Blockchain Technology for Sustainable Waste Management

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The global waste and resource crises necessitate and give great impetus for better and more sustainable management of waste. Increasingly, resource and waste streams that once were sent to landfill or incinerated are now reused, recycled, or recovered. Yet, while many laws and policies have been adopted for this very purpose, a number of recurrent challenges persist across interventions seeking to further facilitate the necessary, widespread transitions to sustainable waste management. This perspective article explores the suitability of blockchain technology in overcoming these challenges. In particular, we discuss the opportunities and challenges for blockchain in (1) offering clarity in property rights of products and wastes, (2) supporting law and policy goals by incentivizing sustainable waste management, and (3) maintaining anonymity and privacy for institutions and individuals.

Keywords: blockchain, waste management, waste law, sustainability, circular economy

1. INTRODUCTION

There are concomitant global waste and resource crises that necessitate more sustainable waste management practices, comprising redirecting waste streams once sent to landfill or incinerated to be reused, recycled, or recovered instead (e.g., Velenturf and Purnell, 2017). To underpin such practices, principles and aims such as "zero waste" (e.g., Silva et al., 2016), "circular economy" (in which wastes and resources are prevented, reused, recycled, or recovered) (e.g., Kirchherr et al., 2017), and "resource efficiency" (e.g., Wilts et al., 2016) have been introduced. The impetus for changes to waste governance to incorporate some of these principles and aims (both in incentivizing their adoption as well as in response to their presence) has resulted in many laws and policies being adopted, such as the European Commission (2020) Circular Economy Action Plan, the Anti-Wastage and Circular Economy Law of France (2020), and the People's Republic of China (2008) Circular Economy Promotion Law. Central to many of these are the tracking and monitoring of wastes. Tracking data is key in complying with existing laws and policies, and it also has the potential to inform laws and policies that may further prevent the "wasting" of waste through landfilling or incineration. Tracking wastes and monitoring their owners to generate this data is, however, a complex undertaking. Complications may arise from, for example: products breaking down into smaller components; existing laws, such as extended producer responsibility (which requires producers to be responsible for subsequent wastes from their products); and the abandonment of property through littering or fly-tipping. Tracking wastes and monitoring their owners therefore requires more practical solutions than currently are widely implemented.

In this perspective article we explore one such practical solution identified in literature and practice, namely blockchain technology (Saberi et al., 2018; Steenmans and Taylor, 2018). Blockchains are a virtual distributed ledger on which data can be permanently stored such that

it is verifiable and auditable (Swan, 2015). In particular, in this brief conceptual and theoretical inquiry, we discuss the capability of blockchain in

- Offering *clarity* in property rights of products and wastes,
- Supporting policy goals by *incentivizing* sustainable waste management, and
- Maintaining *anonymity and privacy* for institutions and individuals.

The remainder of this article is structured as follows. In section 2, we provide the necessary background on blockchain and waste management, including how blockchain is currently employed within the waste management sector and some of the practical limitations and feasibility issues. Section 3 then discusses the opportunities for and challenges of widespread adoption of blockchain for sustainable waste management, with a focus on clarity, incentivization, and privacy, before providing some concluding remarks.

2. BLOCKCHAINS FOR (SUSTAINABLE) WASTE MANAGEMENT

Blockchains store data in a series of connected blocks, such that any change in one block is easily detectable by computing its cryptographic hash and comparing it with the hash stored in the following block. Any difference between the generated and stored hashes is evidence of a change in the first block. Furthermore, updating the hash stored in the second block is detectable by computing and comparing its hash with the one stored in the subsequent block. As a result, any change to a historical block requires all subsequent blocks to be updated. Distributed consensus algorithms such as proof of work, stake, or space ensure it is computationally or financially infeasible to do so. Unfortunately, because blockchain data is persistent, this also means fraudulent data that is entered into a block exists forever.

Blockchains are most famously applied as cryptocurrencies such as Bitcoin, but at their core they are simply data stores that cannot reasonably be tampered, enabling smart contracts that automate transactions without intermediaries. Such a permanent and trusted data ledger may be useful within the waste management sector for a number of reasons. At their core, blockchains are particularly adept at enabling and tracking transactions—such as transfers of digital assets or value, or transactions involving physical objects with digital identifiers, for example via QR (Quick Response) codes or RFID (Radio-frequency Identification) tags—thereby providing provenance (i.e., eliciting origins of assets) and facilitating the initiation of smart contracts. The provided provenance enables auditing to identify wrongdoing and impose penalties (e.g., to track whether toxic waste has been lawfully disposed of) and corroboration to resolve disputes between users (e.g., where companies disagree about a waste transaction). Smart contracts can be used to automate penalization and avoid disputes in the first place. These benefits of blockchain facilitate trustworthiness of users and provide incentives for them to act honestly in their transactions and recording of events.

2.1. Blockchain Application in Waste Sector

The application of blockchain within the waste management sector is a particular example of supply chain management, on which there is increasing attention (e.g., Kouhizadeh and Sarkis, 2018; Saberi et al., 2019). Within the context of waste management, current applications of blockchain typically focus on (1) payment or rewards facilitation (e.g., Agora Tech Lab, 2018; Plastic Bank, 2020); or (2) monitoring and tracking of waste [e.g., initiatives by SNCF (La Rédaction, 2017) and the Dutch Ministry for Infrastructure (Hinchcliffe, 2018)]. In the first case, an entity depositing waste is rewarded or paid with a blockchain-secured digital token, which can be redeemed for goods or exchanged for other currencies. The Plastic Bank uses such blockchain rewards to incentivize individuals to become plastic waste collectors, particularly in developing countries, with an aim of reducing the amount of plastic that ends up in the oceans. The gathered waste is brought to collection locations where the waste is weighed, before a payment is made to the collector through a blockchain-based banking application. The immutability and transparency of blockchain prevents fraudulent and corrupt practices. The checking of waste is often performed by a human, but could be automated in some cases (e.g., reverse vending machine, Tomari et al., 2017). Other examples of blockchain payment or rewards facilitation exist with and without social aims (e.g., Sanderson, 2017).

In the second case, data on the type of wastes collected and waste transfers is recorded on the blockchain. Arep, a subsidiary of SNCF (the French national railway company), used blockchain technology to monitor the amount, type, and frequency of waste collected in train station waste bins in order to optimize waste collection. SNCF recorded the waste data and transfers in blockchain transactions using the digital identities of bins on train platforms. The incentive for this was in part financial; there was insufficient data to produce precise invoices from the waste collector, so there was a risk that the station was being overcharged, which could be overcome using blockchain and the bin sensors. In the long term, it was hoped that there would be environmental benefits by using the data to inform the introduction of more separation of waste. This application has been discontinued as waste management was not a priority for the station management. Initiatives with similar intentions of collecting waste type and amount data in order to inform more effective and efficient waste management are being developed (e.g., Lidbot, 2020).

2.2. Implementation and Feasibility Issues

A number of limitations exist in relation to using blockchains both generally (e.g., Sadhya and Sadhya, 2018; Biswas and Gupta, 2019) and for particular applications within waste management (discussed here). In contrast to rewards facilitation which requires the waste only to be checked (e.g., the Plastic Bank checks the plastic waste received once at the collection location before making a payment), recording the waste chain requires individual or groups of waste items to be repeatedly identified at defined life-cycle stages (e.g., at the train station

this was when waste was first discarded and then again when collected). For both applications, physical objects can be stored on the blockchain via their digital identities, but generating reliable digital identities is challenging, particularly when needed throughout a resource's life-cycle. For instance, QR codes or RFID tags are only reliable if they can be read, which is not guaranteed if waste is broken up. This is a a particular issue with certain plastics that break up into micro-plastics (e.g., Law and Thompson, 2014). Similarly, it becomes infeasible to both join waste streams and retain identities for individual waste components. In practice, applying certain assumptions and limits can help overcome these challenges. For example, material waste from an industrial process may be handled in batches and priced per ton from the beginning, and stored as such on the blockchain with a digital identity for the batch rather than the individual pieces. These barriers are also identified in and relevant to supply chain management (Kouhizadeh and Sarkis, 2018; Saberi et al., 2019).

3. DISCUSSION

We identify three challenges in relation to what blockchain can offer the governance of waste management: clarity, incentivization and privacy.

3.1. Clarity

Recording the generation and transfer of resource and waste streams on the blockchain provides a record of provenance for wastes. This provenance can be used to confirm that a transfer or the discarding of waste occurred, as well as identify the organization or individual that is responsible for the waste. For example, ownership of waste W can be transferred from organization O to individual I and recorded on the blockchain using their digital identities. If this is also the last blockchain record that contains W, we can also discern that I is responsible for the waste if responsibility transfers with ownership. Simultaneously, this record also enables identification for future uses of waste, such as who has the available wastes for the formation of new markets where they are reused, recycled, and recovered (e.g., to transition toward circular economies). Such records on the blockchain are clearly useful for auditing resource and waste streams (which may aid regulatory compliance), but requires a number of assumptions.

First, the data entered on the blockchain must be correct. While the data on a blockchain cannot feasibly be edited, it is possible for incorrect data to appear in new blocks. Furthermore, as blockchain data cannot be edited, incorrect additions cannot easily be fixed. It is therefore important to have robust protocols for recording transactions, such as automating the process using complementary technologies (e.g., via RFID) or requiring digital signatures from all parties involved in a transaction.

Second, it does not help define who in a chain of ownership has (financial, legal, physical, etc.) responsibility for any waste. The type of responsibility and whether it transfers with ownership may be set out in laws and policies, but gray areas exist (e.g., Thomas, 2014; Steenmans and Malcolm, 2020). Simply, this may be the last owner; if O produces

waste, then O is responsible for physically discarding it in a lawful manner, which will often entail transferring it to a waste management operator and paying for its disposal (or other management). In a household context, this may happen upon the collection of the household bin. Extended producer responsibility is an example of a measure where the responsibility for waste does not transfer with ownership, but instead the product producer retains some form of responsibility—this may be physical responsibility, economic responsibility, liability, or informative responsibility (Lindhqvist, 2000). Extended producer responsibility has been implemented within the European Union, for example, for certain products (e.g., end-of-life vehicles, Castell et al., 2004) and is identified as a measure to strengthen the re-use, prevention, recycling, and other recovery of waste (European Parliament and Council, 2008). There may also be instances where the identification and clarity of the owner may be unhelpful and have possible detrimental socio-economic impacts. For example, the livelihoods of informal recyclers or waste pickers could be put at risk if those responsible can be identified and therefore held responsible for their own waste (Barcelona Research Group on Informal Recyclers, 2020).

Furthermore, these assumptions are further complicated by the lack of clear definitions and boundaries. While smart contracts cement definitions once they are made, their subject (i.e., waste) and terms (i.e., pre-requisites for execution) must still be defined by the parties involved, which is problematic when a legal definition has resulted in disputes [as is the case with "waste" in certain contexts such as the European Union, as evidenced by the volume of existing case law (e.g., Steenmans, 2018; Steenmans and Malcolm, 2020)] or does not exist [as is the case with sustainability (e.g., Ross, 2009)].

3.2. Incentivization

The existence of a database containing waste ownership and provenance information can be used to incentivize sustainable waste management. First, it is possible for auditors to analyse the data to identify organizations and individuals that are not practicing sustainable waste management. Fines can be given to those that are non-compliant with laws, or advice given to those that have the potential to improve.

Second, the existence of the database can act as an incentivization mechanism in and of itself, especially if the data or reports generated from it are publicly accessible. In particular, organizations may fear reputational damage if they are found to have poor waste management—though there are questions regarding the strength of reputational penalties in relation to "irresponsible behavior" (in this case unsustainable waste management) (Jackson and Brammer, 2014).

As well as being an incentive for improving waste management, in particular for the current holder, potential recipients may be discouraged due to the extra administration, including validating the blockchain transaction.

Here the aim is to incentivize owners of waste to relinquish their ownership in ways that are sustainable, either by transferring ownership or by disposing of it properly. That is, the incentive is for producers and sellers to manage and transfer their waste sustainably, i.e., that they care where their waste ends up.

In some sense this is the mirror of sustainability incentivization in supply chains, where the aim is to encourage buyers and consumers to purchase goods from sustainable providers, i.e., that they care where their products come from.

3.3. Anonymity and Privacy

The waste generated (including that "wasted," recovered, or discarded) by an organization, individual, or other entity contains information about their practices. Industries, for example, may have intellectual property concerns in relation to their produced waste, and many households would not want their waste to be itemized and detailed due to privacy concerns. In many cases, therefore, it may not be desirable to permanently store this information on a blockchain; but the trade-offs between privacy and benefits in tracking and incentivizing sustainable waste management requires further research. Furthermore, blockchains can be encrypted such that a transaction can be viewed only by the parties involved and accessible by auditors so that they can monitor and track the resource and waste streams. This would, however, limit the incentivization ability as discussed in the previous subsection to enforced auditing.

3.4. Concluding Remarks

The preceding discussions demonstrate that there are some fundamental issues that need to be resolved before blockchain technology applications within the waste sector can have the desired effects for supporting sustainable waste management. In this discussion we have also assumed that "sustainable waste management" is a non-problematic concept and can cover an array of policy aims, such as the circular economy. There are, however, questions in relation to what management operations are considered "sustainable." These may relate to the emphasis placed on the different economic, environmental, and social pillars of sustainable development (Ross, 2009). The focus tends to be on economic and often environmental benefits, but social benefits, and resultant equity and justice issues, are often overlooked (Steenmans and Lesniewska, forthcoming). In practice questions also exist in relation to particular management operations. Incineration, for instance, has been described as promoting and supporting resource efficiency and the circular economy, if used in waste-to-energy systems to support district heating systems (e.g., Malinauskaite et al., 2017). But, other studies have highlighted the misconceived perceptions of benefits of energy recovery (e.g., Steenmans, 2017).

Moreover, waste management is usually focussed on managing waste that has already been created. The direct impact of applying blockchain in this domain is therefore to ensure its proper management and processing (i.e., landfill is avoided). A major law and policy concern and goal, however, is waste prevention. The blockchain data does not achieve prevention, but the data that can be extracted can be used to inform the laws and policies needed to achieve preventive action.

The discussion of challenges also highlights that the usefulness of blockchains currently is in uncovering issues of any technology (whether blockchain or another technology) can be used effectively. These discussions, however, do not imply that blockchain cannot be valuable at this stage, as demonstrated by initiatives such as the Plastic Bank, but emphasize the need to consider certain issues, as blockchain in and of itself cannot solve the waste crises. While the data may be a valuable resource in understanding and improving waste chains, blockchain is not required for such data to be collected. In particular, blockchain is adept in domains where a reliable central authority is infeasible, which is generally not the case in waste management. Indeed, in many applications of blockchain in waste management there remains a central authority that is required to ensure entries to the blockchain are correct. In such cases, the blockchain can be replaced by a centralized database managed by the trusted central authority.

Finally, because blockchain is a developing technology, its use in a domain often becomes the focus rather than the underlying problem being solved. That is, the focus is on using blockchain to solve an issue (i.e., "solution-led" problem solving), rather than focusing on the problem and identifying the most appropriate solution (i.e., "problem-led" problem solving). Further research is thus required to clearly identify the problem, before comparing the possible policy or technological responses in terms of their economic, environmental, and social effectiveness and efficiency. Regardless, the use of blockchain is often seen as a positive factor and can be beneficial in attracting attention when seeking funding for a project.

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PT, KS, and IS contributed to the intellectual development of the main ideas of this manuscript equally. The structure was drafted together, PT led on the writing and KS and IS reviewed and significantly edited.

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