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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 with unsustainable levels of waste production and low levels of recycling, 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. Recent events relating to the COVID-19 pandemic have highlighted, in particular, the role of trust in effective public policy making and consumer behavioural change. Here we propose a hybrid blockchain solution called a Polkadot parachain. Polkadot is a blockchain technology that connects 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 or private blockchain while providing the security, verifiability, and trust of a public blockchain. The solution is developed with a design science approach and 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.

1. Introduction

Despite recent growth in the recycling sector and increases in environmentally friendly consumption, most European countries are still far from achieving their stated target levels for the production of waste and recycling of material. 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 (European Commission, 2018).

These targets are important as they are essential to the European Union's goal of transitioning towards a circular economy (Commission et al., 2015). The circular economy is a system in which we transition from a society that follows a pattern of take–make–use–dispose to one of make–use–reuse–remake–recycle where we replace the end-of-life disposal of material products with an alternative of re-use, recycle or recovery (Mhatre, Panchal, Singh, & Bibyan, 2021).

Recycling is then a key component in our ability to achieve sustainability through a circular economy. In particular the European 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 (European Commission, 2018). For household waste the only economically viable option, given current technology, is for households to separate waste before delivery. It is then required, both under EU targets, and as a matter of achieving a sustainable society and circular economy, that significant increases in both the rate of household waste separation and the care with which this separation is performed are achieved.

However, recycling targets are not being met and the waste management sector has historically struggled with fraud and manipulation, unreliable or unavailable information, significant manual processes, and low levels of control (Ongena et al., 2018).

In this paper we design a technological solution based on a novel form of blockchain to address the issues in household waste management systems. We apply a design science research approach that involves collaboration between industry, government, and academia to carefully define the issues and design a technological solution. The iterative development of this project is collaboratively undertaken by a consortium with five partners: three academic and two industrial, and works closely with the local municipality and waste collection utility, allowing for the incorporation of a wide range of stakeholder input.

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For this research we then present a polkadot parachain blockchain for use in the waste management industry. The system is designed to address the specific challenges in household recycling identified by providing trust and transparency and multiple methods of targeted incentivisation. In comparison to alternative research surveyed we:

- Apply a design science approach to developing and assessing a novel technology solution for recycling and waste management. The system design is based on feedback from interviews with industrial, technology, and government partners and a survey of a representative sample of the Portuguese population.
- Work carefully with industry and survey the research to identify specific problems in waste management that can be addressed with the introduction of new technologies. We identify issues with household trust of waste management utilities, systems, and lack of incentives as two key issues reducing household performance. Both of these issues partly result from a lack of credible information in the sector, both information on households level recycling performance to target incentives and lack of information of the journey of waste and recycling material after leaving the household.
- Leverage the specific characteristics of this blockchain solution to address these fundamental issues associated with waste collection and management. In doing so we combine 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 argue for the important synergies of these use cases and gains that can be achieved by combining them. We believe combination of features is key to contributing to the transition to a circular economy, both by encouraging behaviour change at the household level and creating awareness and building transparency of the complete life-cycle of the material that leaves the household.
- Addresses scalability challenges in blockchain by applying 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. We report valuable insight into the experience of developing these technologies.
- Assess the design of the blockchain solution against the criteria of Lo, Xu, Chiam, and Lu (2017) and the blockchain design approach of Xu, Bandara et al. (2021) and present a detailed description of how the system is implemented in the Substrate framework is provided.

  The remainder of this paper is organised as follows. In Section 2 we present a literature review summarising the challenges in waste management, introducing the blockchain and surveying the existing solutions for blockchain in waste management. In Section 3 we discuss the design science methodology applied in this paper. In Section 4 we present the resulting system design and evaluation. Finally, in Section 5 we provide conclusions from the work and recommendations for future research.

2. Literature review on the application of blockchain in the waste management sector

2.1. Challenges in household waste management

The European Union has been clear in its goal to improve household recycling rates and despite legally binding national targets this is not being achieved (European Commission, 2018). The Waste Framework Directive (2008/98/EC) sets a target of 50% of municipal waste to be recycled by 2020 with future targets of 55% by 2025, 60% by 2030 and 65% by 2030. In 2019, the rate for the EU-27 had risen to 48%, however, increases in this rate are stalling (European Environment Agency, 2022). As is seen broadly with sustainability metrics low income countries lag higher income countries (Singpai & Wu, 2021) and this applies within the EU (European Commission, 2018). Recycling rates range from below 10% in Malta and Montenegro to 65% in Germany. However, even developed countries can still struggle, with Spain reporting rates below 40% and the target country for this intervention, Portugal, only achieving around 30%. Essentially, improving municipal recycling rates requires behavioural change at the household level and several approaches have been explored in the literature and in practice. One of the approaches to achieving this change that has demonstrated success historically is the introduction of economic incentives (Xevgenos, Papadaskalopoulou, Panaretou, Moustakas, & Malamis, 2015). The introduction of incentives to change behaviour is argued to be one of the key policy changes in realising the transition to a circular economy (van den Bergh, 2020). In the area of household waste management one of the most popular approaches, particularly in Europe, that has shown promise is that of Pay-As-You-Throw (PAYT) that imposes costs on consumers for the production of undifferentiated waste. PAYT systems are designed to support more sustainable management of waste flows: starting with producing less waste by reducing waste and re-using products; and then, improving recycling rate by minimising landfill usage (Elia, Gnoni, & Tornese, 2015). These goals are clearly inline with the transition to a circular economy.

While the introduction of PAYT has been found to provide benefits including an increased recycling rate, decreased solid waste production, and provided a more rational payment system for locals (Morlok, Schoenberger, Styles, Galvez-Martos, & Zeschmar-Lahl, 2017; Park, 2018; Weber, Cabras, Calaf-Forn, Puig-Ventosa, & D'Alisa, 2019), there are also associated risks. There is a relatively large body of evidence that financial rewards can undermine intrinsic motivation (Deci, Koestner, & Ryan, 1999). This approach also creates an incentive for households to illegally dump their waste, to avoid the cost of legal disposal. There is evidence both for Dunne, Convery, and Gallagher (2008) and against Hage and Söderholm (2008) an increase in illegal waste disposal being significant in practice.

An alternative approach is that of recycling reward systems (Reichenbach & Requate, 2012) that reward households for the correct separation of recyclable material. While this approach can be preferred by households as it is not seen as a cost, it does not incentivise the reduction in consumption of products that generate waste in the same way PAYT does. In addition behavioural research seems to support the use of penalties over rewards both because people tend to value what they have (money) over what they do not have (rewards) and the disadvantage of losses is perceived to be greater than the advantage of gains (Maki, Burns, Ha, & Rothman, 2016). Alternative non-financial forms of incentives, such as gamification, have also demonstrated some promise for delivering behavioural change in this sector (Briones et al., 2018) and in contributing to sustainable activities more generally (Lounis, Neratzouli, & Pramatari, 2013).

One challenge, all of these approaches face is the reliable identification of the behaviour of the individual (Elia et al., 2015). In regions where households are separated and have individual waste bins this task can be easier, but in situations where many households are located in apartment buildings and share the same waste drop-off or recycling points the challenge is greater and typically requires the application of more sophisticated technology (Elia et al., 2015).

However, even with economic incentives our waste management systems still face a number of challenges. It must be noted that waste management is typically characterised as a low trust industry (Petts, 1998) and consumers can be discouraged to recycle when this is the case (Harring, Jagers, & Nilsson, 2019). In general higher levels of trust have been associated with higher compliance with public policy and greater behavioural change (Devine, Gaskell, Jennings, & Stoker, 2021). This relationship between trust and public policy compliance creates a positive feedback loop. As trust increases, there is greater compliance with public policy directives and this delivers positive change for the public good, which in turn increases satisfaction with public service which increases trust (Christensen & Lægreid, 2005).

A number of studies have found this relationship to hold for waste management and recycling behaviour (Cohen, Halfon, & Schwartz, 2021; Harring et al., 2019; Rompf, Kroneberg, & Schlösser, 2017; Scafuto, Sodano, & La Barbera, 2018). One of the main arguments for this relationship is that recycling is an example of a collective action dilemma and suffers from free riding (Harring et al., 2019). basically we all benefit from recycling at a societal level but our individual efforts do not make a significant difference. When we do not trust that others will contribute to this social good we do not believe it is worth our effort to do so.

One potential solution to the issue of trust is found in Cohen et al. (2021) who provides evidence that transparency should improve trust in an analytical model of waste behaviour. It has also been argued that citizens are more willing to make individual sacrifices if they believe that an external authority is able to monitor and enforce penalties on others, e.g., by monitoring individual actors' behaviour (Mansbridge, 2014). Finally, there is some empirical evidence that transparency has been shown to improve waste separation behaviour generally (Bucciol, Montinari, & Piovesan, 2019) particularly where individual actions can be discerned.

In the waste management sector these is potentially good reason for this lack of trust. The waste management sector has historically recorded relatively high levels of organised crime and illegal dumping of waste (Meneghini, Favarin, Andreatta, & Savona, 2017). 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 (Jereb et al., 2020). The effect trust has on citizens' response has been highlighted by the recent COVID-19 pandemic. The introduction of restrictive measures aiming at changing citizen behaviour, across a number of countries simultaneously, allows for an imperfect natural experiment. It should be clear then that trust is an important component to encourage citizens compliance with public policy goals.

Providing transparency and promoting trust should be an important goal of a future waste management system. Improvements to the tracking and transparency of waste as it leaves the economy, often referred to as reverse supply chains or reverse logistic networks (Xu, Elomri, Liu, Liu and Li, 2021) is a key component of the transition to the circular economy. The recent COVID-19 pandemic highlighted some of these issues in the waste management sector. Throughout cities there were variable changes in waste production, as behaviours changed with teleworking and reductions in tourism (Sarmento, Motta, Scott, Pinheiro, & de Castro Neto, 2022). Real time tracking and reverse supply chains can play a role in optimising the waste management utilities response to these changes in real time. This is important in reducing the diversion or recyclable material into general waste seen during the pandemic period.

We then find three interlinked challenges for waste management systems of the future, providing transparency, implementing incentives and building trust. Each of these factors are important use cases for blockchain technology.

2.2. Blockchain design and development

Blockchain technologies are characterised by their trust free, meaning users are not required to trust a centralised actor, and transparent nature (Casino, Dasaklis, & Patsakis, 2019) and offer a potential solution to the problems with waste management systems presented. In fact, this ability to increase trust and provide transparency are the most cited advantage in the study of their application (Casino et al., 2019).

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 (Pournader, Shi, Seuring, & Koh, 2020), and particularly food and agriculture supply chains (Kamilaris, Fonts, & Prenafeta-Boldú, 2019). However, it is important to note that the characteristics of a blockchain system will depend on the exact nature of the technology applied and a number of design decisions in its implementation. 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. It is then essential to follow a specific and detailed process to match a blockchain solution to the characteristics of a specific problem.

Historically, the most popular option is to incorporate blockchain into a solution is to make use of existing blockchain infrastructure and develop an application that will run on an existing blockchain such as Ethereum. 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 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.

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 open-source blockchain and modify it for the user's needs (as proposed in Reddy and Kumar (2020) 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 (Androulaki et al., 2018). This requires that some sets of users of the application will be responsible for running nodes (servers hosting the blockchain) 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 organisations or a single organisation (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

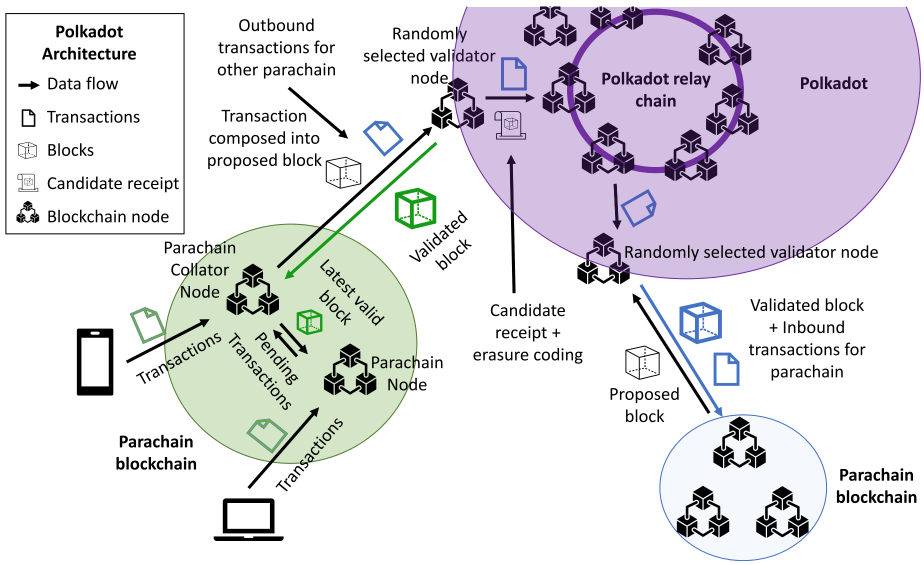

Fig. 1. Polkadot system. This figure demonstrates the relationship between parachains and the polkadot blockchain network. Each parachain consists of a series of nodes which devices can interact with and send data to in the form of transactions. One of these nodes will be designated a "collator" which 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 receive transactions from other parachains through the Polkadot blockchain network.

energy is spent to reach consensus. 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 (Kuo, Zavaleta Rojas, & Ohno-Machado, 2019).

We then have significant drawbacks to the two most common approaches in blockchain development found in the literature: public blockchain provides trust but not performance, and private blockchains provide performance but only trust to members of the private consortium (and not the public at large). Blockchain design is characterised by making trade-offs between these properties of trust and performance, as well as security and decentralisation (Sanka & Cheung, 2021).

Blockchains exist that then try to draw on the best features of public and private blockchain, trading-off between the characteristic of each. One class of these are know as hybrid blockchains (Kim, Turesson, Laskowski, & Bahreini, 2020). Hybrid blockchains combine a part of the system that is operated as a public blockchain, providing trust, and part operated privately providing performance. To our knowledge there is no existing research on the application of such hybrid approaches in the waste management area.

Polkadot is an example of a blockchain protocol that implements a hybrid multi-chain blockchain design intended to address issues with scalability that have plagued other popular blockchain protocols such as Ethereum (Wood, 2016). The Polkadot network is comprised of many different blockchains (called parachains or parathreads), and the Polkadot relay chain 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 semi-private application specific blockchains. A high level overview of the polkadot network infrastructure is presented in Fig. 1.

Fig. 1 demonstrates the distinction between a parachain and another blockchain. With a parachain 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 each parachain. This means the security guarantees for the large Polkadot network, also apply to each smaller parachain, and thus 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. For more detail the reader is referred to Wood (2016).

Hybrid multi-chain blockchains, such as Polkadot, are one example of approaches to the scaling issue of public blockchain. The other approaches broadly include (Sanka & Cheung, 2021):

- **Payment channels** These solutions conduct payments off-chain by creating a network of channels between different parties. This approach only allows for the scaling of payments and not further blockchain smart contract capabilities.
- **Side-chains** A sidechain is a secondary blockchain chain that "attaches" to a main chain with a two way peg. Tokens on the main blockchain can be locked with the two way peg system, such that they are considered to be included in the side-chain, users can then remove the tokens from the side-chain to unlock tokens on the main chain. Sidechains typically require their own consensus mechanism, and the security of the sidechain system relies largely on the security of this consensus mechanism rather than the typically greater trust and security of the public blockchain. However, side-chains can be effective at improving the performance and privacy of a system.
- **Off-chain computation (roll-ups)** In this approach some of the calculation is shifted off the blockchain and only the computation result is sent back to be used by the node. Usually this is done in such a way that these results can be validated. This approach can add significantly to transaction performance and privacy.

In the next section we review the use of these technologies in the waste management sector.

2.3. Blockchain applications in waste management

A limited number of previous studies have proposed the use of blockchain technology in the waste management sector, these are summarised in Table 1 although blockchain is applied more widely in the circular economy (see Böckel, Nuzum, & Weissbrod, 2021;

Table 1
Review of existing literature on blockchain applications in waste management.

Source	Supply chain	Incentives	Exchange Platform	Sector	Blockchain	Blockchain or smart contract	Enabling technology	Pilot
Latif, Rehman, and Zafar (2019)	✓			Not specified	Two custom blockchains (one public one private)	Blockchain	IoT infrastructure, sensors	No
Conforto (2019)			✓	Waste services	Not specified	Not specified	Not specified	No
Zhang (2019)	✓	✓		Agricultural waste to energy	Not specified	Blockchain	Smart bin, sensors, IoT infrastructure, QR Codes, centralised server	No
França, Neto, Gonçalves, and Almeida (2020)		✓		Household recycling	Ethereum	Smart contract	QR Codes, mobile phones	No
Chidepatil et al. (2020)	✓			Household plastic	Not specified	Smart contracts	Multi sensor systems, near infrared lasers diodes, far-infrared (FIR) sensors, AI	No
Tozanlı, Kongar, and Gupta (2020)	✓	✓		Trade-in electronics			Digital twin, RFID, IoT infrastructure	No
Laouar, Hamad, and Eom (2019)	✓			Waste management	Ethereum	Smart contract	QR codes	No
Gupta and Bedi (2018)	✓	✓		E-Waste	Ethereum	Smart contracts		No
Dua, Dutta, Zaman, and Kumar (2020)	✓			E-Waste	Ethereum		5G network and devices	No
Ongena et al. (2018)	✓			Cross border waste transfer	Not specified	Not specified	Not specified	Yes

Kouhizadeh, Zhu, & Sarkis, 2020 for reviews). In addition, a number of commercial blockchain waste management projects have either launched as start-ups or pilot projects including Swachhcoin (Swachhcoin, 2021), Recereum (Recereum, 2021), RecycleGo (RecylceGo, 2021), Partitalia (Partitalia, 2021), Plastic bank (Katz, 2019), End of Waste (EOW) (EndofWaste, 2021).

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, has been 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. Various means of implementing a system that tracks smart bins and garbage collection are discussed. However, it is found that most of these implementations end up relying on a centralised server infrastructure which undermines the trust-less 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 (Chidepatil et al., 2020). Additionally, tracking waste sources and destinations may open up new options in terms of making manufacturers responsible for the disposal of their products (Tozanlı et al., 2020). Transparency, automation, and disintermediation have all been identified as blockchain features driving adoption in supply chains (Dietrich, Ge, Turgut, Louw, & Palm, 2021).
- **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 (França et al., 2020). In an interesting case in the agricultural sector tokens are issued to farmers as the reward for the sorting of waste (Zhang, 2019). The increased sorting of waste should increase the production of fertiliser 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 behaviour (internalising an externality). In a review of the related field of circular economy it was argued that the use of incentivisation is underutilised in proposed blockchain applications, indicating there is still much to explore in this area (Kouhizadeh et al., 2020). In the commercial pilot projects reviewed incentivisation appeared to be a much more common application of blockchain than in the academic literature.
- **Waste services market/platform** – the ability to implement decentralised markets or platforms on a blockchain is presented in the waste management context. In the study of Conforto (2019) it is argued that centralising 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 centralised exchange) and blockchain is only proposed as a possible platform.

Each of these use cases has been explored in separate projects as shown in Table 1. However, there is good reason to believe that synergies may exist between these technologies and that implementing them together in a single environment may create advantages. We believe this remains an unexplored area of the literature which we attempt to partly address in this work.

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 (Wood et al., 2014). 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 Gopalakrishnan and Ramaguru (2019) 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. The scalability and performance of blockchains remains an open problem in blockchain waste management applications with the most promising solutions falling into the categories of layer-2 solutions, side chains, and hybrid approaches (Ahmad, Salah, Jayaraman, Yaqoob, & Omar, 2021), however, no examples of the application of such technologies exists to date.

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 (Lo et al., 2017).

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 (Gopalakrishnan & Ramaguru, 2019). It is difficult to imagine that Ethereum 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.

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. Potentially, this reflects the theoretical nature of previous research. For this reason, we present here two system configurations, one that applies blockchain with a current technology available at a proposed pilot site and one configuration based upon the ideal technology.

Finally, it should be noted that the end goal of these blockchain applications is improvements to sustainability and a transition to a circular economy. As such, the sustainability of the blockchain system itself should be considered (Böckel et al., 2021).

3. Methodology

In this section of the document we describe the design science approach to system development undertaken to produce the final blockchain solution. Design science research is an approach fundamentally interested in the design of new systems and the creation of innovative solutions to existing problems (Dresch, Lacerda, & Antunes, 2015). The goal then of design science research is the creation of an artefact or recommendation to solve problems. These solutions need not be optimal, but instead should provide significant improvements over existing systems, and while design science should be applied to a specific problem the solution should be generalisable for broader application (Dresch et al., 2015).

Design science allows us to achieve a practical solution, by focusing on achieving an actual implemented product that improves over current systems. The iterative development of this project is undertaken by a consortium with five partners[1]: three academic and two industrial, and works closely with the local municipality and a waste collection utility in Portugal, allowing for the incorporation of a wide range of stakeholder input.

In the remainder of this section we detail the approach to system development broadly against the criteria for design science laid out in March and Storey (2008) incorporating the process of Reeves (2006) as presented in 2.

3.1. Problem identification

The design science process starts with a rigorous collaborative problem identification stage that combines researchers, practitioners, and stakeholders. The final output is clear description of the problem and the required properties of desired solution. Problem identification was based on the following activities:

- Collaborative definition of problems and issues within the consortium covering academics in the field of waste management, circular economy, and blockchain, and practitioners in the from waste management, waste management IT solutions, and sustainability.
- Input was sought and provided from additional current practitioners in the areas of waste management and sustainability and a number of site visits were made to waste management facilities.
- Discussions were held with partner municipality and waste management utility on the current problems they face. In addition, a public presentation feedback session was held to allow input from the public in the partner municipality where the pilot is intended to run.
- A systematic literature review covering the SCOPUS, Web of Science, IEEE databases for the following key words: Waste management, blockchain, smart cities, smart city, circular economy for papers published since 2016. The search produced 4541 documents, after screening titles and abstracts 95 documents (23 based on blockchain) were included in the final literature review which was presented to consortium for discussion on the state of the art. The relevant literature is summarised in the literature review section of this document.

It should be noted that the design science process is iterative and the problem definition is refined throughout based on findings in assessment of other solutions, the development of the solution, and the assessment of prototype solutions.

3.2. Assessment of existing blockchain solutions

Based on the literature review on blockchain systems for waste and recycling management we assess existing solutions (both as presented in the academic literature and commercial pilot projects) for their ability to solve the identified problem. As part of this assessment a group of masters students develop a pilot implementation of a simple system for tracking waste based on the Ethereum blockchain. We do not find any system capable of meeting our goals of delivering economic incentives, gamification, and trust in the recycling supply chain. In addition, the Ethereum technology on which existing projects are built is found to not be suitable. As a result development of a full scale solution development exercise is undertaken.

[1] NOVA Information Management School https://www.novaims.unl.pt/, Instituto Superior Técnico https://tecnico.ulisboa.pt/, Carnegie Mellon University https://www.cmu.edu/, 3Drivers https://www.3drivers.pt/, Future Compta https://www.future-compta.com/

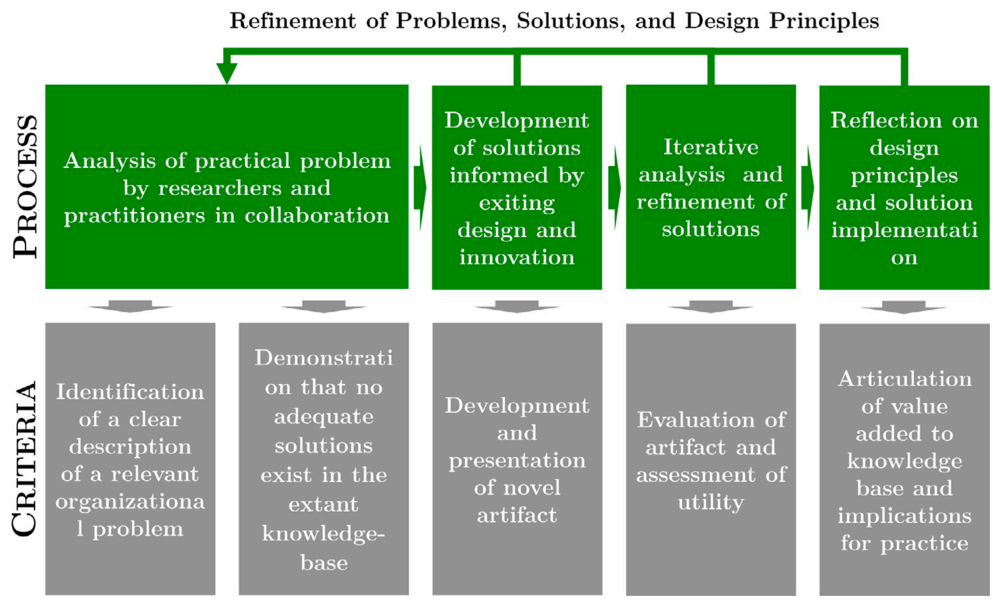

Fig. 2. Design science methodology. This diagram demonstrates the relationship between design process as originally laid out in 2 and criteria of March and Storey (2008).

3.3. Development and presentation of novel technology solution

The major contribution of this research is the presentation of the blockchain solution developed in the course of this project. In line with the design science approach this was a collaborative development between researchers, practitioners, and stakeholders. Both formal and informal collaboration was undertaken throughout with specific events held for feedback and input from experts and stakeholders outside the consortium. However, a key tenet of the design science research is the application of rigour in design (Dresch et al., 2015). As such, we draw on the literature to develop our solution within the bounds of existing blockchain development frameworks. In particular, we apply the criteria of Lo et al. (2017) to the proposed waste management system to identify the areas where the use of blockchain as the technology solution is appropriate. The system design is assessed by the consortium members against these criteria. Where blockchain was identified as appropriate the blockchain design approach of Xu, Bandara et al. (2021) was applied. The approach of Xu, Bandara et al. (2021) identifies the areas where system design is required in the development of a blockchain application, in particular the decision must be made on the approaches to data management, performance, security, oracles, and smart contracts. We then extend this theoretical designed blockchain solution to the Substrate blockchain development framework (Substrate, 2021). Substrate provides a set of functionality that can be used to develop blockchains, a system developer can select a set of "pallets" each containing different functionality, to create a blockchain. We demonstrate how, combining existing pallets with pallets designed specifically for this application, the solution proposed can be implemented.

3.4. Evaluation and assessment of utility

The design science approach to development tends to be iterative, with ongoing assessment feeding into development. The following assessment was applied throughout the project:

- The project has been developed as part of a consortium of industrial and academic partners. Feedback on both the practicality and usefulness of the design has been provided throughout by industrial partners (in the waste management and sustainability solutions and IT services industries), partner academics, and at public presentations. It is difficult to identify distinctly each area this feedback has adjusted, except to note that the final solution is the culmination of a long collaborative process.
- This solution is designed to be consumer facing, and as such public input has been sought throughout the development process. The most significant evaluation was conducted after the completion of the design of the physical system, effectively the part of the solution that the public will interact with. At this stage a short video was developed that explained the proposed system and how households would dispose of their waste and recycling in this system, and interact with the solution (tracking of recycling, rewards and penalty payments, gamification). A survey was conducted of 400 members of the public, drawn to be statistically representative of the population of Portugal,[2] to assess their feedback on this system. The survey was conducted under the framework of the unified theory of acceptance, use of technology 2 (UTAUT2) (Venkatesh, Thong, & Xu, 2012), considered the most complete model for understanding consumer adoption of new technology systems (Tamilmani, Rana, & Dwivedi, 2021). This model, however, needs to be adjusted to the context of the specific technology and sector considered (Venkatesh, Thong, & Xu, 2016) and, as such, was adapted to the waste management sector and to understanding the technologies proposed, including gamification and blockchain. This assessment of the system and technologies based on the UTAUT2 is a significant undertaking and is included in a separate research article, however, the key findings represent an important public evaluation of the project.
- The system design, based on consumer feedback, was additionally evaluated by a local municipality and the waste management utility for that area. This municipality intends to implement the system design presented here in a pilot project. However, the initial design for the system requires a significant investment in enabling technology (either RFID or QR readers for waste collection) and this is not currently justifiable for the pilot project. As such the system was amended to allow for two different configurations, one based on the availability of optimal technology set (OTS) and one based on currently available technology (CT). These differences are discussed further in the results.

[2] Extensive details of the survey can be found in Appendix A.

- The technology partner, who will implement a front end and app for consumer interaction with the blockchain, provided a review of the suggested data structure, oracle system, and interfaces to other systems (for example an android app). As a result of testing the solution in these areas, the data structure was amended and additional means by which to interact with the blockchain added, including the REST API and NoSQL database system.
- Finally, a bench-marking process is undertaken to asses the performance characteristics of the system. A key requirement of system design is that it is able to handle the required level of data input (transactions) at a reasonable cost. We benchmark the functions of each component of the blockchain and comment on the improvements made over the Ethereum based solutions found in the literature.
  The final technology solution presented in this paper then results from a long iterative process of evaluation and amendment, with input provided from fellow academics, industry partners, utilities, municipalities, and finally a large scale survey of the public.

3.5. Articulation of the addition to the knowledge base and discussion of implications

This research article represents an important part of the design science approach, where the solution developed is articulated to add to the existing knowledge base. In addition, this project has been presented at academic, industry, and public events throughout its development. In this publication we demonstrate the addition of this work to the knowledge base, including the fact that, to our knowledge, no existing application of the Substrate blockchain framework exists or any application of a Polkadot parachain blockchain.

4. Results

In this section we detail the novel solution to the issues in waste management identified that is the result of the design science approach applied throughout this project. First, we present the problem identified and then describe the physical system iteratively developed with local municipalities, utilities, and citizens. We then assess the components suitable for blockchain application, and present the blockchain implementation based on the approach of Xu, Bandara et al. (2021) and implemented with Substrate (2021). Finally, we report on the assessment of the solution.

4.1. Problem identification

As discussed in the literature review the European Commission goal of a transition to a circular economy faces many challenges. An issue of particular importance is improving household adherence to the reduce, reuse, recycle framework. In Portugal household recycling rates are significantly below the legally binding targets. Based on our review of the literature, and extensive collaboration with practitioners and stakeholders, we identify two significant potential shortfalls of current systems that are amenable to introduction of new technology: the lack of economic incentives, and a lack of trust and transparency. We then identify two main features to be incorporated into solution:

- Incentives — Economics incentives, know as Pay As You Throw (PAYT) or recycling rewards, are the typical approach used to change household behaviour and should feature in any solution and are typically not applied in Portugal. In addition, the system should be capable of introducing other incentives such as gamification. While there is relatively little literature on the application of gamification to waste management, the degree to which households find recycling enjoyable (or burdensome) is predictive of behaviour. In addition, gamification has demonstrated benefits in other applications for increasing engagement and achieving behavioural change.
- Trust — A key takeaway from interviews with professionals is that households in Portugal do not always trust that the recycling effort is beneficial and that recycled materials actually end up recycled. In the literature we find only limited evidence of this relationship, however, we do find reason to believe that material that is separated does not always end up recycled. The fundamental advantage of blockchain technology is its ability to provide a trust-less system, where users are not required to trust centralised parties. However, blockchain technology can suffer from issues with performance, and a solution must be provided that is fit for the purpose of delivering economic incentives, gamification, and trust in the recycling supply chain.

There are many reasons to believe that features should be considered as interdependent within the system. The UTUAT2 research on the adoption of new technologies found this result to hold. The implications for the project of this research are summarised here:

> Trust was identified as important for explaining consumer adoption (both intention and actual use), and further whether they would recommend the service, a measure of their evaluation of the system. As such, blockchain remains an essential central component of the solution, as a technology primarily focused on delivering trust.
> The effect of gamification was heavily dependent on trust for determining the use of the system, indicating that gamification features should be implemented directly on the blockchain.
> Economic incentives did not play an important role in determining household use of the system. As such, the economic incentivation is implemented independently on the blockchain, such that it is not essential to the operation of the system. However, we keep this functionality based on the input from local municipalities consulted during the project.

4.2. Waste collection and incentivisation solution

Here we propose a unified waste collection and recycling incentivisation system that takes advantage of the characteristics of blockchain technology to address two pressing problems in waste management and collection called BEE2WasteCrypto (Fig. 3. 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. Implementing a system that is verifiable, and not directly under the control of a waste management company that is not trusted by consumers, is designed to 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 municipalities and central government authorities on the quantity of waste and recycling products being produced. This information 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 in

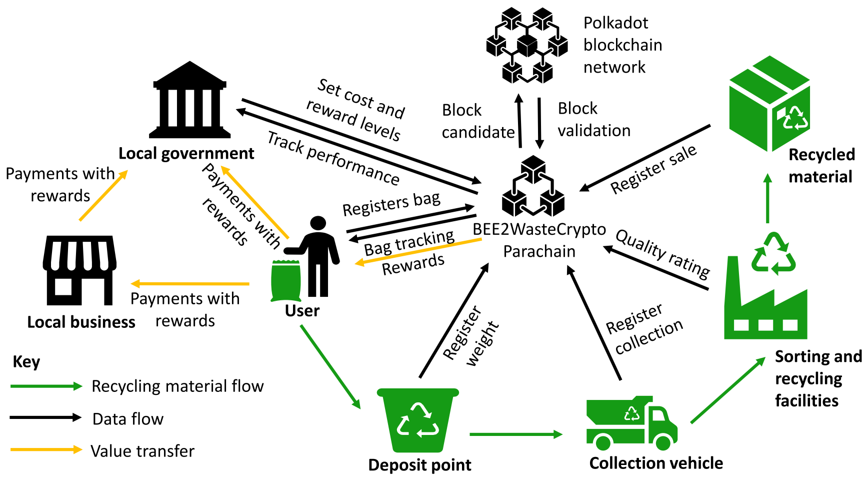

Fig. 3. BEE2WasteCrypto system. BEE2WasteCrypto system overview demonstrating material, data, and value flows as well as interaction with blockchain.

this case, is an identified advantage of blockchain technology (Jardim, Pranto, Ruivo, & Oliveira, 2021). We also find that trust is an important moderator of the effectiveness of gamification, and so it is essential to provide trust in any system looking to utilise gamification.

The technology solution is flexible to different levels of technology availability at the pilot site, a full description of the system is included in Appendix B With the ideal technology the province of waste would be attributable to individual households, both to target rewards and provide personalised feedback on recycling performance.

Regardless of the level of technology associated with the solution the system is designed to:

- 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.
- Provide a platform for the delivery of gamification based on tracked waste and recycling performance.

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

4.3. Assessment of blockchain suitability to application

In Lo et al. (2017) 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 Appendix B against these criteria. The assessment is made by the academic consortium experts in blockchain systems and developers of IT infrastructure for waste management following the approach of Lo et al. (2017). Table 2 demonstrates the suitability of blockchain to this application, which is in line with the findings of Lo et al. (2017) who identify supply chain as a use case where blockchain is a desirable technology solution, and Ahmad et al. (2021) who find this extends to waste management reverse supply chains. 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.

4.4. 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. In this application feedback from industry participants and local municipalities has allowed us to identify the following requirements. The system should provide:

- Trust — through a system that provides sufficient decentralisation, such as achieved with most public blockchains.
- Transparency — is identified as a desirable property to provide trust in the waste management system as a whole
- Performance and affordability — The system must be capable of capturing the level of information required to track a full waste supply chain at reasonable cost.
- Payments capability — The system must be capable of implementing a payment system. In blockchain terms this means finality must be realised in a reasonable time-frame.
- Ease of implementation — a significant issue in blockchain applications and concern of industry participants is the difficulty in implementing a blockchain system.

4.4.1. Assessment of available technologies

As discussed in the literature review there are a number of different approaches to blockchain technologies. We assessed each against the criteria identified as requirements for the waste management system. The main findings are summarised below.

Implementing the system as smart contracts on an existing public blockchain provides the ideal trust properties for the system. In addition the development for Ethereum is the most tested and mature in the ecosystem. However, an initial pilot implementation of the system on the Ethereum demonstrated conclusively that the required cost performance could simply not be achieved with each interaction with the blockchain costing upwards of $20, which is simply not practical for a supply chain application. While many alternative public blockchains gained popularity during the timeframe of the project, their fees tended to rise with their popularity and in general it was evaluated that this approach left the project open to unpredictable changes in fees based upon the popularity of the public blockchain.

An initially trialled alternative approach would be to fork an existing blockchain such as Ethereum so that this project would not compete with others. However, this was assessed to have a number of shortcomings. Firstly, either the consortium would run all the nodes (making the system centralised) or would need to incentivise sufficient participation from the public to run nodes. It was unknown if the later could realistically be achieved and at what cost. Finally, the energy requirement and un-sustainability of the Ethereum proof-of-work system was a concern for a system designed to contribute to the circular economy.

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	✓
Centralised 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 (Casino et al., 2019).	Required	✓
High performance	As discussed in Casino et al. (2019) high performance is relative and the performance of a blockchain system will depend on design. However, high velocity data is not a requirement and at least initially neither is Big Data. The system should be designed to scale to the application requirements.	Not required	✓

Private permissioned blockchain offered a solution to the scalability issues and also offered relatively mature development frameworks for ease of implementation. However, these are simply not able to provide trusted transparency to a consumer facing system, there is little reason for a consumer to trust such a system over a conventional database.

Finally, hybrid blockchain network solutions were considered such as Polkadot or Cosmos. These relatively new developments promised the flexibility to take advantage of the trust benefits of public blockchains and the performance of private blockchains. The Polkadot framework, where we would develop a parachain, was selected for trialling based upon the maturity of the Substrate development framework and the connections to the web3 foundation. The web3 foundation supports the development of Ethereum as well as Polkadot and this provided some assurance that this project would be maintained for the foreseeable future.

Substrate (2021) is a framework 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.

A number of risks and disadvantages to this approach were identified and mitigating measures were undertaken:

- At the commencement of the project no parachain was operating on Polkadot, as such there was a risk this technology would not deliver on its promise within the timeframe of the project. It was assessed that in the event this functionality was not available the system would be transitioned to public blockchain built with Substrate.
- The Substrate framework, while mature by blockchain standards, is still relatively new and under active development. As such, changes which implement important security features but break backwards compatibility can be introduced. This was considered a risk and additional development time was allocated with this in mind.
- At the commencement of the project there was little available information on the performance of Substrate blockchains or polkadot parachains. An early prototype was developed to test that this technology would achieve the performance requirement.
- To secure a slot on the Polkadot network, a parachain must win an auction where it commits to lock a certain amount of "Dot", the polkadot cryptocurrency. While this is a deposit that would be returned it would still reflect a cost, and an unknown one, for the project. To address this issue for the prototype application a parachain will 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. Parathread offers the ideal combination of decentralised trust of a public blockchain and the performance of a private permissioned blockchain. To actually develop a Polkadot parachain we make use of the substrate blockchain development framework.
- A Polkadot parachain is required to add blocks at the speed specified by the Polkadot network, currently every 6 s, 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 parathreads and significantly lower fees are expected. A parathread then is simply a Polkadot parachain that adds blocks at a lower frequency than that required of a parachain and was identified as the ideal solution, however, this functionality remains unavailable.

4.5. Blockchain design and implementation

In this section we apply the decision making model of Xu, Bandara et al. (2021) 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 to the set of potential solutions. We then show how these solutions can be implemented in the selected blockchain development framework of Substrate.

4.5.1. 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 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.

For the final system the basic FRAME Substrate structure is then modified by adding the Cumulus (2021) pallet which adds the functionality required to join the Polkadot network as a parachain. 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.

4.5.2. 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 Ethereum network at considerable cost. 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 supply chain component of the system we develop two new Substrate pallets based upon the supply chain approach outlined in Rius, Chu, and Degosserie (2021).

The first pallet, named waste-registry, is used to generate the information associated with a waste collection. Each individual bag will be tracked by this system. When a collection vehicle starts a collection process it creates a WasteCollection object, and each bag 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 of the arrived WasteCollection.

The reward system is also implemented in two pallets, one that determines the rewards (eco-reward-system) and another 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 rules for how rewards should be distributed must be defined by the municipality and are not included here. The balances pallet is a standard pallet available for FRAME that implements a simple payment system, that allows for the transfer of a currency which we here call Eco-Credits.

A gamification pallet is also developed. This pallet builds 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.

4.5.3. 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.

Finally, in the context of the Polkadot blockchain network a performance decision must be made about whether to implement a blockchain as a parachain (constantly connected to the network and adding blocks every 6 s) or a parathread which can intermittently connect to the network. The supply chain functionality is unlikely to require such a fast block speed as there should be little issue with transactions (registering data) needing to wait more than 6 s before registering to the blockchain, although transaction finality will take slightly longer. 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.

4.5.4. Security design

In regards to security (Xu, Bandara et al., 2021) 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 organisations 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 Agarwal, Barve, and Shukla (2021)).

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 and allows for the application of this approach or the reliance on RBAC.

4.5.5. Oracle design (interaction with the blockchain)

A blockchain operates as a largely self-contained eco-system where transparency, verifiability, and trust can be enforced. 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.

Table 3
Calculated blockchain performance metrics including weight, transaction per second (TPS), and transactions per block (TPB). Weight is defined as 1000 weight = 1 ns, on fixed reference hardware (Intel Core i7-7700K CPU with 64 GB of RAM and an NVMe SSD).

	Transfer	Add new user	Change user collection point	User deposit waste	Collector pickup waste	User claim rewards
Formula for weight calculation						
Base weight (000's)	125 000	125 000	125 000	125 000	125 000	125 000
Constant (000's)	57 580	18 776	70 564	363 951	115 340	284 927
Users (u) (000's)		69	266			
Collection points (p) (000's)			672			
Deposits at collection point (d) (000's)				382	6848	
Unclaimed deposits (c) (000's)						12 555
Reads	1	2	6	9	12 + d	6 + c
Writes	1	2	5	6	6 + d	3 + c
Calculated transaction weights						
Minimum weight(000's)	307 580	393 845	846 502	1 314 333 000	1 272 188	997 482
Typical weight (000's)	307 580	407 576	900 780	1 352 151 000	14 325 140	10 763 887
Maximum weight (000's)	307 580	1 083 776	3 539 164	1 695 951 000	132 988 340	138 414 927
Calculated transaction per block (TPB) and transactions per second (TPS)						
Maximum TPB	14 630	11 426	5 316	3 424	3537	4511
Typical TPB	14 630	11 041	4 996	3 328	314	418
Minimum TPB	14 630	4 152	1 271	2 653	34	33
Maximum TPS	2 438	1 904	886	571	590	752
Typical TPS	2 438	1 840	833	555	52	70
Minimum TPS	2 438	692	212	442	6	5

For submission of data on waste collection a push based inbound oracle design is implemented (Xu, Bandara et al., 2021), 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 (Xu, Bandara et al., 2021) 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.

4.5.6. 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 to 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 by users is not required. This additionally greatly reduces the security risks by only allowing a specific set of activities upon the blockchain.

4.5.7. 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 allow for an elected set of decision makers among all users, which may be appropriate in the future.

4.6. Quantitative performance evaluation

In this section we provide benchmarking results of the blockchain solution developed to demonstrate the performance characteristics.[3] To benchmark the blockchain we calculate the "block weight" or the portion of the available computation in a given block that each action (transaction) will require. Setting this block-weight is then also essential to determining how many transaction should be placed in each block. For a number of the transactions types, the weight will depend on several parameters. For example, when a user wants to claim their rewards, the calculation will depend on the number of tracked deposits of recycling material they have made that have not yet been claimed. We present the formula calculated from the benchmark exercise for each of the typical transaction types in Table 3. We also determine estimates for the weight, transactions per second (TPS) and transactions per block (TPB) under different circumstances,[4] with the intention of deriving practical upper and lower bounds based on the pilot.

[3] Benchmarking undertaken on a 3.5 GHz Ryzen 3950X with 64 GB of ram and m4 SSD running Ubuntu 20.04.

[4] Minimum weight: 1 user, 1 collection point, 1 deposits at collection point, and 1 unclaimed deposit. Typical weight: 200 users, 3 collection point, 100 deposits at collection point, and 72 unclaimed deposit. Maximum weight:

From these results we can conclude the blockchain system is capable of handling the required performance. In this case that the weight of a given action is greater than the available backspace (50 users each simultaneously attempt to claim the rewards from 1000 deposits) some of these transaction would simply need to wait the 6 s for the next block. In the case that the solution intends to be scaled to millions of users each "pallet" can be duplicated within the blockchain.

5. Conclusions

Even developed countries are currently struggling to improve the sustainability of their waste treatment and this area is in urgent need of new solutions. In particular, rates of recycling and quality of recycling separation vary highly and a number of factors have been used to explain these differences. Improving these recycling rates is a key factor in transitioning to a circular economy.

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. The role of trust in institutions has been highlighted as of particular importance in achieving citizen compliance with public policy goals following the recent COVID-19 pandemic. It is then of increasing importance that utilities and governments that serve the public promote public trust in their actions.

In this research we apply a design science approach to develop an innovative waste collection and incentivisation 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 behaviour.

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. 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.

CRediT authorship contribution statement

Ian J. Scott: Conceptualization, Methodology, Software, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Miguel de Castro Neto:** Conceptualization, Writing – review & editing, Supervision. **Flávio L. Pinheiro:** Writing – review & editing.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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Appendix A. Survey methodology

As part of the scientific design process of developing a new waste management system a survey was undertaken of the general public to determine the factors that would influence technology adoption. The survey was based on the Unified Theory Of Acceptance And Use Of Technology 2 (UTAUT2) (Venkatesh et al., 2012) framework of technology adoption with adaptions to account for the waste management sector and the specific technology tested. To explain the new system to respondents a video was developed (the script of which is included below). Before conducting the survey, the constructs were reviewed by a panel of industry experts in Portugal. An online survey pre-test was distributed to 26 participants to guarantee the adequacy of the questions and items. The market research company Netsonda was commissioned to undertake the survey. This approach was selected for its ability to target households within the reference country of Portugal and achieve a representative sample. All the respondents belonged to the company's internal panel and were compensated for their participation. 400 participants took part in the survey. The survey was undertaken in April 2021, in Portugal. It took approximately 10 min to complete. Respondent demographics are included below in Table A.4. These are followed by the script of the informational video used to describe the waste management system and the constructs tested for in the survey as well as their sources in the literature in Table A.5.

A.1. Translated video script and measurement items

In this video, we will present a new and innovative household waste collection system. In this new system, the user will receive a set of different coloured smart waste bags delivered to their home. These smart waste bags can also be collected from grocery stores, post offices, and local shops. The user will sort their home waste into the different colour smart waste bags, with each colour representing a different type of waste. For example, plastic recycling will be sorted into a yellow bag, glass into a green bag, compostable waste into a brown bag, and all other waste into a black bag. The bags used for recycling material will be available without cost; however, bags for unrecycled waste will have a cost for the user, reflecting the costs of disposing of this waste. The user will deliver the sorted bags in the way they usually dispose of their waste and recycling, whether it is collected from a bin in their building, should they live in an apartment block, or if they need to deliver it to local drop off points, in cases where they live in single dwellings. Each of these smart waste bags is registered to the user and tracked through a system. When the waste collection truck picks up the bags, this event will be registered. When the bags arrive at the waste treatment facilities, this occurrence will also be registered. Then, when the final recycling materials are sold on to potential manufacturers to be recycled into new products or other disposed waste, these details will also be recorded. All of this information will be available to the

10 000 users, 50 collection point, 1000 deposits at collection point, and 1000 unclaimed deposit.

Table A.4
Study demographics.

Demographic characteristic		Sample (n = 400)	Percentage (%)
Gender	Male	184	46.00%
	Female	216	54.00%
Age	20–29	52	13.00%
	30–44	100	25.00%
	45–64	147	36.75%
	>64	101	25.25%
Highest level of education	No degree completed	14	3.50%
	High school degree	177	44.25%
	Bachelor's degree	73	18.25%
	Master's or Postgraduate degree	123	30.75%
	Doctorate	13	3.25%
Monthly income per family	Below 1000 euros	86	21.50%
	1001–1500 euros	77	19.25%
	1501–2000 euros	83	20.75%
	2001–3000 euros	77	19.25%
	>3000 euros	45	11.25%
	Prefer not to answer	32	8.00%
Area	Rural	81	20.25%
	Urban	319	79.75%
People in household	1	51	12.75%
	2	136	34.00%
	3	113	28.25%
	>3	100	25.00%

user through a waste collection system app, where they can track the progress of their waste and recycling through the system. The app will provide feedback on the recycling performance of the user, helping to inform them of how well they separated their waste into different recycling categories, and they may receive penalties where products have been incorrectly included for recycling. The app will provide detailed instructions, frequently asked questions, and information on how to sort different products that the user can access at any time. Users will receive points on the app, unlock achievements for their recycling efforts, and check how their performance compares to the average recycling characteristics in their neighbourhood. They will also be able to check how well their neighbourhood compares to others, and competitions will be run with rewards allocated to the most sustainable neighbourhood. In addition, the points received by users for recycling can be spent on reducing their utility bills, such as their water bill, or purchasing black bags for unrecyclable waste. The innovative waste collection system will provide users with transparency on how their waste and recycling is treated and where it ends up. At the same time, it will allow users to benefit from their recycling efforts while helping to protect their immediate local environment and create a sustainable community.

Appendix B. Description of waste management solution

The system that achieves this functionality is outlined below and is presented with two specifications, one based on the current technology (CT) available at the site of a potential pilot project, and one based on optimal technology set (OTS). 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 PAYT. 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 volume of collected product, and a spot check evaluation of the quality of separation of recycled material.
4. Having completed a waste collection route the vehicle will deposit all material at a treatment facility. Again, this action will be registered on a blockchain. At this point the total weight of the material will also be recorded.
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. 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 municipality then has the option to base the payments for waste disposal of the household on the information provided by the system. For example, it also allows the provision of rewards to households based upon their recycling performance

Table A.5
Survey measurement items and sources.

Construct	Items	Source
Performance Expectancy (PE)	PE1. I feel the waste management system (WMS) will be helpful in my daily life. PE2. Using the WMS will help me accomplish things more quickly. PE3. Using the WMS will increase my productivity.	Venkatesh et al. (2012)
Effort Expectancy (EE)	EE1. Learning how to use a WMS looks easy to me. EE2. The WMS looks clear and understandable. EE3. I feel the WMS will be easy to use. EE4. It will be easy for me to become skillful at using the WMS.	
Social Influence (SI)	SI1. People who are important to me think that I should use the WMS. SI2. People who influence my behaviour think that I should use the WMS. SI3. People whose opinions that I value prefer that I use the WMS.	
Facilitating Conditions (FC)	FC1. I have the necessary resources to use the WMS. FC2. I have the necessary knowledge to use the WMS. FC3. The WMS is compatible with other technologies I use. FC4. I can get help from others when I have difficulties in using the WMS.	
Hedonic Motivation (HM)	HM1. Using the WMS looks like fun. HM2. Using the WMS looks enjoyable. HM3. Using the WMS looks very entertaining.	
Pay as you throw (PAYT)	PAYT1. The payment should increase when users produce more unsorted waste. PAYT2. If I do not recycle, I should pay a fee. PAYT3. I should be charged a rate based on how much unsorted waste my household produces. PAYT4. It is fair to pay for unsorted waste disposal.	From authors
Save as you throw (SAYT)	SAYT1. It is fair to get a reward for recycling. SAYT2. If I recycle, I should get a reward. SAYT3. I should be rewarded based on how well my household recycles. SAYT4. The reward should increase when users produce less unsorted waste.	
Habit (HT)	HT1. The use of the WMS can become a habit for me. HT2. I could become addicted to using the WMS. HT3. I must use the WMS.	Venkatesh et al. (2012)
Behavioural Intention (BI)	BI1. I intend to use the WMS in the future. BI2. I will always try to use the WMS in my daily life. BI3. I plan to use the WMS frequently.	
Use Behaviour (USE)	US1. Rewards US2. Tracking US3. FAQ US4. Instructions US5. Competition US6. Smart Waste Bags US7. Points	
Intention to recommend (IR)	IR1. I will recommend my friends to use the WMS. IR2. If I have a good experience with the WMS, I will recommend friends to use it. IR3. I would recommend the WMS to someone who seeks my advice.	Naranjo-Zolotov, Oliveira, and Casteleyn (2018)
Trust (OT)	OT1. I would like to trust this WMS. OT2. I would find this WMS trustworthy. OT3. I would like the reliability of this WMS. OT4. I would value the trustworthy characteristics of this WMS.	Oliveira, Alhinho, Rita, and Dhillon (2017)
Gamification (GA)	GA1. Collected points GA2. Achievements GA3. Competition between neighbours GA4. Competition between neighbourhoods	Hamari, Hassan, and Dias (2018)

and the introduction of gamification based upon neighbourhood performance.

8. With a specified payment/reward scheme the 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 households 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 (Elgaaied, 2012).

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 OTS 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 Fig. 3.

Regardless of the level of technology associated with the solution the system is designed to:

- 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.
- Provide a platform for the delivery of gamification based on tracked waste and recycling performance.

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

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