and 5, the value is less than 1, indicating that the suppliers are not able to serve the available consumer companies.

Fig. 3 summarizes the methodology part discussed in Sections 3 and 4. First, the cost model is developed. Then, an optimization model is defined, and finally, a dataset was created to show the application of the model with several sensitivity analyses.

6. Conclusion

The capabilities of Blockchain show promise in terms of product tracking, data sharing, and waste control in SWM systems. This study discusses the concept of Blockchain in SWM and proposes a framework to facilitate the supplier-consumer connection for achieving a transparent and economically viable system. The paper explicitly discusses the cost elements of Blockchain implementation for SWM systems.

Further, an optimization model has been developed for determining the optimum quantity of waste to be traded among entities to maximize profit, and several numerical examples have been provided to show the application of the proposed model. This model helps the municipality in solving the traceability of EOL of waste. The current system lacks a sense of accountability, leading to frustration with recycling efforts. Also, consumer companies can enhance their economic viability as they buy quality products which are already sorted based on their grade. This framework would place accountability on every member of the chain rather than just on the producer as traditionally done, yielding a more effective recycling process.

The future scope involves using the cost aspects in different supply chain models where higher investments are possible. This paper considers a permissioned Blockchain platform for the case study, considering that the SWM process does not require higher investments. However, given the significance of solid waste processing with growing concerns over environmental degradation, the authorities can implement consensus protocols and high-security public Blockchain platforms to SWM. The Blockchain platform can be augmented with economic models to determine the optimal level of incentives offered to each entity to maximize their contributions. Customers are assigned based on different types of services. This can be further explored with considerations of different grades of wastes as raw materials by different types of customers. The system can be further expanded by offering more options for Blockchain usage to the customers when the SWM operates on a larger scale. The paper was based on the assumption that all entities would agree to be part of the system. In reality, there might be resilience in adopting this technology since it monitors companies' operations. Finally, blockchain-based applications can be developed and hosted on current Blockchain platforms available in the market to further test the feasibility of implementing Blockchain in practice.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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