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Blockchain-Based Forward and Reverse Supply Chains for E-waste Management

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Abstract

In this paper, we propose a novel smart e-waste management system, by leveraging the power of blockchain technology and smart contract, that considers both forward and reverse supply chains. This allows the proposed system to capture whole life cycle of e-products, starting from their manufacturing (as new products) to their disposal (as e-wastes) and their recycling back to raw materials. In this context, we address various challenges and limitations which existing blockchain-based solutions are facing, especially incomplete coverage of e-products' life cycle, access control, payment mechanism, incentivization, scalability issue, missing experimental validation, etc. We present a prototype implementation of the system as a proof-of-concept using Solidity on Ethereum platform, and we perform an experimental evaluation to demonstrate its feasibility and performance in terms of execution gas cost.

Keywords

E-waste management Blockchain Smart contract Traceability Supply chain

1 Introduction

Due to the advancement in modern technology and change in consumer demands, the global market of Electrical and Electronic Equipment (EEE) has grown exponentially. Several factors, including built-in obsolescence, shorter lifespan, presence of more non-repairable parts, etc., have resulted into generation of e-waste at an unprecedented rate [28, 31]. When e-waste products are placed in landfills or incinerated, they impose a severe threat to the environment and human health due to the presence of hazardous materials/substances such as lead, mercury, cadmium, etc. As reported in [27], this is observed that 50 million tonnes of e-waste are produced every year, and it will grow up to 25–50 billion by this year end. In reality, e-waste management and recycling market face major challenges due to lack of proper regulatory interface and supporting infrastructure. The Basel Action Network (BAN)[1] in its report stated that many developing and underdeveloped nations are used as dumping ground of e-waste products by the developed nations, where recycling is almost entirely left to the informal sector, which does not even have adequate means to handle this. In most of the cases, the whole process of e-waste products collection, segregation, dismantling, and recycling is done manually by untrained labours or they are thrown along with garbage. The current lack of interactiveness among different stakeholders, improper dissemination of information, unmonitored activities, etc., make the e-waste regulatory framework almost impossible to implement.

1.1 Motivation and Contributions

Blockchain technology [23] enables secure, transparent, and immutable record keeping in distributed systems, without the need of any trusted intermediary. A new addition to the power of blockchain technology comes with the support of smart contracts [21], an executable codes on blockchain written in high-level turing complete language. The role of smart contracts is to remove all intermediary untrusted third parties between the participating members and to automatically execute and enforce the terms of agreement between them. Research on blockchains has gained significant momentum with a wide range of applications spanning cryptocurrencies, supply chain, health care, IoT, and many others [8, 32]. Interestingly, in recent times, we are also witnessing its footstep in e-waste management, as detailed in Sect. 2.

After an exhaustive search, we observed that few research proposals and few business products are available in the literature. While the research proposals [17, 24, 30] lack in many aspects such as incomplete coverage of e-products' life cycle, access control, payment channel (in few cases), incentive mechanism, scalability issue, missing experimental validation, etc., the other proposals [1, 2, 3, 4, 5, 6, 7, 13] exist only in the form of business products without any publicly available research component. Moreover, many of them target different kinds of waste, and therefore they are not directly applicable to the case of e-waste due to the involvement of different stakeholders and the waste-flow specific to e-products. These give us a motivation to investigate various challenges and limitations as mentioned above and to propose a novel approach covering complete life cycle of e-products, starting from their manufacturing to e-waste conversion to recycling back to raw materials. To this aim, we leverage the power of blockchain technology in order to achieve the following desire goals:

- **Transparency and Traceability:** One of the most prominent capabilities of blockchain technology in this context is to enable transparency and traceability of e-products by storing the entire life cycle, starting from their origin through every point of contact on the journey. The form of a decentralized ledger that recorded all activities in a verifiable and permanent way and replicated among participants establishes a complete trust and transparency in the system.

- **Cost Savings:** In e-waste management system, use of blockchain and smart contract play a vital role in massive cost-cutting by removing all un-trusted intermediaries in the system. Moreover, the technology also eliminates fees associated with funds passing into and out of bank accounts and payment processors. Such fees cuts turn into profit margins, so being able to take them out of the equation is significant.

- **Monitoring of e-waste Generation:** Blockchain technology helps to monitor the growing volume of e-waste by capturing the moment of e-products manufacturing to their expiry. Blockchain technology can be adapted for automated event generation when any e-product reaches its end-of-life as per the expiry date recorded during registration. This allows the system to easily track the generation of e-wastes and to start monitoring their afterward activities.

- **Optimized Sorting and Automated Segregation:** To maximize recycling efficiency and consequent raw material recovery, processing of e-wastes to sort and segregate into right bins is an important task. Blockchain technology can significantly facilitate to design a cost-effective automated means of e-waste segregator. It would be driven by the stored details of e-products along with their types and by the events to be generated as soon as they meet their expiry dates.

- **Elimination of error prone paper works:** The seamless collaboration between all parties through blockchain eliminates the need of manual paper-works and dramatically speeds up all validation and certification processes.

- **Fraud and Manipulation:** The current e-waste management system doesn’t use any proper mechanism to examine e-waste disposal reports submitted by stakeholders. Since reports can be manipulated, one can easily perform payment frauds. Blockchain technology is found to be most suitable to prevent this kind of fraud and manipulation.

- **Black market and Counterfeit Products:** The blockchain-based immutable audit trail of complete life cycle of e-products to e-waste generation and the association of related documents in a tamper-proof manner make the approach powerful enough to prevent any kind of black marketing and the creation of counterfeit products in the market.

To summarize, this paper makes the following contributions:

1. 1.

   We propose a novel approach which provides a smart e-waste management system by leveraging the power of blockchain technology and smart contracts. We show in detail how our approach overcomes the challenges and limitations in the existing solutions.

2. 2.

   We consider both Forward Supply Chains (FSC) and Reverse Supply Chains (RSC) of e-waste management, enabling the proposed system to capture all activities happening throughout the life cycle of e-products, starting from their manufacturing (as new products) to their disposal (as e-wastes) and their recycling back to raw materials.

3. 3.

   We come up with an access control mechanism which ensures that only authorized stakeholders can get access to the right documents associated with desire products.

4. 4.

   We introduce a payment mechanism in the system to digitize fair trade among stakeholders on the product marketplace. In addition, an incentive mechanism is introduced to attract more participants and to motivate them to act honestly in the system.

5. 5.

   Finally, we present a prototype implementation of the system as a proof-of-concept using Solidity language on Ethereum platform, and we perform an experimental evaluation to demonstrate its feasibility and performance in terms of execution gas cost.

The structure of the paper is organized as follows: The related works are discussed in Sect. 2. The detailed descriptions of our proposed approach are presented in Sect. 3. Section 4 presents a proof of concept and experimental results. We provide a detail discussions in Sect. 5. Finally, Sect. 6 concludes our work.

2 Related Works

Post the advent of the bitcoin by Satoshi Nakamoto in 2008 [23], blockchain technology has emerged as a ground-breaking disruptive technology showing its enormous potential to a wide range of applications, such as E-waste Management, Supply Chain Management, Land Registry, Insurance, E-Governance, Health Care, Smart Agriculture, and many more. A comprehensive survey of possible applications of blockchain technology can be found in [8, 32]. The prime objectives of the use of blockchain technology is to increase accountability, transparency, and trust with regard to the storage, safeguarding and sharing of information among the stakeholders.

Supply Chain Management [10, 15, 18, 19, 22] is considered as one of the most significant and beneficial use cases of this technology. [18] proposed a blockchain-based logistics monitoring system aiming to achieve traceability, authenticity, and accountability of parcel. The authors in [10] adopted blockchain technology to enable customers to verify the composition of wines and to ensure accountability, protection and security from grape growers to retailers. The authors in [19] proposed the system to address the issue of drug safety using blockchain and encrypted QR code, allowing one to trace the drugs (including their pharmaceutical ingredients) from manufacturer to end consumer and to identify counterfeit-drug. The author in [15] proposed blockchain-based system for food agriculture, which helps to assure geographic and biological origin of the products and to trace them from farm to fork. In [22], the authors proposed a blockchain-based system for traceability of carbon fibre components used in aerospace and composite materials used in live seafood.

Let us now discuss the state-of-the-art on blockchain-based solution to waste management. Gupta and Beddi [17] proposed the flow of EEE products among five stakeholders through a number of smart contracts. The primary aim of the proposal is to validate the amount of e-waste to be exchanged between the stakeholders. In [30], the blockchain-based solution aims to provide effective management of various activities pertaining solid waste and trash bins. The microcontrollers and sensors associated with trash bins collect information about the status of trash bins and store them into a public blockchain. Gudio et al. [24] discussed the benefits and various design challenges involved in adopting blockchain technology in the case of waste management.

In addition to the above, few other solutions in the form of business products are also available, which are developed by various start-up companies [1, 2, 3, 4, 5, 6, 7, 13]. Plastic Bank [4] is an app for global recycling ventures to reduce plastic waste in developing countries. People who bring plastic garbage to bank recycling centers are rewarded by issuing blockchain-secured digital tokens. The initiative in [6] offers users to earn coins from waste sorting. People can deposit aluminum, e-waste, and plastic bottles through vending machine and receive reward-coins in their account as an exchange. Swachhcoin [7] provides blockchain-based solution for existing waste management companies where the household waste contributors are rewarded for the waste they produce. Agora Tech Lab [1] offers digital tokens in return of recycled goods, which can be used for various public services later on. The Dutch Ministry for Infrastructure [2] plans to use blockchain technology to enhance accountability and visibility of waste in transit. HashCash [3], a Blockchain-based waste management platform, offers monitoring, analysis, and management related to waste disposal and recycle processes to help enterprises. Prismm Environmental company [5] facilities waste management by accepting information and paying Bitcoins for recycling. Goodr [13] is an app to solve problem of food waste in America using blockchain technology. It allows food service agencies to connect with local charities to facilitate the delivery of leftovers. A brief survey on the above products can be found in [16].

As e-waste management has a long research tradition, let us highlight briefly a number of non-blockchain-based proposals [9, 11, 12, 20, 26]. Ravi et al. [26] proposed an analytic network process model to analyze an alternative for the reverse logistics option for End-of-Life computers in a hierarchical form. The proposed Reverse Supply Chain (RSC) model in [12] is specifically designed for Taiwanese electronic companies, which adapts fuzzy analytic hierarchy process. Hung Lau and Wang [20] presented a model for RSC of electronic companies in China, taking into consideration the key factors such as financial issues, management skills, technical issues, public awareness, environmental regulations, etc. The effect of improper e-waste management and possible implementation barrier in India are reported in [9, 11].

3 Proposed E-waste Management System

We are now in a position to describe in detail our proposed blockchain-based solution to e-waste management system.

As our objective is to enforce effective monitoring and regulatory activities throughout the whole life cycle of e-products, we consider a generic model of the e-waste supply chain depicted in Fig. 1. The model can be divided into two parts: Forward Supply Chain (FSC) and Reverse Supply Chain (RSC). The forward flow of the supply chain focuses on the trading of e-products that starts with raw material suppliers and ends with consumers/bulk consumers as end-users. This involves a number of stakeholders (producer, importer/exporter, wholesaler, retailer, etc.) with necessary technologies for producing, importing/exporting, assembling, and delivering products to the end-users. In contrast, the reverse supply chain flow mainly deals with e-waste collection, segregation, refurbishment, and recycling back to raw materials. These are performed through specific channels, such as e-waste collection centers, repairing shops, Municipal Solid Waste (MSW), Ragpickers, etc. The primary reason to consider both FSC and RSC in our proposal is to capture all activities happening throughout the life cycle of e-products, starting from their manufacturing (as new products) to their disposal (as e-wastes) to their recycling back to raw materials.

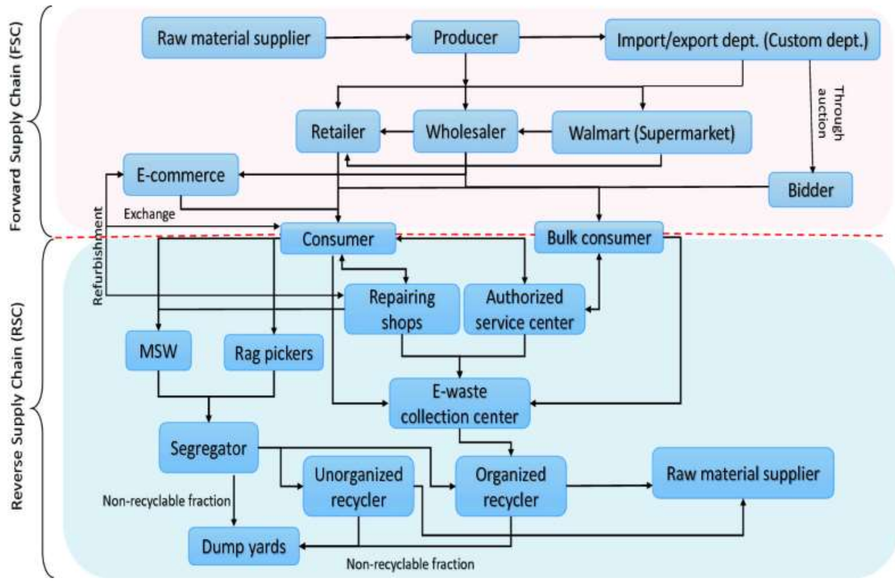

Fig. 1.

Forward and reverse e-waste management supply chain

Figure 2 depicts the overall components in our proposed system, where different stakeholders and a set of smart contracts serving various functionalities are involved. Since our proposed system is able to capture both forward and reverse supply chains, we consider all stakeholders right from the beginning of e-product manufacturing until the end of their lifetime. This includes producers, suppliers, wholesalers, customers, etc., in case of FSC, and recyclers, disposers, e-waste collectors, etc., in case of RSC. Observe that all stakeholders involved in both FSC and RSC use the services(such as registration, transfer ownership, access control, payment, incentive) provided by the smart contracts. The system comprises of the following phases:

1. 1.

   Registration of Stakeholders

2. 2.

   Collection and Channelization of E-waste Products

3. 3.

   Access Control and Data Retrieval

4. 4.

   Incentive Mechanism

5. 5.

Payment Channel

Let us now describe each phase in detail.

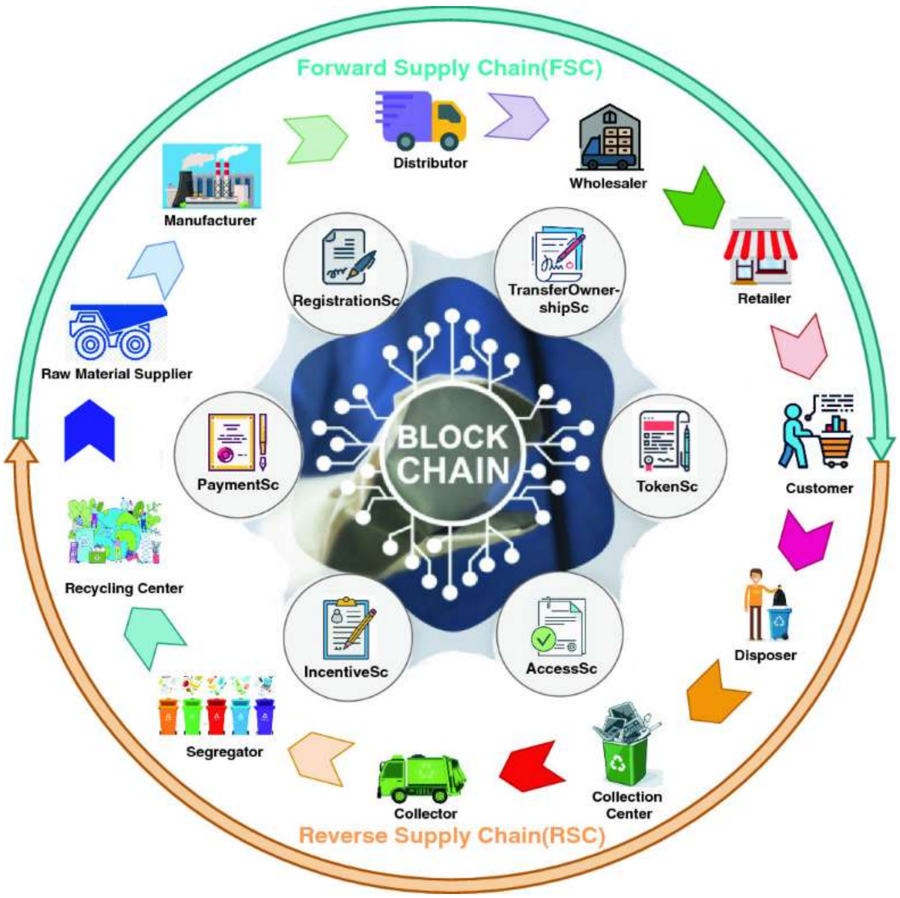

Fig. 2.

Proposed blockchain-based e-waste management system

3.1 Stakeholders Registration

The first task of all stakeholders in the system is to register themselves through RegistrationSc smart contract. On successful registration, each stakeholder receives a unique digital identifier which needs to be used in future to associate relevant information with the corresponding stakeholder. To prevent counterfeit, any government certified national identity database could be interfaced to verify the correctness of the submitted details during registration process. This can be achieved either through a merkle-tree-based verification approach [25] or through a designated trusted miner node

[29]. Figure 3 depicts the interactions among stakeholders, RegistrationSc smart contract and national identity database, where steps 1 – 3 perform the registration process.

3.2 Collection and Channelization of E-waste Products

This is the core phase in our approach to control the flow of e-products (under FSC) and e-wastes (under RSC) through proper channel in the system and to ensure their traceability and auditability. The following subphases assist to achieve these objectives:

Product Registration. To enable supply chain flow under both FSC and RSC, the producers are responsible for registering products at the early phase of their life cycle just after manufacturing. Now onwards, we use the term "product" to refer all products which are currently in use under FSC and to refer e-waste products in case of RSC. Observe that registration of e-products is done by only manufacturers, which requires product-specific details such as make, model, color, etc. Each product obtains a unique product ID through this registration process. Note that, recycling process under RSC may generate raw materials which may require to pass through this registration process again to acquire new unique identifies for them. The product registration phase is shown in steps 4 and 5 in Fig. 3.

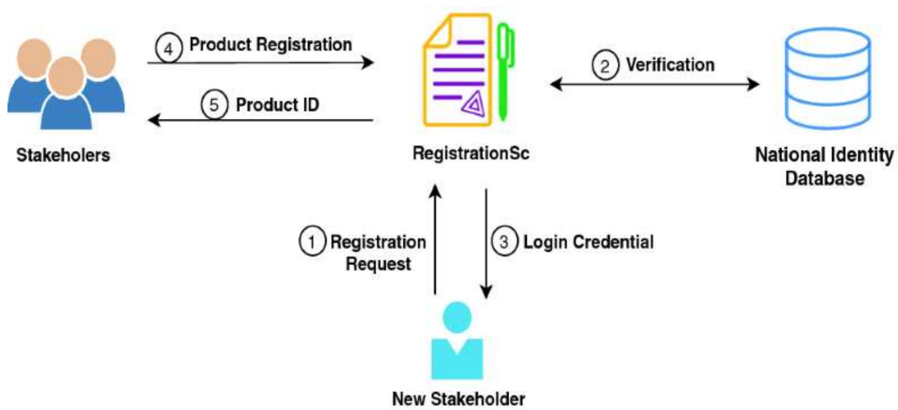

Fig. 3.

Interaction-diagram during registration phase

Product Transfer. Any product after manufacturing can be transferred to other stakeholders down the line. Under FSC, the transfer takes place among manufacturers, producers, wholesalers, retailers, etc., whereas in the same takes place among disposer, collector, and recycler under RSC. The smart contract TransferOwnershipSc is introduced to facilitate this transfer process by changing the ownership information in the corresponding state variables.

In order to improve scalability in case of transferring products in bulk amount, we introduce aggregate operation and adopt digital tokenization, which provides unique token value to group of products enabling their traceability as a whole. Moreover, given a group of products represented by a unique token value, we also introduce splitting mechanism as a way to allow transfer of only a part of it without disturbing their traceability property. The smart contract TokenSc is responsible for performing these aggregate and splitting tasks.

In the rest of the paper, we use the notations $'\langle\ \rangle'$ and '✂{ }' to denote aggregate and splitting operations respectively. Figure 4 exemplifies these aggregation, splitting and transfer processes. On the left side, observe that the token value ‘0×500’ denotes a group of three products represented by product IDs ‘0×10’, ‘0×20’ and ‘0×30’ respectively. In the same way, token value ‘0×600’ supports nested tokenization consisting of products ‘0×45’, ‘0×90’ and the token value ‘0×500’. On the other hand, token value ‘0×800’ is obtained by performing splitting operation, which consists of product ‘0×600’ and a part {‘0 × 10’, ‘0 × 30’} of products represented by token value ‘0 × 500’ which is a part of 0 × 600 token. The creation of token ‘0×500’ (shown within dotted box on left side) and its transfer is shown on the right side in Fig. 4.

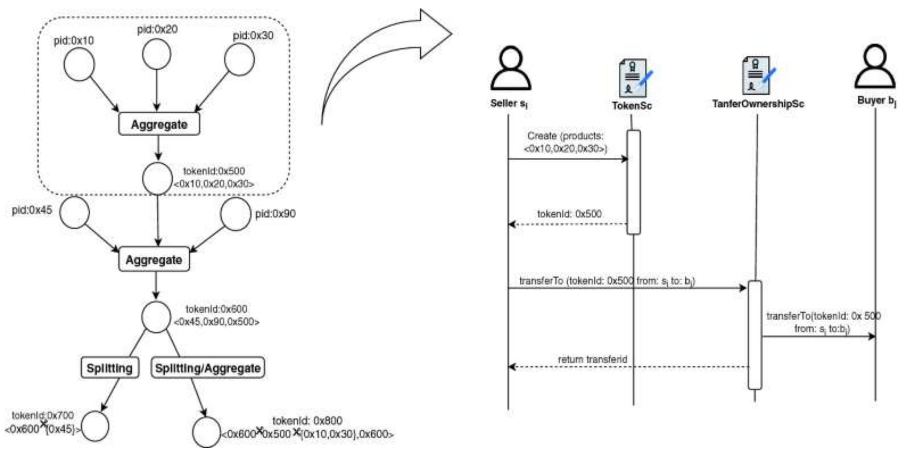

Fig. 4.

Tokenization, splitting and transfer.

The overall algorithm to perform product-transfer and product-traceability is depicted in Algorithm 1. The algorithm takes seller identity s_i, buyer identity b_j, and the collection *P* of products for which ownership needs to be transferred. Observe that *P* may contain either a number of basic product *p* or previously generated tokens t_i or splitted tokens t_j. Steps 2, 8, and 14 identify a set of all basic products, tokens, and splitted tokens belonging to *P*. Steps 3, 9, and 15 verify whether the transfer request is issued by original owner of the product. After successful verification, it updates the ownership information in steps 4, 10 and 16. The algorithm not only transfers the product ownership but also maintains a trace by appending all new owners to the list in steps 5, 11 and 17. Finally, a transfer identifier is generated afterward.

Algorithm 1: TransferOwnership

Input : Seller s_i, Buyer b_j, Collection P
Output: Transfer ID h

Create a new token t to uniquely identify P;
for *all basic product unit* $p \in P$ **do**
    if Owner$(p) = s_i$ **then**
        Replace s_i by b_j;
        Append b_j to the list inheritOwners(p);
    else
        exit;
for *all token* $t_i \in P$ **do**
    if Owner$(t_i) = s_i$ **then**
        Replace s_i by b_j;
        Append b_j to the list inheritOwners(t_i);
    else
        exit;
for *all splitted token* $t_j \bowtie \phi \in P$ **do**
    if Owner$(t_j \bowtie \phi) = s_i$ **then**
        Replace s_i by b_j;
        Append b_j to the list inheritOwners$(t_j \bowtie \phi)$;
    else
        exit;
Generate and **Store** the transfer ID h;
Return h;

This is worthwhile to mention that e-wastes can be generated in two possible ways under reverse supply chain.

- When the e-product reaches expiry date or End-Of-Life (EOL), and
- When e-products get damaged or non-reparable before it expires.

In the first case, the status is converted from e-product to e-waste automatically, based on the expiry date of the product recorded during registration. As the e-waste management system has collection centers in strategic locations, in the second case, either owner or any collection center (after damaged products are deposited and transferred by the owners) can change the status of the product into e-waste. People who deposit e-wastes to a collection center will be entitled to receive incentives in the form of reward points depending on the quantity, quality, etc., of the e-wastes (discussed in Sect. 3.4). Observe that, on e-wastes deposition, events would be generated to notify legitimate collectors to collect e-wastes from the collection points. In the same way, when products are transferred down the line, events would be generated and notified to the next level stakeholders for further processing of the e-products.

InterPlanetary File System (IPFS) Storage. Any product in the system may have a number of supportive documents such as purchase-bill, warranty-card, transfer documents, e-waste disposal reports, etc. In order to associate these documents with the corresponding product during either registration or transfer process, we use the InterPlanetary File System (IPFS), which facilitates these documents to upload in its servers and returns their corresponding IPFS hash. This IPFS-hash is encrypted by owner's public key and stored it into the corresponding smart contract's state variable. The whole process is depicted pictorially in Fig. 5. Observe that, along with ownership transfer of any product, all documents associated with the product will also be transferred. To achieve this, proxy re-encryption [14] is applied, which converts the cipher-text of the IPFS-hash (originally intended for the previous owner) into another cipher-text (intended for new owner).

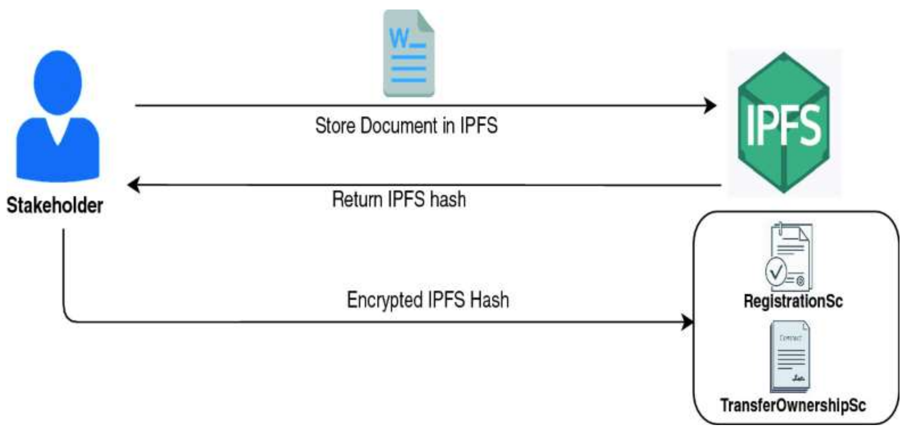

Fig. 5.

Document storage in IPFS during registration and transfer

3.3 Access Control and Data Retrieval

At the time of buying or transferring products, if the recipient wants to check/download product-related documents (such as product bills, warranty cards, e-waste disposal reports, etc.), which are stored in IPFS, the recipient must pass through an access control mechanism. The access control policy is deployed through the smart contract AccessSc. When a stakeholder s_i requests for a document associated with product p_j, AccessSc first checks with RegistrationSc whether both s_i and p_j are already registered. If both are already registered, AccessSc creates an entry in the look-up table LookTab with record ID r_k for the issued request and then fetches the list of documents D from TransferOwnershipSc stored under p_j. Once $d \in D$ is selected by s_i, the access request $\langle r_k, p_j, d, s_i \rangle$ for d is issued to TransferOwnershipSc to search product's owner. After getting owner information, AccessSc smart contract asks for owner's permission. The permission by owner would be given in the form of interaction ID I which is being generated based on the interaction between owner and AccessSc meanwhile. When TransferOwnershipSc realizes that the interaction ID provided by the owner having owner ID o_l is same as the one notified by AccessSc through an event generation, the encrypted IPFS-hash is shared with AccessSc passing through a proxy re-encryption process. The proxy re-encryption converts the encrypted IPFS-hash (which is intended for o_l) into another form (which is intended for s_i). Finally, AccessSc forwards this to the requester s_i who decrypts it using her private key and gets access of the document from the IPFS. The algorithm is depicted in Algorithm 2.

Algorithm 2: AccessControl

Input : Stakeholder s_i, Product p_j
Output: Display requested document from IPFS associated with p_j

s_i requests to the AccessSc smart contract for document of the product p_j;
AccessSc interacts with the RegistrationSc smart contract to check weather s_i and p_j are registered;
if s_i *is valid stakeholder* **then**
  if p_j *is registered product* **then**
    Store a new tuple $\langle p_j, s_i \rangle$ into LookTab;
    Generate an unique record ID r_k;
AccessSc invokes TransferOwnershipSc smart contract to retrieves document-list D of the product p_j and display it to s_i;
s_i selects the required document d from D and forwards the request to TransferOwnershipSc to search product's owner o_l;
AccessSc asks o_l for the permission;
Owner o_l checks LookTab through AccessSc to grant permission for accessing document;
if $\exists(r_k, s_i, p_j) \in LookTab$ **then**
  Store $\langle d, o_l \rangle$ into LookTab;
  Return interaction ID I to the owner through AccessSc and simultaneously notify TransferOwnershipSc;
Owner gives permission to TransferOwnershipSc by sharing I and subsequently it shares re-encrypted IPFS-hash Y (intended for s_i) to AccessSc;
AccessSc forwards it to s_i;
s_i decrypts Y with her private key and download the document d from IPFS;

3.4 Incentive Mechanism

The primary goal of this phase is to encourage people to use the proposed blockchain-driven e-waste management system, and to promote more organized and unorganized sectors to participate for disposal, collection, processing, and recycling of e-waste products. This can be achieved by giving incentives to the stakeholders involved in RSC (disposer, collector, segregator, etc.) who are helping to channelize the e-waste products. The incentives are given in the form of some reward points and the amount of rewards depends on the quantity, quality, etc., of e-wastes and the type of stakeholders. For example, more incentives should be given to the customers (i.e., disposer) who wish to dispose their EOL products, as this is the starting point of e-wastes channelization. Stakeholders can use these rewards points in future in many possible ways, such as availing discount on product's MRP, tax benefit from Government, etc.

3.5 Payment Channel

To enable payment in the system during the purchase or transfer of products, the smart contract PaymentSc is deployed. This payment channel is applicable for trading among stakeholders in both FSC and RSC.

Let s_i be the seller and b_j be the buyer of the requested product p_k. Once the orders are placed through PaymentSc, s_i shares the price information of p_k with b_j. When b_j deposits the required amount '*val*' to PaymentSc, this triggers a notification to s_i to initiate the dispatch of the product. On successful product delivery, b_j sends an acknowledgment to PaymentSc which immediately releases the payment to the seller's account. The whole process is shown in Fig. 6.

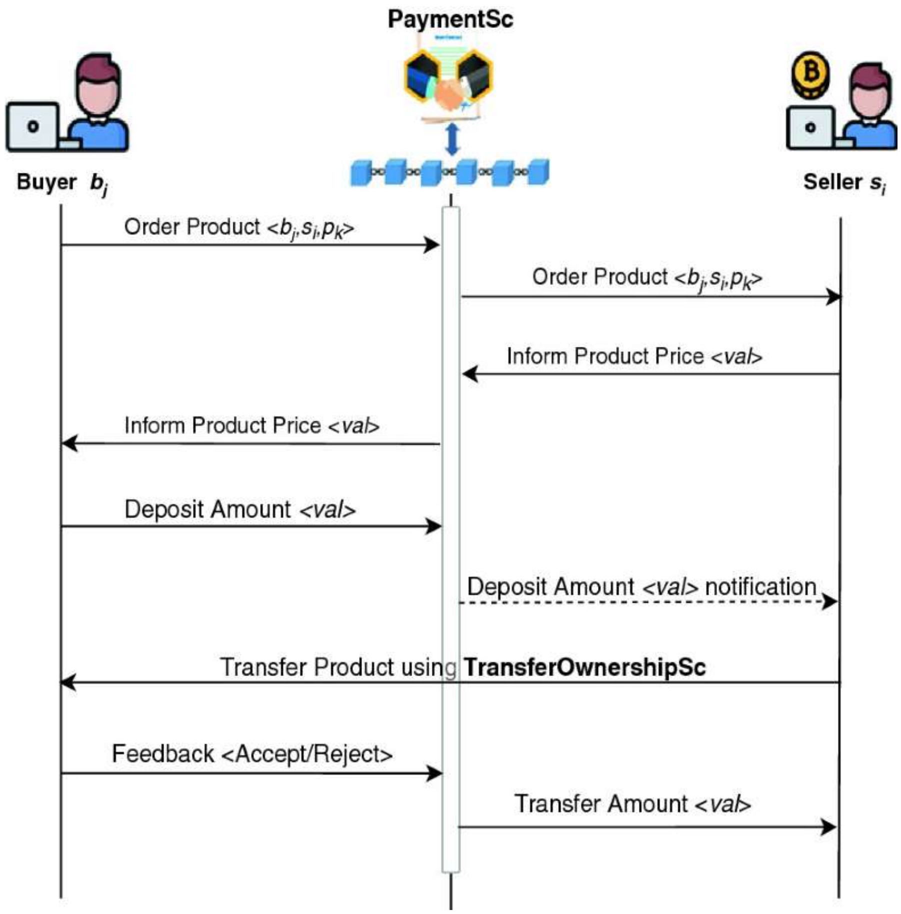

Fig. 6.

Payment interaction-diagram between sender, receiver and PaymentSc

4 Proof of Concept and Experimental Results

In this section, we present a prototype to evaluate the practicality of our proposal. The programming language that we have used in the implementation is Solidity and Python. The current prototype version has six different smart contracts implementation: RegistrationSc, TransferOwnershipSc, TokenSc, AccessSc, IncentiveSc and PaymentSc.

We perform smart contract compilation, deployment and executions on the system configured with Intel i5 processor, 1.90 GHz clock speed, 8 GB RAM and Windows 10 Professional 64-bit Operating System. Table 1 depicts the experimental results which record smart contract's deployment and execution costs in terms of gas consumption. In the experiment, we set the gas price to 2 *Gwei*, where 1 *Gwei* = 10^9 *wei* = 10^{-9} *Ether*. First six rows show the deployment gas cost for the above-mentioned smart contract, whereas other rows show the execution gas cost for various functionalities in smart contracts. This is to observe that these smart contract functions always consume fixed amount of gas during their execution irrespective of the inputs. For example, when a stakeholder joins the system, the userRegd operation needs the gas amount 237,614 (equivalent to $0.14) where productRegd operation for product registration uses gas amount 291,866 (equivalent to $0.18). Similarly, costs for the functionalities in TransferOwnershipSc, AccessSc,TokenSc, IncentiveSc, and PaymentSc smart contracts are depicted in Fig. 7.

Table 1.

Transaction gas costs for smart contract functionalities

Sl. No.	Functions	Task	Transaction gas	Execusion gas	Actual cost (*Ether*)	*USD* ($)
1	RegistrationSc	Deployment	3,441,178	2,549,599	0.006882356	2.13
2	TransferOwnershipSc	Deployment	4,656,882	3,606,784	0.009313764	2.88
3	TokenSc	Deployment	2,569,725	1,998,765	0.005139450	1.59
4	AccessSc	Deployment	6,878,071	5,624,807	0.013756142	4.26
5	PaymentSc	Deployment	3,952,163	2,452,798	0.007904326	2.45
6	IncentiveSc	Deployment	170,975	88,935	0.00034195	0.10
7	userRegd	Execution	237,614	206,563	0.000475228	0.14
8	productRegd	Execution	291,866	241,342	0.000583732	0.18
9	userLogin	Execution	27,902	2,581	0.000055804	0.017
10	tracing	Execution	23,752	2,288	0.000047504	0.014
11	conHash	Execution	29,509	9,352	0.000059018	0.018
12	verifyLookup	Execution	21,806	17,832	0.000051612	0.015
13	geneID	Execution	21,509	5,909	0.000043018	0.013
14	accPerm	Execution	16,764	7,668	0.000033528	0.010
15	makePayment	Execution	251543	201,987	0.000059086	0.018
16	reward	Execution	17,675	5,645	0.000035350	0.010

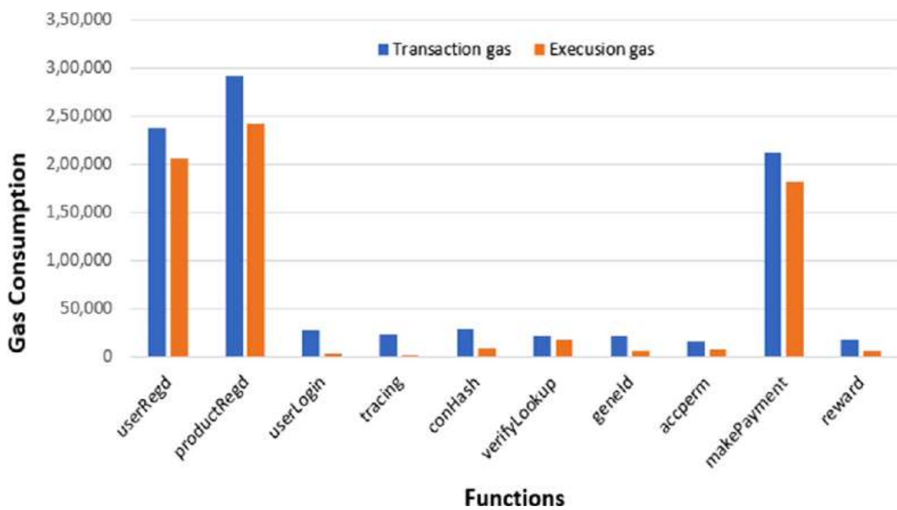

Fig. 7.

Gas costs of different functions in smart contract

Figure 8 illustrates how TokenSc smart contract affect the scalability in the system through recording the execution costs of TransferOwnershipSc with tokenization and without tokenization. Observe that the gas cost varies linearly w.r.t. input data collection size. Note that, in order to perform encryption of IPFS-hashes (during Registration) and their proxy re-encryption (during Product Transfer and Access Control), we used 'npre'[2] library which requires 'libssl-dev' and 'libgmp-dev' as its pre-requisites. This is a customized library written in Python and is a slightly refined version of the same algorithm in the charm crypto library. The interaction between proxy re-encryption off-chain computation and the smart contract is established using oraclize[3].

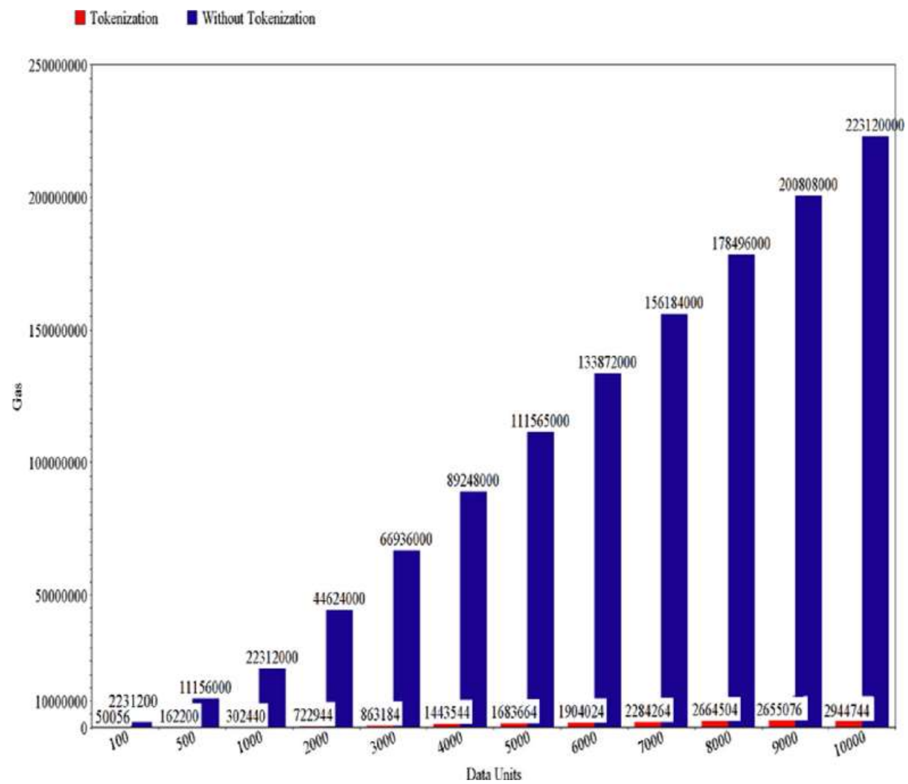

Fig. 8.

Gas costs for TransferOwnershipSc with tokenization and without tokenization w.r.t. input size.

5 Discussion

In this section, we perform a comparative study among the existing research proposals and the software products (discussed in Sect. 2) with our proposal. Then we assess our proposed system in terms of blockchain-assisted goals mentioned in Sect. 1.1. We also highlight the scope of possible improvements in our system.

The system proposed in [17] aims to validate the amount of e-waste to be exchanged between five stakeholders. The waste-flow in the proposal is very restrictive in the sense that consumers send the e-wastes to collection centers via producers. The authors in [24] do not propose any new solution. Rather, they discuss only the benefits and design challenges involved in adapting blockchain technology to the case of waste management. The prime focus of [30] is to perform coordinated actions by a number of municipality workers using blockchain according to the states of the deployed trash bins (under cleaning, already cleaned, full, etc.). In case of the business products [1, 2, 3, 4, 5, 6, 7, 13], we observed that the associated websites and few white-papers highlight only various features of the product, rather than their technical details.

Table 2 depicts a comparative summary of the proposals (including supply chain management of the products other than e-waste) in the literature, where BC, FSC, RSC, R, and BP stand for "Blockchain Technology", "Forward Supply Chain", "Reverse Supply Chain", "Research-based" and "Business Product" respectively. The notation "NM" indicates that the authors have not mentioned anything about the blockchain platform they used in their proposal, whereas "NA" stands for "Not Applicable". We have used the notations 'Y' and 'N' to indicate 'Yes' and 'No' respectively. This is to observe that the existing proposals [10, 15, 18, 19, 22] on supply chain management of products other than e-waste do not involve RSC and they do not consider any access control mechanism, payment channel, and incentive mechanism. Interestingly, all proposals on e-waste, except [17], are restricted to RSC only. Although [17] addresses both FSC and RSC, the solution does not consider any access control mechanism or payment system. As highlighted in the last row of the table, our proposal addresses all of them.

Table 2.

A comparative summary w.r.t. literature

	Metrics							
Proposals	**Is BC-based ?**	**Blockchain platform**	**Product type**	**Support FSC/ RSC/Both?**	**Support access control ?**	**Use payment system?**	**Incentive?**	**Availability**
Helo et al. [18]	Y	Ethereum	Parcel	FSC	N	N	N	R
Biswas et al. [10]	Y	Multichain	Wine	FSC	N	N	N	R
Kumar et al. [19]	Y	NM	Drugs	FSC	N	N	N	R
Galvez et al. [15]	Y	NM	Food	FSC	N	N	N	R
Mondragon et al. [22]	Y	NM	Aerospace sector and sea food	FSC	N	N	N	R
Agora Lab [1]	Y	Ethereum	Solid waste	RSC	N	N	Y	BP
Swachhcoin [7]	Y	Ethereum	Households and industries waste	RSC	N	N	Y	BP
Plastic Bank [4]	Y	Hyperledger fabric	Plastic waste	RSC	N	N	Y	BP
Dutch [2]	Y	Ethereum	Solid waste	RSC	N	N	Y	BP
Recereum [6]	Y	Ethereum	Household waste	RSC	N	Y	Y	BP

	Metrics							
Proposals	**Is BC-based ?**	**Blockchain platform**	**Product type**	**Support FSC/ RSC/Both?**	**Support access control ?**	**Use payment system?**	**Incentive?**	**Availability**
HashCash [3]	Y	NM	E-waste	RSC	N	Y	Y	BP
Prismm [5]	Y	NM	Paper and factory aste	RSC	N	Y	Y	BP
Goodr [13]	Y	NM	Food waste	RSC	N	N	Y	BP
Thada et al. [30]	Y	NM	Solid waste	RSC	N	N	N	R
Ongena et al. [24]	Y	NM	Dump waste	RSC	N	N	N	R
Chiou et al. [12]	N	NA	E-waste	RSC	N	N	N	R
Lau et al. [20]	N	NA	E-waste	RSC	N	N	N	R
Rani et al. [26]	N	NA	E-waste	RSC	N	N	N	R
Awasthi et al. [9]	N	NA	E-waste	RSC	N	N	N	R
Chaudhary et al. [11]	N	NA	E-waste	RSC	N	N	N	R
Gupta et al. [17]	Y	Ethereum	E-waste	Both	N	N	Y	R

				Metrics				
Proposals	**Is BC-based ?**	**Blockchain platform**	**Product type**	**Support FSC/ RSC/Both?**	**Support access control ?**	**Use payment system?**	**Incentive?**	**Availability**
Our Proposal	Y	Ethereum	E-waste	Both	Y	Y	Y	R

Let us now assess our proposed system in terms of blockchain-assisted goals mentioned in Sect. 1.1. Given unique identifier to every stakeholder and e-products in the system using RegistrationSc, one can easily trace the movement of products under FSC and RSC with the help of TransferOwnershipSc smart contract. It records ownership of the e-products during their transfer in FSC, their transition from e-products to e-wastes when EOL is reached, and their journey as e-wastes under RSC. The ability to trace product's complete journey and to record of a complete audit trail of all changes using TransferOwnershipSc definitely help the regulatory bodies of the country to monitor e-waste generation, hence improves the transparency and trust in the system. Our system makes use of IPFS pinning service[4] to store all relevant documents (which are associated with stakeholders and e-waste products) permanently in the IPFS. Few alternatives to IPFS are Swarm, Sia, Stroj, etc.[5] Observe that the deployment of smart contracts TransferOwnershipSc and PaymentSc leads to a cost-cutting by eliminating fees involved in handling intermediaries, fulfilling common contractual conditions and legal obligations. As recyclables materials need to be sorted and segregated efficiently, TokenSc facilitates optimizing the sorting and to automatically segregate (based on their types recorded in RegistrationSc) by using the mechanism of tokenization and splitting. AccessSc, on the other hand, prevents the system from any fraud and manipulation by restricting the access to the documents and by establishing proper payment channels among legitimate stakeholders using PaymentSc. The registration of all e-products after their manufacturing and details of their journey in the blockchain removes any possibility of black market and counterfeit products.

This is to observe that a permissioned blockchain is best suited in our proposed system due to its access control feature for efficiently managing and protecting crucial data in the system. As the execution of smart contracts on Ethereum blockchain platform requires gas cost, Hyperledger Fabric can be considered as an alternative to this.

As possible future scopes, the proposed system can be integrated with AI techniques and IoT-enabled smart dustbins to facilitate various tasks under FSC and RSC, such as image analysis to identify e-waste type, automated sorting and segregation processes, etc.

6 Conclusion

This paper presents a novel blockchain-driven approach to e-waste management. In comparison to the related research [17, 24, 30] in the literature, our proposed system improves in many aspects: (i) by covering complete life cycle of e-products, starting from their manufacturing to e-waste conversion to recycling back to raw materials, and (ii) by addressing various challenges and limitations, including access control, scalability issue (in terms of the number of stakeholders and the flow of wastes), incentive mechanism and payment channel (in few cases), etc. To the best of our knowledge, none of the existing research proposals [17, 24, 30] demonstrates any experimental validation results. As our future aim, we are now exploring its possible extension to other kinds of waste products and their management.

Footnotes

1. 1.

   https://www.ban.org (https://www.ban.org).

2. 2.

   https://github.com/nucypher/nucypher-pre-python/tree/master/npre (https://github.com/nucypher/nucypher-pre-python/tree/master/npre).

3. 3.

   https://provable.xyz/ (https://provable.xyz/).

4. 4.

   https://docs.ipfs.io/concepts/persistence/#pinning-in-context/ (https://docs.ipfs.io/concepts/persistence/#pinning-in-context/).

5. 5.

   https://ethersphere.github.io/swarm-home/ (https://ethersphere.github.io/swarm-home/), https://sia.tech/ (https://sia.tech/), https://storj.io/ (https://storj.io/).

Notes

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