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Bringing trust and transparency to the opaque world of waste management with blockchain: a Polkadot parathread application

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Abstract

The majority of countries are currently struggling to achieve sustainable levels of recycling and waste treatment, particularly relating to household waste, and this area is in urgent need of new solutions. In general, the waste management sector has struggled with low consumer trust, fraud, manipulation, significant manual processes, and low levels of information and control. Here we propose a hybrid blockchain solution called a Polkadot parachain. Polkadot is a blockchain technology that allows for the development of a network of blockchains, each called a parachain that can be customised to the business needs of a given application. This solution provides the cost benefits, scalability, and control of a permissioned blockchain while providing the security, verifiability, and trust of a public blockchain. The solution combines three typically separate blockchain use cases: supply chain tracking, incentivisation through a payment system, and gamification to achieve a complete solution for waste management. We provide a detailed discussion on the design of this blockchain solution with the use of blockchain functionality assessed against the criteria and development approaches found in the literature. Finally, we demonstrate how such a blockchain can be implemented with the Substrate blockchain development framework and detail a pilot project where this system will be implemented.

Keywords: Blockchain; Polkadot; Waste management; Recycling; Supply chain; Pay as you throw; Substrate; Parachain

Introduction

Despite recent growth in the recycling sector and increases in environmentally friendly consumption, most European countries are still far from achieving sustainable levels for the production of waste. The European Commission has identified that many member states are at risk of significantly missing legally binding targets for the reuse and recycling of municipal waste [1]. The commission identifies household municipal waste as one of the most complex streams to manage due to its diverse composition, the large number of individual household producers, and the problem of divided accountability. For household waste the only economically viable option, given current technology, is for households to separate waste before delivery. This challenge has recently increased significantly, as while waste has historically been cost-effectively transported long distances for treatment, one of the most common pathways (transport to Asia) has been halted as China and other countries have enacted policies with strict material purity constraints (99%) on imported waste. It is then required, both under EU targets, and as a matter of achieving a sustainable society, that significant increases in both the rate of household waste separation and the care with which this separation is performed are achieved.

Several methods that encourage citizens to change their behaviour, in order to reduce waste generation and increase recycling, have been implemented and tested. Popular approaches include monetary incentives [2], regulations [3], or altering the convenience of recycling [4], to cite just a few. One approach that has shown promise is that of Pay-As-You-Throw (PAYT) or recycling reward systems [5] that impose costs on consumer for the production of undifferentiated waste or reward households for the correct separation of recyclable material. PAYT systems are often preferred for the ability to incentive producing less waste overall by reducing consumption, encouraging waste separation, and the re-use products [6]. These approaches can effectively be considered as providing economic incentives to consumers. Alternative forms of incentives, such as gamification, have also provided some promise for delivering behavioural change in this sector [7].

However, these systems still face a number of challenges including preventing the increased production of waste due to rebound effects, maintaining the quality of waste separation, verifying the treatment of waste, and encouraging uptake by consumers. On this last significant challenge, it must be noted that waste management is typically characterised as a low trust industry [8] and consumers can be discouraged to recycle when this is the case [9]. There is potentially good reason for this lack of trust as the waste management sector has historically recorded relatively high levels of organised crime and illegal dumping of waste [10]. Even today there are serious issues in the treatment of waste once it hits the waste management sector, for example, in many European countries over 40% of hazardous waste "disappears" from the market [11]. In general, the waste management sector has struggled with fraud and manipulation, the level of incorrect information, significant manual processes, and low levels of information and control [12].

In this paper we propose a waste management and incentivisation system, called BEE2WasteCrypto, that is built on a Polkadot parachain [13] as a promising potential solution to address these specific challenges. Polkadot is a technology envisaged as a network of connected blockchains. These specific blockchain implementations, called parachains, provide "globally-coherent dynamic data structures" [13]. While one of the main use cases for this developing technology is the ability to transmit information between different blockchains, it also provides additional advantages of specific use here. Because parachains are linked through the Polkadot relay chain, they share a level of security and provide a level of trust without the requirement that each individual parachain achieves complete independent security.

Blockchain technologies are characterised by their trust free and transparent nature [14], in fact, this ability to increase trust is the most cited advantage in the study of their application [14]. Due to this and other advantages blockchain technologies have generated significant interest and found some recent success in the related fields of supply chain management [15], and particularly food and agriculture supply chains [16].

A blockchain is a relatively unique data structure which generally achieves a specific set of characteristics including decentralisation of consensus, immutability, transparency, automation, and security [17]. Although these characteristics will depend on the exact blockchain technology applied they can allow for additional features such as financial incentives, self governance, and data ownership [14]. Perhaps the most important of these characteristics are decentralisation and immutability from which the case is made that blockchain can offer a system that produces trust. With a decentralised consensus no entity has control of the system, so we do not need to trust that a third party will treat our data securely, as no party has the control over this data. When we combine this with immutability, that property that past actions cannot be changed, a complete record of all previous actions, that cannot be altered by any party is secured on the blockchain. This property is sometimes described as "trust-free" in that users are not required to trust any third party when using a blockchain system. In a recent review of the blockchain literature, [14], finds the most cited benefit of applying blockchain mentioned by 50% of studies, is this "trust-free, transparent nature which eliminates the need for intermediaries". However, it is important to note that the characteristics will depend on the exact nature of the blockchain solution applied. There are in fact a vast range of technology solutions that can broadly be classified as "blockchain" technologies which each take different approaches and make different trade-offs in characteristics, for example sacrificing decentralisation for improving speed or lowering costs.

For this research we then present a polkadot parachain blockchain for use in the waste management industry. In comparison to alternative research surveyed the solution proposed here:

- Applies a hybrid blockchain solution (parachain) based on a blockchain network (Polkadot) that provides the cost benefits, scalability, and control of a permissioned blockchain while providing the security, verifiability, and trust of a public blockchain such as Ethereum. We believe this to be one of the first applications of a Polkadot parachain in the literature in any field and one of the first to discuss the application of the Substrate blockchain design framework.
- Leverages specific characteristics of this blockchain solution to address the fundamental issues associated with waste collection and management.
- The blockchain design is provided in detail with the use of blockchain functionality assessed against the criteria of [18]. Given the identified system goals we design a blockchain solution following the approach of [19] and show how this is implemented within the Substrate blockchain framework.
- Combines three typically separate blockchain use cases: supply chain tracking, incentivisation through a payment system, and gamification to achieve a complete solution for waste management.

Literature review

A limited number of previous studies have proposed the use of blockchain technology in the waste management sector, these are summarised in Table 1. In addition, a number of commercial blockchain waste management projects have either launched as start-ups or pilot projects including Swachhcoin [20], Recereum [21], RecycleGo [22], Partitalia [23], Plastic bank [24], End of Waste (EOW) [25].

The literature review identified several different areas where blockchain has been proposed for application in the waste management system including:

- **Supply chain management** – the benefits of blockchain for both coordinating the supply chain (the flows of waste between different facilities) and for tracking waste and recycling is proposed in the literature in a number of studies. Supply chain management is the most common category of application found in the waste management literature and various means of implementing a system that tracks smart bins and garbage collection are discussed, however, it is found that a number of these implementations end up relying on centralized server infrastructure which undermines the trustless nature of the blockchain. In the case of tracking recycled materials, it is argued that creating a blockchain record of material flows will improve the information on recycled material which will increase efficiency and increase prices for such material [26]. Additionally, tracking waste sources and destinations may open up new options in terms of making manufactures responsible for the disposal of their products [27]. Transparency, automation, and disintermediation have all been identified as blockchain features driving adoption in supply chains [28].
- **Providing incentives** – Using tokens to provide incentives is discussed in a few studies. In one case the blockchain tokens are simply used to replace physical tokens that citizens receive for recycling [29]. In an interesting case in the agricultural sector tokens are issued to farmers to reward the sorting of waste [30]. The increased sorting of waste should increase the production of fertilizer and energy in waste treatment which the farmers can then trade tokens for. This case study provides an example of using tokens to share the benefits of a changed behavior (internalizing an externality). In a review of the related field of circular economy it was argued that the use of incentivization is underutilized in proposed blockchain applications, indicating there is still much to explore in this area [31]. In the commercial pilot projects reviewed incentivization appeared to be a much more common application of blockchain than in the academic literature.
- **Waste services market / platform** – the ability to implement decentralized markets or platforms on a blockchain is presented in the waste management context. In one study [32] it is argued that centralizing the European trade of goods and services will provide competition benefits and reduce regulatory burden. However, these benefits are not specific to blockchain (the benefits of centralized exchange) and blockchain is only proposed as a possible platform. In another study a community sized services exchange platform is proposed.

However, the literature on blockchain applications reviewed typically suffers from a number of shortcomings, the most significant of which is scalability. In particular, both the applications found in the literature and the commercial projects typically proposed the use of the Ethereum blockchain [33]. Ethereum was the first blockchain to allow for smart contract functionality and is by far the most common platform for blockchain projects found in the literature. Unfortunately, over the last several years Ethereum has become a victim of its own success and due to competition between projects to make use of the limited Ethereum block bandwidth, the fees for the use of Ethereum have become excessive for all but the highest value applications (typically finance based) with each interaction with the blockchain costing upwards of $20, which is simply not practical for a supply chain application. In [34] the authors reviewed three of the Ethereum based commercial projects (Swachcoin, Recereum, and Plastic Bank) and found them to be immature and unable to handle the quantity of data that would be required in a realistic scale application.

In addition, while these applications propose a system to be implemented on a blockchain they do not justify the use of blockchain or match its particular characteristics to the specific problem being solved. For a blockchain to provide a successful technological solution to a given problem, the specific characteristics of blockchain (including advantages and disadvantages) should be matched to the detail of the problem [18].

It should also be noted that most of these studies are highly theoretical and have not involved the development of a solution and so have not addressed the practical challenges of applying current blockchain technologies to their design specification. These practical details are important as the majority of the commercial pilots have been hampered by some of the typical limitations of blockchain technology including cost, security, and scalability [34]. It is difficult to imagine that Etheruem can be a practical solution for a blockchain application, such as waste management, where many small updates are being made to the system to track the high quantity of waste produced by households.

Finally, the literature demonstrates that blockchain technology is typically implemented in combination with a number of enabling technologies including, smart bins, 5G, Radio Frequency identification (RFID), QR code readers, artificial intelligence (AI), digital twin technology, Internet of Things (IoT), and large-scale sensors. Many of these technologies play important roles as interfaces with the physical world as blockchain is an entirely digital technology. However, this fact should be noted as both it is not always clear if the benefits of the system presented in the literature are due to blockchain, the other technologies involved, or the combination proposed. In addition, the requirements for significant investment in enabling technology adds to the already significant hurdles of applying blockchain technology. For this reason, we present here two system configurations, one that applies blockchain with current technology available at a proposed pilot site and one configuration based upon the ideal technology.

Methodology

In this section of the document, we introduce the reader to blockchain by giving a brief overview of how the technology operates before identifying and explaining the specific blockchain technology selected for application in this project. Next, we outline the waste collection and incentivization system to be implemented on the selected blockchain before discussing the criteria used to design and assess the specifications of the blockchain implementation.

Basic structure of a blockchain

Blockchain, as the name implies, can be thought of as a connected series, or chain, of blocks. Each block contains data that is recorded in the system and a representation of the previous block (a hash). This means the chain cannot easily be altered, for if an attacker altered the information in a block the next block would no longer match, and the chain would be broken. Therefore, to alter any part of the blockchain requires the alteration of all following parts of the blockchain, which becomes computationally prohibitively expensive when using a consensus algorithm such as Proof of Work.

The real advance in blockchain technology arrived with the launch of the Ethereum blockchain [33]. Ethereum, rather than simply adding transactions to blocks allowed users to add code called smart contracts. This meant users could submit code, that can be run on the blockchain, that was publicly verifiable and unalterable. This meant users could for instance create a smart contract to track the whereabouts of products in a supply chain, with operators updating the status as products arrived at different locations. This record of where each product was sent then cannot be altered and is publicly verifiable for all to check. Such an approach is, for example, being used to create system where we can verify exactly where food originated from (to provide proof of locality) and exactly how fresh it is [16].

Blockchains are then exciting as they provide a neutral architecture, where no entity has control, and the operation of code and information can be trusted [35]. In this way blockchain system are sometimes described as trust-less, as in we do not need to trust that our smart contract will be applied as no entity is in control to stop or alter its execution.

Finally, it should be noted that many blockchains require cryptocurrencies. Cryptocurrencies, such as Ether on Ethereum, that are part of the blockchain and can be sent as transactions between addresses owned by users on the blockchain. Typically, a "wallet" software is used that will automatically create new addresses for the user to send their crypto currencies to or from. An important aspect of crypto currencies is that they are rewarded to the miners which add blocks to the blockchain. What this means is that the value of these crypto currencies is an important part of the security of the system. If the value falls too low, less miners will work to secure the system, and attack becomes much easier or less expensive (and therefore the system less secure) with a proof of work (PoW) consensus system. Modern consensus algorithms, such as proof of stake, are even more sensitive to the value of the crypto currency. With the low value of a cryptocurrency in such a system an attacker can modify additional blocks added to the system. However, such an action will likely reduce the value of the crypto currency (which by definition the attacker holds a lot of) and this fact creates an economic cost for this type of attack.

Similar to cryptocurrencies, tokens, are often allowed on a blockchain. Tokens are implemented as smart contracts and like crypto currencies can be sent between wallets. The main difference between crypto currencies and tokens, is that crypto currencies are an inherent part of the blockchain and part of the security of the system. This means that typically there is only one cryptocurrency associated with a given blockchain and the value of cryptocurrencies can fluctuate based on many factors (see for example [36]), be dificult to predict [37] and, as such, are not always suitable to introduce incentives to a blockchain application. Conversely, usually any number of tokens can then be added to the blockchain by users and the rules for how these operate again can be controlled by users.

Polkadot blockchain network

Polkadot is a blockchain protocol that implements a multichain blockchain design intended to address issues with scalability that have plagued other popular blockchain protocols such as Etheruem [13]. The Polkadot network is comprised of many different blockchains (called parachains or parathreads) and the Polkadot relay chain that acts to connect the parachains together into a network. In the case of Polkadot individual parachains are allowed a reasonable degree of freedom in their design, however, all of the connected blockchains effectively share a security layer meaning that the level of trust and verifiability of a large public blockchain can be achieved in small application specific blockchains.

A high level overview of the polkadot network infrastructure is presented in Figure 1, for more detail the reader is referred to [13]. The polkadot network consists of a series of linked parachains, each an independent blockchain in its own right. The distinction between these parachain and another blockchain is that the rules for state transition (essentially the rules for adding a new block) and a simplified representation of the current state of the parachain (candidate receipt + erasure coding) are additionally part of the Polkadot blockchain. Validators, which are a type of blockchain node that determine which new block gets added to a blockchain from the Polkadot network are also used to validate blocks for the parachain. This means the security guarantees for the large Polkadot network, also apply to each smaller parachain, as to change a parachain or write an invalid block an attacker would need to attack the Polkadot blockchain itself. In addition, transactions can be sent between parachains, allowing them to act as a network of blockchains.

Waste collection and incentivisation solution

Here we outline the solution to be implemented on the blockchain. A blockchain is an entirely digital construct and to be useful for an application in the physical world it must be clear how this interaction occurs and the nature of the physical system being implemented or represented on a blockchain. Here we propose a unified waste collection and recycling incentivisation system that takes advantages of the characteristics of blockchain technology to address two pressing problems in waste management and collection. The system, called BEE2WasteCrypto [38], developed in cooperation with FUTURE-COMPTA [39] implements a transparent and verifiable supply chain. The intention of this supply chain is to track consumer waste products and recycling material after leaving the household and provide verifiable information to households on the final destination of the material as well as feedback on their recycling performance. The intention is that implementing a system that is verifiable and not directly under the control of a waste management company that is not trusted by consumers should help to reduce mistrust in the waste collection system as a whole. This verifiable and transparent supply chain also provides clear and timely information to local and central government authorities on the quantity of waste and recycling products being produced, and will allow them to respond faster and pinpoint with greater precision any issues that are preventing sustainability targets from being met. A verifiable supply chain also helps to address issues of waste being lost from the system and dumped as it becomes clear where numbers are no longer matching up and waste or recycling products are leaking from the waste collection process.

Secondly, the BEE2WasteCrypto system allows for an integrated implementation of Pay-As-You-Throw (PAYT) policies, recycling rewards, and gamification. While policies that target economic incentives to waste production and recycling behaviour are common in Europe there are typically issues with measurement that are addressed by this system. By leveraging the verifiable record of waste production and recycling behaviour provided by the blockchain a systematic reward system can be implemented that is transparently based upon household behaviour. The ability to combine multiple sources of information that would typically be held by separate organisation but that can be leveraged together, such as supply chain tracking and customer rewards here, is an identified advantage of blockchain technology [40]. In a non-blockchain centralised system, these two sources of information would be held by separate actors and the ability to combine them less straightforward and lacking in verifiability.

The system that achieves this functionality is outlined below and is presented with two specification, one based on current technology (CT) available at the site of the pilot project, one based on ideal technology (IT). The option of a configuration based on current technology makes the proposed project viable without significant economic investment. However, it is also important to consider the characteristics that would be required of the system with the application of more advanced technology to make sure the blockchain system is future proof to these needs.

In the CT configuration the system works broadly as follows:

1 Each household will register with the BEE2WasteCrypto system and register the method in which they dispose of waste and recycling material. In some instances a household will have an individualised deposit point, so material (and recycling behaviour) can be specifically traced to an individual household. However, the majority of households in the case study area share a single deposit point for multiple households such as a single bin for an apartment building, or a collection of households in a neighbourhood that share a large deposit point.

2 Households separate waste as usual in the household into different product streams (undifferentiated, plastic and metallic packaging, paper and cardboard, and glass). The recyclable products should be included in clear plastic bags. Undifferentiated material (general waste) must be placed in a specific type of bag which must be purchased for a fee. The use of paid bags is the simplest means to implement Pay-As-You-Throw charging. These product streams are then deposited at collection points by the household as is currently the case.

3 Waste collection services will pick up waste as usual and upon each collection the action will be registered with the waste collection vehicle on the blockchain. The information registered will include the location, the time, the waste product type, the weight of collected product, and a spot check evaluation of the quality of separation of recycled material.

4 Having completed a collection route waste material will be deposited at a treatment facility. Again, this action will be registered on a blockchain.

5 The actions of the treatment facility will depend on the type of waste received, however, typically this involves sorting material. In the case of undifferentiated

waste the waste is still processed to try to identify recyclable material that has been included or dangerous materials inappropriately disposed of. Recycling material processing facilities typically look to identify and sort different types of recyclable material and package these together to be auctioned to produces who will actually make use of the material. All of these actions, provide data that can be registered to the blockchain indicating the quality of the recycling sorting process undertaken by households. In addition, the final quantities of materials that are on sold for recycling and the price received for these can be registered to provide transparency on the entire waste treatment process.

6 The household then has access to an app which allows them to view the journey through the supply chain of material originating at their deposit points. They are able to receive feedback on both the material separation performance at their deposit points and see the total quantity of material recycled or disposed of and the means of this disposal.

7 The local government policy maker then has the option to base the payments for waste disposal of the household based on the information provided by the system. For example, it also allows the provision of rewards to households based upon their recycling performance and the introduction of gamification based upon neighbourhood performance.

8 With a specified payment/reward scheme the blockchain system will issue reward tokens based upon performance. These reward tokens, awarded for recycling performance, in the pilot project can be used to purchase additional waste bags for undifferentiated waste. In addition, they can be used to pay for waste utility bills or exchanged for use of services offered by the municipality (concerts, swimming pools, museums, etc). In this way an additional economic incentive is created for proper waste separation and local municipalities can experiment with finding the balance between costs and rewards.

9 Additional functionality, such as provision of information on how to recycle or available uses for rewards can also be provided on the app.

The above system provides the greatest degree of functionality without significant investment in new technologies, outside of the implementation of the blockchain. One feature of the system is that it is not possible to identify the exact recycling behaviour of an individual household. While the Pay-As-You-Throw principle is applied, and household pay for the disposal of undifferentiated waste based on their production, this information is not available for the purposes of tracking sustainability or providing rewards. In general rewards must also be provided only on an apartment building or neighbourhood basis (depending on deposit site of the household). There is some reason to be optimistic about this approach as it has been found that peer pressure and local norms play a strong influence in recycling behaviour [41].

However, ideally the province of waste would be attributable to individual households, both to target rewards and provide personalised feedback on recycling performance. A number of potential solutions to this currently exist or are proposed in the literature:

- Smart bins: With smart bins a household would deposit waste in a specific bin. Typically, they need a specific key (usually RFID) to unlock and deposit waste into the smart bin. By combining this function with weight sensors, smart bins are able to record the quantity of waste deposited by specific users, however, it would still not be possible to differentiate recycling separation performance between users.

- Smart bags: With smart waste bags individual bags used for recycling are identifiable, either with QR codes or RFIDs. This solution requires that the identity of these bags is registered to the blockchain upon collection or upon processing of the bags. The advantage of this solution is that each bag is specifically traceable to a given user so that rewards or penalties for recycling performance can be targeted precisely. The disadvantage is the additional cost associated with both the smart bags themselves and the equipment required to read their identities.

For the purpose of designing a blockchain system we consider that both of these technologies may be available under the IT system configuration and that the blockchain system must be designed to address these requirements. A representation of this system and its interaction with the blockchain is provided in Figure 2.

Regardless of the level of technology associated with the solution the aims of the system are the same:

- Increase trust in the waste management sector through increasing transparency and verifiability of the waste management supply chain.
- Transparently combine the waste and recycling performance information with policies of penalties and rewards to achieve the basis for an economic incentive system.
- Implement economic incentives through the ability to collect and spend rewards generated on selected products and services (implement a payment system).

These aims must be considered as the system design presented here is translated to a blockchain design and implementation.

Case study details

The BEE2WasteCrypto system will be implemented, in cooperation with the tehcnology partner FUTURE-COMPTA [39], in Arruda dos Vinhos, a small city north of Lisbon in Portugal. Arruda dos Vinhos is a fast-growing city with the highest population growth in the country over the previous ten years to 2019. Nearby cities in the region have won awards in sustainable tourism and both natural population growth and increasing tourism are expected to add to growing environmental pressure in the area. While growth and tourism are essential for development they must be encouraged to occur in a sustainable manner to retain the environmental charm of the surrounding area. In general, Portugal, as with many European member states, is currently at risk of failing to reach European targets for the reuse and recycling of waste and is still significantly behind 2020 targets. Arruda dos Vinhos was a contributor to this issue with recycling rate below the national average.

Blockchain design approach

In the remainder of this paper we present the blockchain system designed to achieve these goals by implementing the system presented in the previous section. First, we assess the suitability of blockchain as a technology for this problem against the criteria provided by [18], given the goals of the system presented. Having, assessed where blockchain can be successfully applied we present the different blockchain specifications possible for use in this application and select the most appropriate by matching the characteristics to the desired goals of the system. Next, given the selected blockchain protocol we design the system using the criteria and approach of [19] which requires specification of the approach to data management, performance, security, oracles, and smart contracts. Finally, we show how these approaches can be implemented in practice with the selected blockchain protocol using the selected blockchain development framework.

Blockchain system design

The first step in the application of a blockchain system, having designed the system functionality requirements, is to assess the suitability of blockchain as technology platform [19].

Assessment of blockchain suitability to application

In [18] the authors present a set of criteria to implement a blockchain solution to a given problem. In Table 2, we assess the waste management application described in here against these criteria. Table 2 demonstrates the suitability of blockchain to this application, which is in line with the findings of [18] who identify supply chain as a use case where blockchain is a desirable technology solution. It should be noted, however, that the degree to which these criteria are achieved will depend on the specifics of the blockchain design and, as such, it is important to keep in mind the required properties of the described solution.

Selection of blockchain framework

Having identified blockchain as the potential solution for an application the next question that must be answered is whether the project will build upon an existing blockchain or develop an independent and application specific blockchain.

Historically, the most popular option is to make use of existing blockchain infrastructure and develop an application that will run on an existing blockchain such as Ethereum, the majority of waste management applications found in the literature adopt this approach. The advantage of this approach is that the development process is greatly simplified as all of the blockchain infrastructure already exists (protocol, nodes, blockchain structure) and the developer needs only concentrate on developing the application that will run on this blockchain as smart contracts. The tools and documentation for developing smart contracts on the major blockchains are relatively well developed and this likely offers the fastest path to implementing a blockchain project.

There do, however, exist a number of drawbacks to this approach. Firstly, the developer is restricted to the features of the blockchain as it currently exists and cannot customise these for the specific project needs. The feature set, cost, and operation of the blockchain is also dependant on the governance decisions of the group controlling the blockchain and an individual project is likely to have little influence on these. In addition, while the cost and complexity of setting up and running a blockchain can be avoided the user is instead required to pay fees in some form for the use of the existing network. The level of these fees in fiat currency can be high, volatile, and unpredictable. This means that considerable effort can be expended developing a project for an existing blockchain only for the fee levels to spike and make the project economically unfeasible. Recently, fees on the Ethereum blockchain that is used by the majority of waste management applications found in the literature hit a record high equivalent to $22 per transaction [42], meaning even the most simple updates to the blockchain, such as submitting that waste had been collected would cost $22.

Developing an application specific blockchain is an alternative approach that is rapidly maturing. The original means to do so would be to take a fork (a copy) of an existing opensource blockchain and modify it for the user's needs (as proposed in [43] for example). However, this approach is relatively complex and can require a high level of blockchain development skill to implement. Recent developments have made the creation of an application specific blockchain much simpler. In the case of permissioned blockchains the Hyperledger set of tools allows a developer to easily setup their own independent blockchain with Hyperledger Fabric [44]. This requires that some set of users of the application will be responsible for running nodes with only selected functionality made available to the public in general. However, this approach limits the user to a private permissioned blockchain design with the specifications used by Hyperledger without significant additional development work.

Private blockchains allow for the private exchange and sharing of data among multiple organizations or a single organization (or among a group of individuals) with generation of blocks and consensus controlled by selected individuals. Private blockchain are an example of a fully permissioned blockchain, where users require permission to interact with the blockchain and the level of interaction is controlled depending on their permission level. Unknown members cannot achieve access to the blockchain and hence it can be considered a private data store to the permissioned individuals. This means an authority must be created, centralised, or decentralised, to grant permissions to users and control access to the system. In comparison with public blockchain, private blockchains are cheaper and faster as less time and energy is spent to reach consensus. Some of the examples of private blockchains are Corda, Hyperledger Fabric, and Quorum. Private blockchains are sometimes referred to as enterprise blockchain and are typically intended to be applied to enterprise problems, such as creating a shared database between business partners [45].

Polkadot: a network of blockchains

The Polkadot network allows the flexibility to take advantage of the benefits of public and private application specific blockchains which are desirable for this application. By developing a parachain, we are allowed the flexibility to design a system that can deal with the number of transactions, and more importantly the level of data, required to be tracking the large quantity of waste produced in a city without incurring the costs of trying to do so on public blockchain. However, we maintain the property of trust, as each block that is added to the blockchain must be validated by the wider Polkadot network, not just the actors using the BEE2WasteCrypto blockchain. This means that even if the control of the BEE2WasteCrypto blockchain is centralised, the centralised actors cannot change historical information (break immutability) as this would be detected and prevented by the Polkadot network. A Polkadot parachain is required to add blocks at the speed specified by the Polkadot network, currently every 6 seconds, however, this may be excessive for the current application. An alternative approach, called a parathread, operates as part of the network, however, it shares a single parachain slot with other parathread[1]. A parathread then is simply a Polkadot parachain that adds blocks a t a lower frequency than that required of a parathread and is the solution that will be used here.

For this application a Polkadot[2] parathread offers the ideal combination of decentralised trust and the performance of a permission blockchain.

Substrate: a framework for blockchain development

To actually implement a parachain we make use of the Substrate programming framework. This framework is designed to allow any user to create a blockchain from scratch based on selecting the functionality they desire which is contained in different "pallets". For example, a blockchain developer selects the pallet for the consensus algorithm they prefer to determine how consensus will work on their blockchain. A wide and growing range of pallets exist, which allow a blockchain developer to quickly add functionality to a blockchain, without having to develop this functionality themselves. This allows for a wide range of blockchain designs. In addition, Substrate allows a blockchain developer to be able to connect their application specific blockchain to a blockchain network such as Polkadot or Kusama through the inclusion of the Cumulus pallet.

Blockchain design and implementation

In this section we apply the decision making model of [19] to determine the blockchain design required to fulfil the project goals. A decision-making model allows us to map elements of the problem we are trying to solve the set of potential solutions. We then show how these solutions can be implemented in the selected blockchain development framework of Substrate.

Basic blockchain system design

A blockchain requires a certain amount of basic functionality to operate. For example, each of the nodes in the blockchain need a method to find other nodes, the nodes need a method to agree on the state of the blockchain and add blocks (consensus algorithm), etc. Here we make use of the Substrate Framework for Runtime Aggregation of Modularized Entities (FRAME) which provides a set of pallets which implement all the basic functionality required to implement a blockchain. One of

[1]Parathread functionality is not fully implemented on Polkadot at time of writing, however, this is expected to be finalised in the near future. However, this means that exact details of the cost differences to parachain is not available.

[2]For the case study the parachain developed may be deployed to one of the other blockchain networks based on Polkadot, such as Kusama or Rococo, as these networks require a significantly lower cost to join.

the most important characteristics of a blockchain is the consensus algorithm. Here FRAME operates AuRA which we maintain for the purposes of testing the pilot project. AuRA is a Proof-Of-Authority (PoA) approach to consensus where a set of authorities take turns authoring blocks. This approach obviously does not achieve the level of trust and transparency intended of the system.

The basic FRAME Substrate structure is then modified by applying Cumulus [46] which adds the functionality required to join the Polkadot network as a parachain or parathread. Operating as a parachain or parathread effectively outsources consensus to the larger Polkadot network and instead nodes needs to provide collator functionality. A collator proposes the blocks that should be added to the blockchain, however, it is only validators from the Polkadot network that will authorise a block to be added to the blockchain.

Data management design

A blockchain is fundamentally a data management structure, like a database, and decisions around the management of data will be fundamental to the construction of the blockchain system. In the case of blockchain design a user must decide both where to store data (on chain or off chain) and how to store the data (raw, encrypted, tokenised, hashed).

In this application we broadly need to consider the management of two data flows, those associated with supply chain activity, and those associated with rewards and exchanging rewards for goods and services (a payment system).

For both of these applications integrity and transparency are crucial, as these are fundamental goals of the system and essential for the implementation of a payment system. This leads us to the conclusion that raw data should be held on chain, despite the potential performance requirements. One advantage of the Polkadot framework is that this data only needs to be held on the parathread developed specifically for this application and not on a public network. This vastly reduces costs as the level of replication required is only related to the number of nodes that participants in this system wish to create. In contrast, previous literature which chooses to store data on the Ethereum blockchain, must be replicated across the many nodes operating the Etheruem network at considerable cost[3]. Here, we select not to encrypt data as the transparency of data is a key requirement of the supply chain component of the system. Transparency can be an advantage or disadvantage for a payment system depending on concerns about privacy. In this case we decide to rely on pseudonymity to provide the desired level of privacy for payments as is typical in blockchain applications.

To implement the data management system in Substrate is the most significant development task associated with this solution. This is the case as both a supply chain and a payment system are largely about storing and retrieving data.

To implement the supply chain component of the system we develop two new Substrate pallets based upon the supply chain approach outlined in [47]. A high-level description of the functionality implemented is discussed here and these pallets will be made open source upon implementation of the pilot.

[3]It should be noted that there is currently no “cost” to store data on the Ethereum network directly, instead the cost of storing data is incorporated into the transaction cost of submitting that data.

The first pallet, named waste-registry, is used to generate the information associated with a waste collection. In the case of the CT system, a transaction is sent to the Waste-Registry pallet by the collection vehicle when picking up waste from a deposit point to create a digital record of the waste collected in the form of a WasteDeposit object which represents the collected waste on the blockchain. In the case of the IT system, each individual bag will be registered an individual WasteDeposit. In second pallet, the waste-tracking pallet, we implement the functionality to track the created WasteDeposit through the different stages of the supply chain. When a collection vehicle starts a collection process it creates a WasteCollection object, and each WasteDeposit collected is associated with that WasteCollection. When the vehicle arrives at the collection facility this is registered to the WasteCollection and the facility can register information on the quality or the arrived WasteCollection.

The reward system is also implemented in two pallets, one that determines the rewards (eco-reward-system) and another to implements the payment system called the balances pallet. The eco-reward-system determines the rewards for each user and transfers Eco-Credits to the associated user address based on behaviour observed in the supply chain pallets. The balances pallet is a standard pallet available for Substrate that implements a simple payment system, that allows for the transfer of a currency which we here call Eco-Credits. This pallet is the first example of the usefulness of Substrate approach, where we enable prebuilt functionality to our blockchain. In a large-scale implementation of the project, the reward payment system may be moved to another blockchain, due to the different data, block frequency, and security requirements of the two systems. A blockchain network such as Polkadot allows for this system structure.

A gamification pallet is also under development. This pallet will build on information provided from the waste-tracking pallet to determine progress of different neighbourhoods, or different streets, against recycling and sustainability goals. Competitions, achievements and prizes can be implemented by the local municipality within this system.

Performance design

The performance decision model allows the blockchain developer to define a strategy to deal with the processing of big data, here, big data being a quantity that cannot easily be stored on chain. Here we have concluded that raw data can be stored on chain. This decision reflects the fact that the history of this data will be held on a parachain (or parathread) run by members of the consortium using the BEE2WasteCrypto system and so does not incur the costs of storing data on a completely public blockchain. The Polkadot relay chain will only hold a short history of the BEE2WasteCrypto system to ensure that the transition between new blocks is always completed in a valid system. Another performance decision possible with Substrate, but not discussed in [19], is that some computation can be performed off chain with an off-chain worker. However, this does not appear to be necessary within the scope of the BEE2WasteCrypto system.

Finally, in the context of the Polkadot blockchain network a performance decision must be made about whether to implement a blockhain as a parachain (constantly connected to the network and adding blocks every 6 seconds) or a parathread which can intermittently connect to the network. The supply chain functionality is unlikely to require such a fast block speed, there should be little issue with transactions (registering data) needing to wait more than 6 seconds before registering to the blockchain. It is likely possible that even hourly blocks would not add a particular burden to system functionality. However, a payment system requires reasonable block frequency so payment can be confirmed in a reasonable time.

Security design

In regards to security [19] identifies that both authentication (the means to identify users) and authorisation (the permissions of users) must be accounted for.

For authentication we implement a decentralised identity solution on the blockchain using a registry. We implement this functionality using the decentralised ID (DID) pallet available for Substrate and a pallet called user-registrar which maintains a list of organizations and the users associated with each organisation. In the future this functionality may be outsourced to a parachain on the network specifically designed for identity management, several of which are under development for Polkadot. Enforcing authentication helps reduce the significant issues with identifying and controlling malicious actors in a system (see for example [48]).

For authentication we make use of the role based access control (RBAC) pallet available for Substrate. The RBAC allows us to create a permission system for access to the BEE2WasteCrypto functionality. Under this system organisation managers can select which accounts should have access to which functionality. In the case of household users permissions are unlocked once a decentralised identity has been associated with the given account.

Security is then maintained by ensuring all transactions or extrinsics (interactions with on chain functionality) must be "signed" by an account. This means all transactions have an assigned sending account, the RBAC pallet is then used to check the account is associated with a decentralised identity and that the identity has permissions to access the desired functionality.

Typically, in blockchain systems, economic security is enforced to prevent certain methods of malicious behaviour. To do so a transaction fee is associated with most actions on the blockchain, this transaction fee prevents the spamming of requests or distributed denial-of-service (DDoS) attacks by making these actions prohibitively expensive. Substrate allows us to specify costs for each transaction, however, here we rely on the authentication security although this may need to change if the system is used outside of the small pilot case.

The approach of [19] does not discuss the means for ensuring security of the blockchain system itself and this is one of the largest challenges for a small application specific blockchain. It is typically the case that between 33%-51% of the nodes (or hash power produced by nodes) can be used to break the security guarantees of blockchain system depending on the consensus algorithm . In this application we take advantage of the shared security layer offered by the Polkadot blockchain system. In this case 33% of the nodes of the entire blockchain network (with a current market around 30bn USD) would need to act maliciously to attack the network, which is economically infeasible given the penalties for doing so and the minor gains in changing the information on one small specific blockchain.

Oracle design (interaction with the blockchain)

A blockchain operates as a largely self-contained eco-system where transparency, verifiability, and trust can be enforces. A blockchain, however, is typically only useful when it has interaction outside of its enforced ecosystem. Communication with the outside world is done with oracles, which is simply the name given to the bridges that allow data into and out of the blockchain.

For submission of data on waste collection a push based inbound oracle design is implemented. Where waste collection vehicles and treatment facilities submit information to the blockchain. This approach has the disadvantage of forcing other users to trust that the information they provide is accurate. However, there is some decentralisation here, as typically treatment facilities and waste collection centres are different operators and each will submit waste quantities and where these do not match it will be possible to identify discrepancies.

For customers receiving information on their current recycling performance, a pull based outbound oracle pattern is applied where users request this information from the pallets.

The on-chain functionality to submit or request waste tracking information, check waste performance and account balances, and send and receive Eco-Credits is implemented in the previously discussed pallets. For users to actually make use of this functionality they need a method to call these functions exposed in the pallets. With Substrate this is done using a node.js based frontend that is able to send transactions to the blockchain. As such the user interaction is similar in practice to using a website. The user must, however, “sign” transactions sent to the blockchain to prove they are authorised. This can be done either by using a wallet (such as Polkadot.js) or the user can select to simply enter a password to decrypt a locally stored account key that can be used by the frontend. The later approach is significantly less secure, however, the level of economic risk associated with having an account compromised is likely to be low in this system. All of this functionality is implemented based on the Substrate-frontend-template which provides functionality for interacting with any Substrate blockchain and accessing functionality within the implemented pallets.

Smart contract design pattern

Substrate offers the ability to implement one of several smart contract pallets into a blockchain. However, in this case we choose not allow for a full smart contract platform. The purpose of the BEE2WasteCrypto parachain is to achieve the specific functions of waste tracking and user rewards and a platform capable of implementing any logic requested requested by users in not required. This additionally greatly reduces the security risks by only allowing a specific set of activities upon the blockchain.

Governance and maintenance

A significant challenge for blockchain systems is implementing governance and determining a process for maintenance and upgrades. In this case we implement a simplistic framework suitable for the small case study for which this project will be applied, however, this is an area in which significant changes would need to be made to scale to larger implementations with more stakeholders. As a governance system we implement the democracy pallet which allows the ability to propose and conduct votes on any issues such as changes to the blockchain. For the purpose of the pilot study only a select set of users can vote or make proposals, however, Substrate allows for the implementation of an elections pallet to allows for an elected set of decision makers among all users which may be appropriate in the future.

Conclusions

Even developed countries are currently struggling to achieve sustainable levels of recycling and waste treatment and this area is in urgent need of new solutions. One area of particular concern is the treatment and sorting of household waste which relies on household to do much of the separation in home. Rates of recycling and quality of recycling separation vary highly and a number of factors have been used to explain these differences. One factor of particular interest is the role of trust, where this sector has traditionally suffered from a lack of trust and transparency and an association with crime.

In this research we propose the use of an innovative waste collection and incentivization system called BEE2WasteCrypto. This system is developed with blockchain technology to provide a transparent and trusted record of the supply chain journey of consumer waste after leaving the household and link economic incentives and penalties to household recycling behavior.

An innovative hybrid blockchain, called a Polkadot parachain, is implemented for this project. Polkadot is a blockchain network that allows for the flexibility to take advantage of the benefits of public and private blockchains which each have proporties that are desirable for this application. By developing a parachain, we are allowed the flexibility to design a system that can deal with the number of transactions, and more importantly the level of data, required to track the large quantity of waste produced in a city without incurring the costs of trying to do so on a public blockchain. However, we maintain the property of trust, as each block that is added to the blockchain must be validated by the wider Polkadot network, not just the actors using the BEE2WasteCrypto blockchain.

To build this parachain we make use of a set of blockchain decision making criteria from the literature intended to identify the decisions that must be made in implementing a blockchain project. Having specified the approach to blockchain runtime, data management, performance, security, oracle design, smart contracts, and governance we show how a blockchain can be constructed to achieve this design with the Substrate blockchain framework.

The final system will be piloted in a small town in Portugal and the system designed allows for either current technology or and ideal set of technology availabilities. While the current system is designed for a particular case study there is significant potential for future research to expand this blockchain to be capable of handling multiple locations and applications. The supply chain tracking functionality additionally opens the door to the introduction of reverse supply chains, such as in the disposal of e-waste, where household items are tracked after disposal for the manufacturer to ensure their correct recycling or disposal.

Abbreviations
AI: Artificial Intelligence
CT: Current technology
DDoS: Distributed denial-of-service
DID: Decentralised ID
EO: End of Waste
FRAME: Framework for Runtime Aggregation of Modularized Entities
IoT: Internet of Things
IT: Ideal technology
PAYT: Pay-As-You-Throw
PoA: Proof-Of-Authority
PoW: Proof of work
RBAC: Role based access control
RFID: Radio Frequency Identification

Availability of data and materials
Not applicable. Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

Competing interests
The authors declare that they have no competing interests.

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Authors' contributions
IS contributed to the conceptualization and design of the work, literature review, development of methodology, design and development of solution, assessment of solution, and drafting of the manuscript. MN contributed to the conceptualization of the project and the work, review of the manuscript, and supervision of the project. FP contributed to the review of manuscript and conceptualization of work. All authors read and approved the final manuscript.

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References
1. Commission, E.: Report from the commission to the european parliament, the council, the european economic and social committee and the committee of the regions on the implementation of eu waste legislation, including the early warning report for member states at risk of missing the 2020 preparation for re-use/recycling target on municipal waste. Technical report, European Commission (2018). http://ec.europa.eu/eurostat/web/waste/data/database,
2. Bucciol, A., Montinari, N., Piovesan, M.: Do not trash the incentive! monetary incentives and waste sorting. The Scandinavian Journal of Economics **117**(4), 1204–1229 (2015)
3. Hicks, C., Dietmar, R., Eugster, M.: The recycling and disposal of electrical and electronic waste in china—legislative and market responses. Environmental impact assessment review **25**(5), 459–471 (2005)
4. Zhang, S., Zhang, M., Yu, X., Ren, H.: What keeps chinese from recycling: Accessibility of recycling facilities and the behavior. Resources, Conservation and Recycling **109**, 176–186 (2016)
5. Reichenbach, J., Requate, T.: Subsidies for renewable energies in the presence of learning effects and market power. Resource and Energy Economics **34**(2), 236–254 (2012)
6. Elia, V., Gnoni, M.G., Tornese, F.: Designing pay-as-you-throw schemes in municipal waste management services: A holistic approach. Waste Management **44**, 188–195 (2015)
7. Briones, A.G., Chamoso, P., Rivas, A., Rodríguez, S., De La Prieta, F., Prieto, J., Corchado, J.M.: Use of gamification techniques to encourage garbage recycling. a smart city approach. In: International Conference on Knowledge Management in Organizations, pp. 674–685 (2018). Springer
8. Petts, J.: Trust and waste management information expectation versus observation. Journal of Risk Research **1**(4), 307–320 (1998)
9. Harring, N., Jagers, S.C., Nilsson, F.: Recycling as a large-scale collective action dilemma: A cross-country study on trust and reported recycling behavior. Resources, Conservation and Recycling **140**, 85–90 (2019)
10. An Exploratory Estimate of the Extent of Illicit Waste Trafficking in the EU. http://www.blockwaste.eu/
11. Jereb, S., Henderson, K., Vrabič, J., Bain, M., Edwards, N., Roşca, L., Kokot, J., Braz, P., Meisenzahl, M.: Eu action to tackle the issue of plastic waste. Technical report, European Court of Auditors (2020). https://www.eca.europa.eu/en/Pages/DocItem.aspx?did=55223
12. Ongena, G., Smit, K., Boksebeld, J., Adams, G., Roelofs, Y., Ravesteyn, P.: Blockchain-based smart contracts in waste management: a silver bullet? In: Bled eConference, p. 19 (2018)
13. Wood, G.: Polkadot: Vision for a heterogeneous multi-chain framework. White Paper (2016)
14. Casino, F., Dasaklis, T.K., Patsakis, C.: A systematic literature review of blockchain-based applications: current status, classification and open issues. Telematics and informatics **36**, 55–81 (2019)

15. Pournader, M., Shi, Y., Seuring, S., Koh, S.L.: Blockchain applications in supply chains, transport and logistics: a systematic review of the literature. International Journal of Production Research **58**(7), 2063–2081 (2020)
16. Kamilaris, A., Fonts, A., Prenafeta-Boldύ, F.X.: The rise of blockchain technology in agriculture and food supply chains. Trends in Food Science & Technology **91**, 640–652 (2019)
17. Tasca, P., Tessone, C.J.: Taxonomy of blockchain technologies. principles of identification and classification. arXiv preprint arXiv:1708.04872 (2017)
18. Lo, S.K., Xu, X., Chiam, Y.K., Lu, Q.: Evaluating suitability of applying blockchain. In: 2017 22nd International Conference on Engineering of Complex Computer Systems (ICECCS), pp. 158–161 (2017). IEEE
19. Xu, X., Bandara, H.M.N.D., Lu, Q., Weber, I., Bass, L., Zhu, L.: A decision model for choosing patterns in blockchain-based applications. In: 18th IEEE Int. Conf. on Software Architecture (ICSA 2021) (2021)
20. Swachhcoin Whitepaper. http://swachhcoin.com/
21. Recereum. https://recereum.com/
22. RecycleGo. https://recyclego.com/
23. Partitalia. https://www.partitalia.com/
24. Katz, D.: Plastic bank: launching social plastic® revolution. Field Actions Science Reports. The journal of field actions (Special Issue 19), 96–99 (2019)
25. End of Waste (EOW). https://endofwaste.com/
26. Chidepatil, A., Bindra, P., Kulkarni, D., Qazi, M., Kshirsagar, M., Sankaran, K.: From trash to cash: how blockchain and multi-sensor-driven artificial intelligence can transform circular economy of plastic waste? Administrative Sciences **10**(2), 23 (2020)
27. Tozanlı, Ö., Kongar, E., Gupta, S.M.: Evaluation of waste electronic product trade-in strategies in predictive twin disassembly systems in the era of blockchain. Sustainability **12**(13), 5416 (2020)
28. Dietrich, F., Ge, Y., Turgut, A., Louw, L., Palm, D.: Review and analysis of blockchain projects in supply chain management. Procedia Computer Science **180**, 724–733 (2021)
29. França, A., Neto, J.A., Gonçalves, R., Almeida, C.: Proposing the use of blockchain to improve the solid waste management in small municipalities. Journal of Cleaner Production **244**, 118529 (2020)
30. Zhang, D.: Application of blockchain technology in incentivizing efficient use of rural wastes: a case study on yitong system. Energy Procedia **158**, 6707–6714 (2019)
31. Kouhizadeh, M., Zhu, Q., Sarkis, J.: Blockchain and the circular economy: potential tensions and critical reflections from practice. Production Planning & Control **31**(11-12), 950–966 (2020)
32. Conforto, R.: WSX-European waste services exchange, instrument to start the transition towards circular economy. Procedia Environmental Science, Engineering and Management **6**(1), 61–71 (2019)
33. Wood, G., *et al.*: Ethereum: A secure decentralised generalised transaction ledger. Ethereum project yellow paper **151**(2014), 1–32 (2014)
34. Gopalakrishnan, P., Ramaguru, R.: Blockchain based waste management. International Journal of Engineering and Advanced Technology **8**(5), 2632–2635 (2019)
35. Xu, X., Weber, I., Staples, M.: Architecture for Blockchain Applications. Springer, ??? (2019)
36. Dipple, S., Choudhary, A., Flamino, J., Szymanski, B.K., Korniss, G.: Using correlated stochastic differential equations to forecast cryptocurrency rates and social media activities. Applied Network Science **5**(1), 1–30 (2020)
37. Zhang, Z., Zargham, M., Preciado, V.M.: On modeling blockchain-enabled economic networks as stochastic dynamical systems. Applied Network Science **5**(1), 1–24 (2020)
38. BEE2WasteCrypto. https://www.bee2wastecrypto.com/
39. FUTURE-COMPTA. https://www.future-compta.com/
40. Jardim, L., Pranto, S., Ruivo, P., Oliveira, T.: What are the main drivers of blockchain adoption within supply chain?–an exploratory research. Procedia Computer Science **181**, 495–502 (2021)
41. Elgaaied, L.: Exploring the role of anticipated guilt on pro-environmental behavior–a suggested typology of residents in france based on their recycling patterns. Journal of Consumer Marketing (2012)
42. ETH Flash Crashes 60% on Kraken, Gas Fees Hit All-Time High. https://cryptobriefing.com/eth-flash-crashes-60-on-kraken-gas-hits-all-time-high/
43. Reddy, G.B., Kumar, K.R.: Quality improvement in organic food supply chain using blockchain technology. In: Innovative Product Design and Intelligent Manufacturing Systems, pp. 887–896. Springer, ??? (2020)
44. Androulaki, E., Barger, A., Bortnikov, V., Cachin, C., Christidis, K., De Caro, A., Enyeart, D., Ferris, C., Laventman, G., Manevich, Y., *et al.*: Hyperledger fabric: a distributed operating system for permissioned blockchains. In: Proceedings of the Thirteenth EuroSys Conference, pp. 1–15 (2018)
45. Kuo, T.-T., Zavaleta Rojas, H., Ohno-Machado, L.: Comparison of blockchain platforms: a systematic review and healthcare examples. Journal of the American Medical Informatics Association **26**(5), 462–478 (2019)
46. Cumulus. https://wiki.polkadot.network/docs/en/build-cumulus
47. Substrate Enterprise Sample. https://github.com/substrate-developer-hub/substrate-enterprise-sample
48. Agarwal, R., Barve, S., Shukla, S.K.: Detecting malicious accounts in permissionless blockchains using temporal graph properties. Applied Network Science **6**(1), 1–30 (2021)
49. Latif, S., Rehman, A., Zafar, N.A.: Blockchain and iot based formal model of smart waste management system using tla+. In: 2019 International Conference on Frontiers of Information Technology (FIT), pp. 304–3045 (2019). IEEE
50. Laouar, M.R., Hamad, Z.T., Eom, S.: Towards blockchain-based urban planning: Application for waste collection management. In: Proceedings of the 9th International Conference on Information Systems and Technologies, pp. 1–6 (2019)
51. Gupta, N., Bedi, P.: E-waste management using blockchain based smart contracts. In: 2018 International Conference on Advances in Computing, Communications and Informatics (ICACCI), pp. 915–921 (2018). IEEE
52. Dua, A., Dutta, A., Zaman, N., Kumar, N.: Blockchain-based e-waste management in 5g smart communities. In: IEEE INFOCOM 2020-IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS), pp. 195–200 (2020). IEEE

Figures

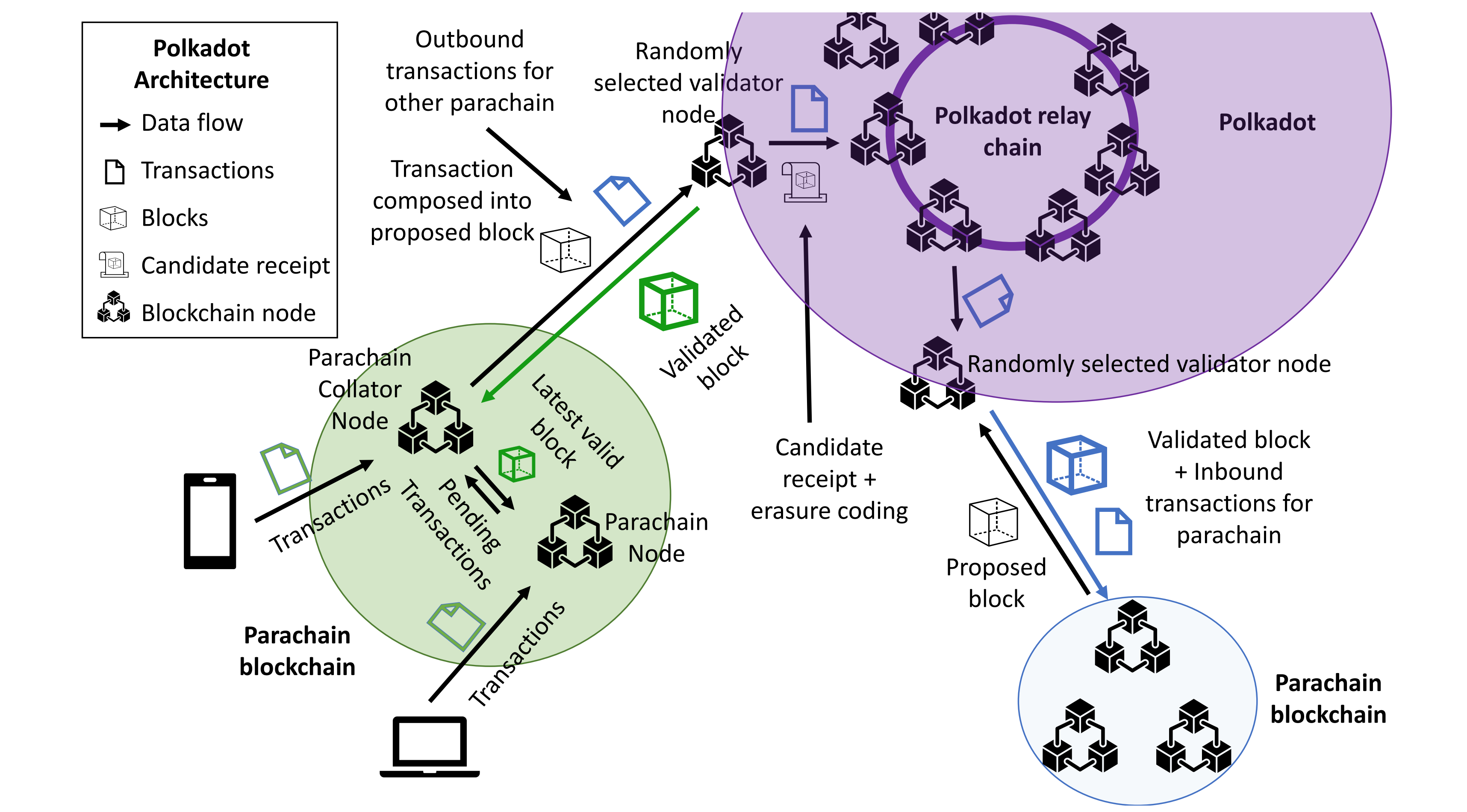

Figure 1 Polkadot system This figure demonstrates the relationship between parachains and the polkadot blockchain network. Each parachain consists of a series of nodes which devices can interact with and send data to in the form of transactions. One of these nodes will be designated a "collator" which collects pending transactions into a proposed "block" to be added to the blockchain". However, a "validator" node from Polkadot is required to validate the proposed block for addition to the parachain. A simplified representation of each parachain block, a candidate receipt, is added to the Polkadot relay chain. Each parachain can additionally send and recieve transactions from other parachains through the Polkadot blockchain network.

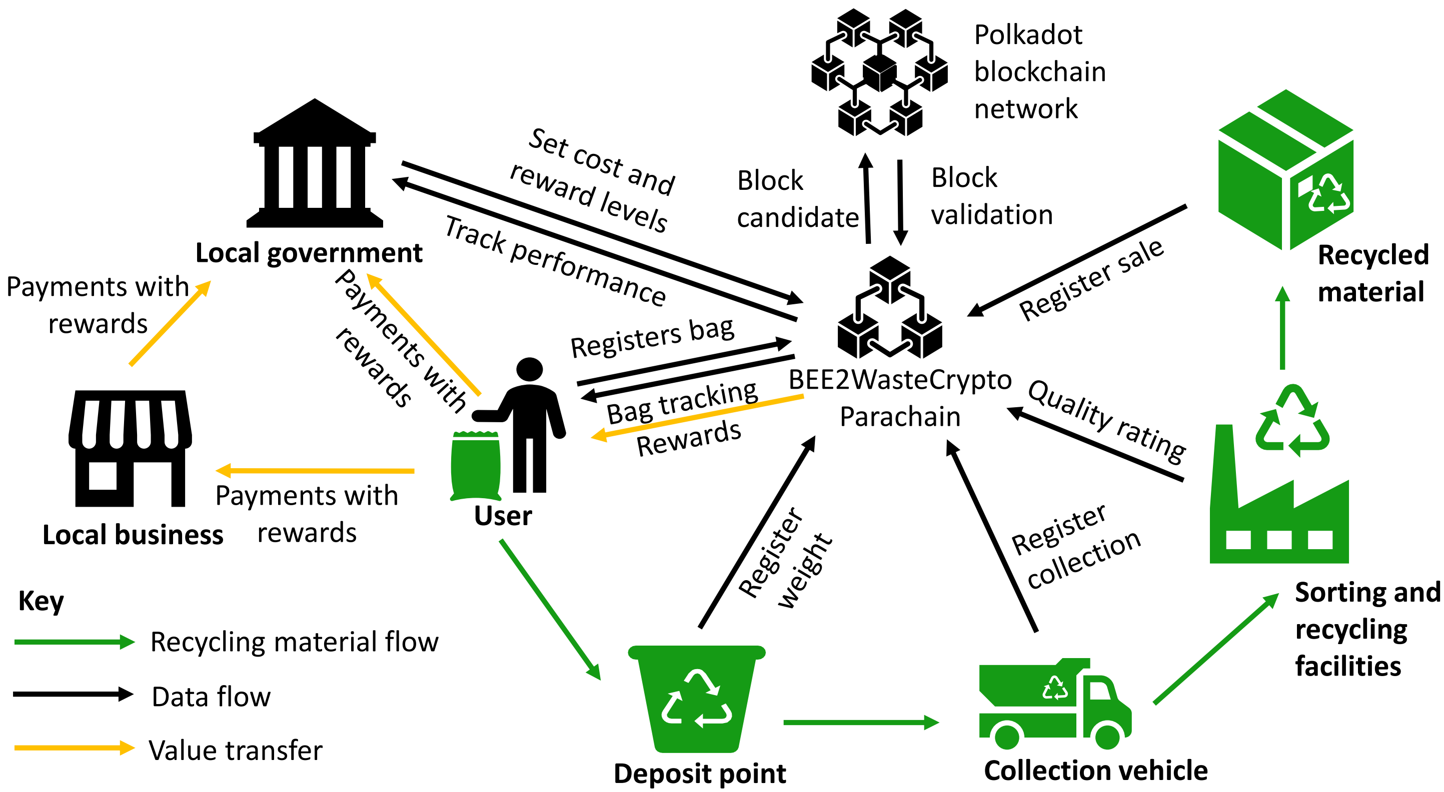

Figure 2 BEE2WasteCrypto system BEE2WasteCrypto system overview demonstrating material, data, and value flows as well as well as interaction with blockchain.

Tables

Tables

Table 1 Assessment of system against blockchain suitability criteria.

Source	Supply Chain	Incentives	Exchange Platform	Sector	Blockchain	Blockchain or smart contract	Enabling technology	Pilot
[49]	✓			Not specified	Two custom blockchains (one public one private)	Blockchain	IoT infrastructure, sensors	No
[32]			✓	Waste services	Not specified	Not specified	Not specified	No
[30]	✓	✓		Agricultural waste to energy	Not specified	Blockchain	Smart bin, sensors, IoT infrastructure, QR Codes, centralsied server	No
[29]		✓		Household recycling	Etheruem	Smart contract	QR Codes, mobile phones	No
[26]	✓			Household plastic	Not specified	Smart contracts	Multi sensor systems, near infrared lasers diodes, far-infrared (FIR) sensors, AI	No
[27]	✓	✓		Trade-in electronics			Digital twin, RFID, IoT infrastructure	No
[50]	✓			Waste management	Ethereum	Smart contract	QR codes	No
[51]	✓	✓		E-Waste	Ethereum	Smart contracts		No
[52]	✓			E-Waste	Ethereum		5G network and devices	No
[12]	✓			Cross border waste transfer	Not specified	Not specified	Not specified	Yes

Table 2 Assessment of system against blockchain suitability criteria.

Criteria	Application to waste collection system	Result	Blockchain suitable
Multi-party	Multiple parties are involved in this system, including the household, the waste collection utility, waste and recycling treatment facilities, and local municipalities.	Required	✓
Trusted authority	Unfortunately, the waste management sector suffers from a lack of trust and there are incentives for actors in this sector to report inaccurate information. For this reason, a trusted central authority is not appropriate for this application	Not possible	✓
Centralized operation	The system envisaged required operation of the system from multiple parties for registering data, allocating rewards, and spending rewards.	Not required	✓
Data transparency vs confidentiality	Data transparency is a key goal of this solution and so is a required feature of the data management system.	Required	✓
Data integrity	Data integrity is again a requirement, both in ensuring that supply chain tracking is trusted and to implement a payment type reward system	Required	✓
Data immutability	Data immutability provides a trusted record to implement a supply chain tracking system. Data immutability is a identified as a key characteristic to deliver trust [37].	Required	✓
High performance	As discussed in [37] high performance is relative and the performance of a blockchain system will depend on design. However, neither Big Data or high velocity data are required.	Not required	✓